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Special Issue Reprint

Spatial Planning and Land-Use Management

Edited by
Eduardo Gomes, Eduarda Marques da Costa and Patrícia Abrantes

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About the Editors

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Eduardo Gomes (EG) holds a Ph.D. in Geography and currently serves as an Assistant Professor at the Institute of Geography and Spatial Planning at the University of Lisbon. His recent research is centered in designing models and collaborative simulations to analyze changes in land use and land cover. The majority of his published works strongly emphasize geospatial modeling, land use, and decision-making processes. EG has been a Visiting Research Fellow at prestigious institutions worldwide, including the Institut des Systèmes Complexes de Paris in France, the Future Cities Laboratory in Singapore, the University of Copenhagen in Denmark, and the Royal Melbourne Institute of Technology in Australia. In recognition of his outstanding contributions, EG has received notable awards, including the Portuguese National Geography Award in 2020 for the best Ph.D. thesis (Orlando Ribeiro). Additionally, EG actively contributes to the scientific community by serving as an editor and reviewer for several esteemed scientific journals.

Eduarda Marques da Costa

Eduarda Marques da Costa, PhD in Spatial Planning in 2001, is associate professor in the Institute of Geography and Spatial Planning of University of Lisbon. She has taught Geography and Spatial Planning since 1990, and she has been a researcher in the Centre of Geographical Studies since 1987 and member of Terra Laboratory of Excellence. Her main scientific areas interest are Sustainable urban development; Regional, Urban and Local Planning; Cohesion Policy and Evaluation of Public Policies. Since 1988, EMC has consultanted for private and public institutions and participated and coordinated a large number of projects, namely ESDP and ESPON. From 2015 to 2022, she was an ad hoc expert in the URBACT III Programme (European Commission). She was also a visiting Professor in U. Bordeaux, U. Washington and U. Paris 7-LabEx DynamiTe as well as a Board Member of IUPEA—International Urban Planning and Environment Association.

Patrícia Abrantes

Patrícia Abrantes holds a Ph.D. in Geography with a specialization in spatial planning. Since 2018, she has been serving as an assistant professor at the Institute of Geography and Spatial Planning, Universidade de Lisboa. In this role, she teaches courses on Spatial Analysis, GIS, Statistics and Spatial Planning, Urban Agriculture, and Modeling across various undergraduate, master’s, and Ph.D. programs.

Additionally, Dr. Abrantes is a researcher at the Centre of Geographic Studies and serves as the co-coordinator of Research Line 5 - Socioecological Systems, Planning, and Policies at the Laboratory TERRA within the same university. She has actively contributed to numerous research projects, such as DAUME (Sustainability of Urban Agricultures in the Mediterranean Area) and AgriMet-MOD (Metropolitan Agriculture Spatial Modeling). More recently, she has been involved in the ACCTING project (Advancing Behavioral Change through an Inclusive Green Deal). Currently, she leads the research project Care4Food, focusing on choices and perceptions of food security and sustainability in a changing climate.

Dr. Abrantes’ research interests are on the application of geographic technologies to spatial planning, with a particular emphasis on metropolitan spaces. Her expertise spans various subject areas, including land use and urban agriculture, agriculture ecosystem services, urban form, spatial analysis, and participatory GIS.

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Editorial

Spatial Planning and Land-Use Management

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1. Introduction

Preserving natural and semi-natural areas has become a crucial consideration for policymakers, with several drivers recognized as pivotal forces that shape landscapes globally. Among these drivers, socioeconomic, demographic, climatic, and political factors have the most significant implications for landscape changes, contributing to land fragmentation, biodiversity and habitat loss, and overall land degradation [1–4].

To preempt these potential challenges, effective spatial planning instruments are essential, playing a crucial role in striking a balance between enhancing the quality of life of populations and safeguarding the management of natural resources [5,6]. They also involve intricate decisions related to land-use optimization, strategic location of activities, and the establishment of infrastructure to achieve diverse socio-economic and environmental goals.

One of the primary objectives of spatial planning and land-use management is to promote territories that are environmentally sustainable, functional and aesthetically pleasing, ultimately enhancing the population's quality of life [7–10]. To achieve these goals, the integration of factors such as economic demand, the population's needs and environmental protection must be considered. Various mechanisms may be implemented in pursuit of this goal, including (i) evaluating existing land-use patterns and identifying suitable areas for specific types of development; (ii) ensuring compatibility between land uses in contiguous and nearby areas; (iii) defining appropriate density and intensity of urban development; (iv) supporting the integration of different land uses within the same area; (v) implementing zoning regulations and incentives to guide land-use decisions and encourage desired territorial development outcomes; and (vi) involving the public and stakeholders in the land-use planning process to gather feedback and co-create comprehensive decisions.

Understanding the shifts in the spatial planning dimension, particularly the evolving interrelationships between different governance scales, is crucial for advancing insights into spatial planning practices. As Gualini [11] suggests, the establishment of new governance spaces redefines the nexus between politics and territory. In line with this, Allmendinger & Haughton [12] distinguish between 'hard' planning governance and 'soft' planning governance. The latter lacks formal planning powers but is intricately connected to these formal spaces, reflecting the increasingly intricate network of relational geographies. These concepts may also assist researchers in examining how strategic spatial planning practices are negotiated and implemented. 'Hard' planning is anchored in regulatory frameworks and prescriptive rules, following a top-down approach in which centralized authorities establish and enforce stringent guidelines for land-use management [13,14]. Control mechanisms predominantly involve zoning and legal regulations. Implementation is characterized by strict rules for non-compliance, providing a structured but less-flexible framework.

Decision-making in hard spatial planning is often centralized, with limited input from local communities [15,16]. Conversely, soft planning embraces a collaborative and flexible approach, adopting a bottom-up perspective that emphasizes community engagement, negotiation, and consensus-building. Rather than relying solely on regulations, soft spatial

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planning utilizes tools such as incentives, partnerships, and dialogue [17,18], allowing greater adaptability to changing circumstances and encouraging continuous communication among diverse stakeholders. Soft spatial planning acknowledges the significance of local input, involving communities in decision-making processes. While it may introduce uncertainties, soft spatial planning effectively manages risks through adaptability and a holistic understanding of local dynamics [19–21].

In the end, the various spatial planning processes should provide a range of options for optimizing land use that align with social, economic, political, cultural, and environmental considerations, while upholding principles of equity, effectiveness, efficiency, and sustainability [22–24]. Recognizing the long-term impacts of spatial planning instruments on the future development of societies, it becomes imperative to establish effective land-use optimization practices today to pave the way for the implementation of sustainable land-use management policies [25,26]. Both spatial planning and land-use planning are integral components in the design of sustainable, well-organized, and inclusive strategies and plans that contribute to the development of more resilient and livable communities [27,28].

Several global-level planning strategies have established guidelines to enhance local territorial management, including the Sustainable Development Goals 2030, The United Nations Decade on Ecosystem Restoration (2021–2030), The Paris Agreement, and the COP28 Agreement.

2. An overview of the Articles Featured in the Spatial Planning and Land-Use Management Special Issue

This Special Issue comprises 11 articles that cover a diverse range of topics related to spatial planning and land-use management. Authored by 50 contributors from 31 university institutes spanning 14 countries (Portugal, Lithuania, China, Morocco, Hungary, Egypt, Spain, Brazil, Mexico, Serbia, USA, Paraguay, Algeria, and Yemen), the articles include case studies from Brazil, China, Paraguay, Serbia and Spain. The Special Issue is structured as follows: after the first paper, which offers a bibliometric analysis of High Nature-Value and Ecosystem Services, the subsequent papers are organized under two main themes, namely (a) examining the dimensions of socioeconomic, political, and environmental impacts of historical land-use/land-cover changes (connecting with spatial planning instruments), and (b) assessing the influence of these dimensions while projecting future land use/land cover changes, thereby anticipating potential adverse impacts.

In the first article, Girão et al. (Appendix A, 1) conducted a bibliometric analysis to scrutinize trends in High Nature-Value Farmland and Ecosystem Services Valuation. The study revealed (i) the predominant concentration of research on High Nature-Value Farmland in Europe, and (ii) the these studies' primary focus on environmental science, agriculture, and biological sciences.

From the second article to the seventh, the studies primarily focus on analyzing land use/land cover changes, spanning from the past to the present. These investigations critically evaluate these changes from the perspective of spatial planning instruments. Specifically, in the second article, Qi et al. (Appendix A, 2), delve into the relationship between economic development and industrial land expansion from the perspective of decoupling, employing a novel decoupling viewpoint. The results recommend the formulation of differentiated industrial land-supply and supervision policies to propel the transformation and upgrading of land use and economic development methods. In the third article, Delphin et al. (Appendix A, 3) explore the feasibility and relevance of integrated land-use planning and data acquisition in developing countries. The results suggest that developing an integrated land-use plan may be challenging due to factors such as data availability, lack of stakeholder engagement, and insufficient financial and human resources. In the fourth article, Almansoub et al. (Appendix A, 4) analyze the effects of transportation supply on mixed land-use change. Their findings reveal (i) a robust relationship between public transportation supply and mixed land use, and (ii) the prevalence of mixed land use in areas with high accessibility, density, and proximity to the city center. In the fifth article, Wang, Krstikj, and Liu (Appendix A, 5) provide evidence of the performance of new-type urbanization planning from the spatial dimension. The authors conclude that new-type urbanization planning positively promotes urban functional diversity and land development efficiency at the local scale. In the sixth article, Živanović Miljković, Dželebdžić, and Čolić (Appendix A, 6) provide a quantitative analysis of agricultural land-use change dynamics within the Belgrade–Novi Sad highway corridor, a critical route connecting Serbia's two largest cities. The results indicate that agricultural land loss primarily occurs in the form of urban sprawl. In the seventh article, García-Ayllón and Franco (Appendix A, 7), analyze the spatial statistical correlation between urban planning patterns of growth in a Mediterranean city in southeastern Spain and the increased risk of flooding. This study recognizes that variables such as urban fragmentation and the transformation of the traditional agricultural hydrographic network can have a more negative impact on vulnerability to flooding than the soil-sealing effect caused by land use changes.

From the eighth to the eleventh article, the studies employ complex spatial models to project future land use and land cover changes. These models help to address the uncertainties associated with future landscape transformations and offer solutions to unforeseeable changes [29]. In this context, and more precisely in the eighth article, Fan, Cheng, and Li (Appendix A, 8) focus on (i) studying land-use changes under different scenarios. The authors observed slight changes to the water area and rural settlements, a significant decrease in cultivated land, and a remarkable increase in urban and other construction land under various scenarios. In the ninth article, Zhu et al. (Appendix A, 9), simulate land-use changes under multiple scenarios, considering social, economic, and ecological policies. Their findings indicate that urban expansion will experience the most significant growth in all scenarios, with substantial environmental impacts. In the tenth article, Souza et al. (Appendix A, 10) evaluate different predictive land-use/land-cover scenarios, considering the public policies of the Chapecó River Ecological Corridor in Santa Catarina, Brazil. They conclude that physical and natural driving forces exert the greatest influence on land use/land cover changes. Lastly, in the eleventh article, Zhang et al. (Appendix A, 11) optimized the areas of various land-use types under strict ecological constraint, moderate ecological constraint, and relaxed ecological constraint scenarios. The authors acknowledge the need for strengthened spatial governance across all counties in the Three Gorges Reservoir Area territory, the development of more coordinated land development and protection patterns, and the comprehensive implementation of ecological protection and restoration projects in mountains, rivers, forests, fields, lakes, and grasslands to enhance regional ecosystem services functions.

3. Conclusions

In this Special Issue, various methodological approaches were employed to analyze both historical land-use and land-cover changes, as well as to project future land-use and land-cover changes. Nevertheless, despite the acknowledgment that stakeholder engagement is a valuable process for exploring landscape transformations and enhancing spatial planning, a gap persists in the literature. This gap is particularly evident when it comes to fostering greater engagement with stakeholders and ensuring the effective communication of findings to decision-makers [30]. The significance of engaging stakeholders in decision-making processes is widely acknowledged [31,32]. For optimal efficiency and effectiveness of land-use management, it is recommended that stakeholders be actively involved in all stages of the spatial planning process [33,34]. The careful selection of groups or individuals representing key actors within a specific region's land-use management sector becomes critical. This not only fosters increased knowledge but also contributes to the reduction of future uncertainties and conflicts. Moreover, it plays a pivotal role in fostering commitment, validity, and acceptance. While this Special Issue does not fill this gap, it does recognize recent advancements in analytical techniques that empower researchers to comprehensively analyze various trajectories across different territories. It offers an in-depth evaluation of the challenges and opportunities surrounding the complex interplay between land use and spatial planning and explores critical issues that affect our planet. Each article provides valuable insights into how spatial planning and land-use management play a pivotal role in the quest for a sustainable balance between economic development and environmental conservation. The contributing authors delve into various facets associated with improving land-use optimization through the application of diverse methodological approaches.

The articles featured in this Special Issue collectively paint a diverse and enriching picture of the prospects in spatial planning and land-use management. They underscore the critical importance of studying these subjects and emphasize how such research significantly contributes to supporting policymakers in making more informed decisions. These studies may be indispensable for researchers, policymakers, urban planning professionals, and anyone intrigued by the intersection of spatial planning and land-use management. They offer valuable insights that not only enhance our understanding but also contribute to the development of more sustainable land use practices.

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

Appendix A

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Article

Trends in High Nature Value Farmland and Ecosystem Services Valuation: A Bibliometric Review

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Abstract: High Nature Value farmland (HNVf) represents a rural landscape characterized by extensive farming practices. These lands not only deliver vital ecosystem services (ES) but also serve as significant harbors of biodiversity, underscoring their critical conservation status. Consequently, European Union countries have prioritized the identification, monitoring, and enhancement of HNVf systems in their policies. As governments and international organizations increasingly lean on green subsidies to promote sustainable environmental practices, the valuation of ecosystem services (VES) emerges as a crucial tool. This valuation offers both an economic rationale for conservation and aids in determining the optimal allocation of these subsidies for maximum environmental and economic return on investment. Given the potential for such valuations to shape and justify conservation subsidies, there is a growing imperative to understand the research trends and knowledge gaps in this realm. This article, through a bibliometric review, seeks to illuminate the size, growth trajectory, and thematic tendencies within HNVf and VES literature. Bibliometric analysis is recognized as promising in identifying research trends; thus, this article consists of a bibliometric review of HNVf and VES research. The objective is to identify the size, growth trajectory, and geographic distribution of HNVf and VES literature between the first publication until 2022, while assessing the critical publishing journals, authors, documents, and conceptual structure of the research fields (e.g., economic, social, and environmental). The analysis revealed a predominant concentration of research on HNVf in Europe, with limited studies conducted outside this continent. The primary focus of these studies revolved around subject areas such as environmental science, agriculture, and biological sciences. Conversely, regarding research on VES, there was no clear regional concentration. VES research publications mainly covered the interdisciplinary fields of economics, biology, and policymaking. As the fields of HNVf and VES have evolved, it is evident that there has been a stronger push towards data-driven approaches, emphasizing the need for tangible assessments and precise understanding. In examining the overlap between topics, the analysis revealed a gap between methodologies for HNVf monitoring and conservation and VES, highlighting the need for further development in crafting an integrated approach encompassing both areas.

Keywords: high nature value farmland; valuing ecosystem services; bibliometric review; science mapping

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1. Introduction

Historically, a considerable proportion of agricultural and forestry activities in Europe were considered to have high natural value [1]. However, technological advances in the twentieth century—including advances in mechanization, fertilizers, and pesticides—effectively eliminated barriers to the intense exploitation of soil's productive potential [2]. Unsustainable agricultural practices are frequently identified as the primary instigators of numerous environmental disruptions. The repercussions of such activities extend far beyond immediate regional impacts, leading to irreversible loss of extensive, ecologically significant agricultural areas. On a global scale, the intensification of these practices has exerted considerable influence on habitats, biodiversity, and the provision of ES [3–6]. The detriments manifest in varied forms, including landscape homogenization and biodiversity loss, underscoring the vital importance of shifting towards more sustainable agricultural techniques. Such techniques, mindful of ecological equilibrium and long-term resource conservation, offer the potential to mitigate these detrimental effects and promote more harmonious interactions between agriculture and the environment [7–11].

High Nature Value farmland (HNVf) is a concept coined in the early 1990s as a strategic instrument to typify and aid in protecting European farming systems with high biodiversity value. HNVf embodies critical ecosystem services essential to environmental sustainability and human welfare. These landscapes, characterized by their biodiversity, facilitate ecosystem functions ranging from maintaining soil fertility and carbon sequestration to crucial services like water purification and pollination [12–16]. However, comprehensive evaluation of these functions surpasses mere ecological parameters. They encompass considerable economic, social, and cultural implications, impacting both localized economies and broader global frameworks, shaping community livelihoods and resonating with cultural values [17–25].

Despite the acknowledged importance of HNVf and VES research and the research efforts made, there remains a need for continued exploration. The current literature often misses an integrated approach for HNVf identification, qualification, and monitoring. A lack of standardized frameworks leads to varied identifications and protections across regions. Although the ecological importance of HNVf is documented [26–44], there is a need to understand the relationships between communities, land management, and conservation. Furthermore, many critical ecosystem services of HNVf are either undervalued or ignored in economic evaluations [45–65].

To analyze the rapid growth and complexity associated with research on HNVf and VES, bibliometric analysis provides a systematic and unbiased way to map out the vast domain of knowledge. It not only captures the most influential works and emerging themes but also enables identification of potential gaps and trends in the research community [66,67]. The technique unveils pivotal intersections across diverse research areas, highlighting collaborative patterns and setting the stage for future interdisciplinary research [68–70]. By employing this approach, our study aims to present a thorough overview of the existing body of knowledge on HNVf and VES [54,71,72].

2. Review Framework

Bibliometric techniques, recognized for their strengths in citation analysis and data mining, were employed in our study [73]. Utilizing tools like VOSviewer, NetDraw, and BibExcel, we processed data from renowned sources that allowed us to pinpoint dominant research trends and provide a holistic overview of the subject's evolution [74,75]. Thus, such a review provided a comprehensive view of the network and structure of the field of interest. The methodological approach is shown in Figure 1.

Essentially, the article reviewed state-of-the-art research in HNV, specifically, HNVf and VES.

The review applied science mapping techniques to produce a bibliometric synthesis of research trends identified in Scopus-indexed publications [76,77]. To correctly analyze the body of literature, the review considered four dimensions [78]:

- Size: Quantity of gathered knowledge.
- Time: Publication evolution within the research field.
- Space: Geographic source of publications within the domain.
- Composition: Intellectual composition of the knowledge base.

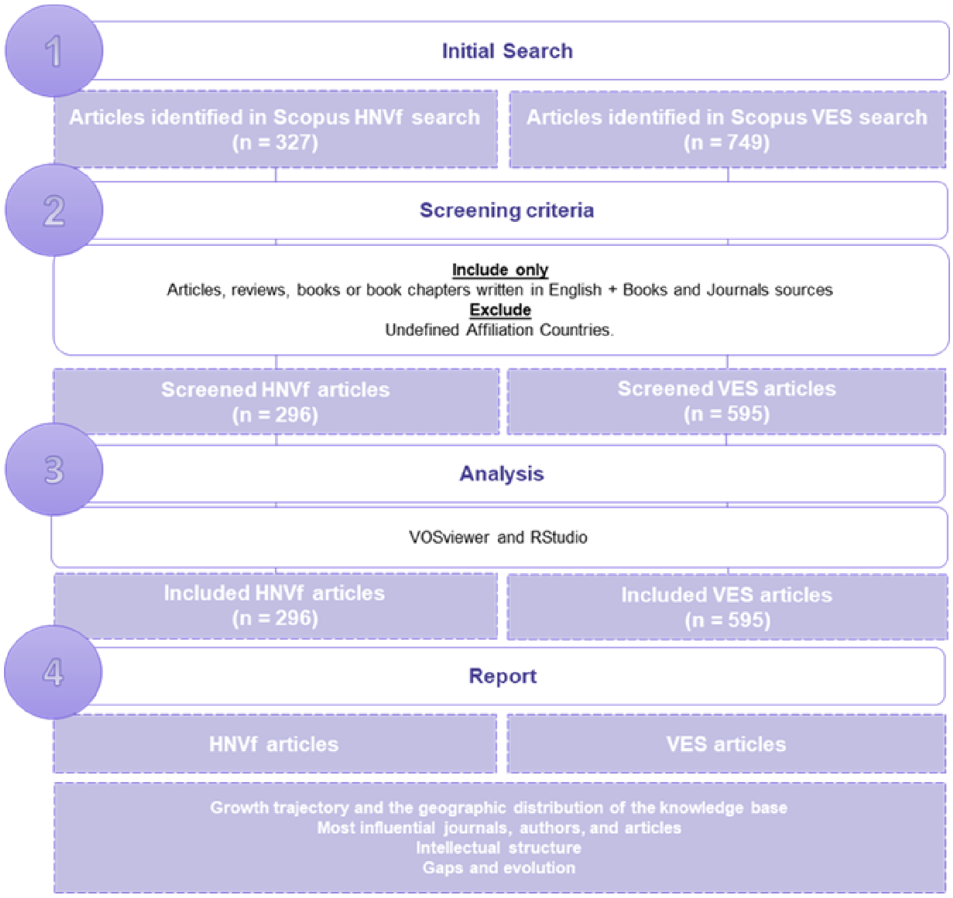

Figure 1. Methodological approach.

The first step consisted of ascertaining the search criteria. For this purpose, PRISMA guidelines were applied to ensure the scientific quality and transparent selection of the articles for analysis [79]. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 provides a framework for reporting systematic reviews and meta-analyses to ensure comprehensive and transparent presentation. One of the crucial steps in a review is the literature search, and PRISMA 2020 offers specific recommendations regarding the search process, such as the reporting of information sources, search criteria used, and study selection process. Secondly, Boolean operators were used to extract data from the selected scientific literature platform, Scopus. The choice of only using Scopus was based on the fact that it is the largest database of peer-reviewed literature and widely used to create datasets for reviews. The Elsevier Scopus database is also considered to be more comprehensive in representing research in social sciences, thus incorporating the social and cultural facets of VES and HNVf [80]. Moreover, there has been increasing overlap between Scopus and the Thompson Reuter Web of Science [81]. The third step involved data analysis through bibliometric methods and finally, the fourth and last step, consisted of interpreting and visualizing the results.

2.1. Search Criteria and Data Extraction

Initially, two separate searches were conducted: one delving into the scientific domain of HNVf, and the other examining VES. After the initial review, it became evident that only one article connected HNV and VES, while no articles bridged HNVf and VES. Prompted by this revelation, a further more targeted search was conducted to investigate connections between these research areas, particularly focusing on articles that might weave together HNVf and ES. While our main goal was to map out the principal research themes, this third exploration was vital to understand, highlight, and navigate apparent gaps when considering the confluence of both subjects.

The initial search encompassed a comprehensive review of all documents published until December 2022. The search was carried out using the Boolean operator "OR" since we wanted to include all documents that used specific terms. These terms were used to search all records that mentioned them in either their title, abstract, or keywords:

- TITLE-ABS-KEY ("high nature value" OR "hnv farmland" OR "hnv farming" OR "high nature value farmland" OR "high nature value farming").
- TITLE-ABS-KEY ("valuing ecosystem services" OR "valuation ecosystem services" OR "ecosystem services valuation" OR "ecosystem services valuing" OR "modeling ecosystem services" OR "ecosystem services modeling").
- TITLE-ABS-KEY ("hnv farmland" OR "hnv farming" OR "high nature value farmland" OR "high nature value farming") AND TITLE-ABS-KEY ("ecosystem services").

Following a brief analysis of the initial search results, the screening criteria were defined, as shown in Figure 1. Originally, only particular subject areas were considered; however, after several search attempts, all subject areas were included since the corresponding featured articles offered valuable insight for this bibliometric review.

Finally, the dataset was extracted from Scopus as a comma-separated values file (.csv) for use in VOSviewer software 1.6.16 and a BibTeX Bibliographical Database file (.bib) for use in the Bibliometrix package in R [81]. The extracted data included the author name(s), author affiliation(s), article title, keywords, abstract, and multiple citation data.

2.2. Data Analysis

The data analysis in this review relied on descriptive statistics and bibliometric analysis. The descriptive statistics were obtained using Bibliometrix in R. The software used to carry out the bibliometric analysis and visualization of the results was VOSviewer, a tool for visualizing data in network maps [74]. VOSviewer was used because it allowed us to map the knowledge present in the selected materials (Table 1).

Table 1. Types of VOSviewer analysis of bibliographic data [70].

Type of Analysis	Description
Co-authorship	Established based on the number of co-authored documents.
Citation	Established based on the number of times the articles cite each other.
Co-citation	Established based on the number of times the articles are cited together.
Bibliographic coupling	Established based on the number of shared references.

VOSviewer was used since it can provide information such as the affiliation of authors working in these matters; the journals that publish more articles on the subject; the most cited authors or documents; which authors work together; and the essential concepts in each research field. Network maps were created utilizing bibliographic and text data to enable visualization and a more simplified examination of the linkages that existed between authors, documents, and study fields. For the bibliographic data, co-authorship and citation analyses were applied, and for text data, the most mentioned terms were extracted. R software's 4.2.1 Bibliometrix package was used to enhance the exploration of the findings obtained from VOSviewer and employ different visualization techniques. Also, a methodology proposed by Pagani et al. [82] was used regarding the most influential documents in order to rank them. This methodology sorted the articles using the InOrdinatio (*IO*) equation to find the rank index, as follows:

$$IO = (IF/1000) + \left(\alpha * \left(10 - \left(Y_r – Y_p\right)\right)\right) + \left(\sum C_i\right),$$

where *IF* refers to the journal impact factor, Y_r is the year when the data was collected, Y_p is the publication year of the article, and $\sum C_i$ is the total citations of an article between Y_p and, Y_r. Finally, α is a weighting element, ranging between 1 and 10. For a value of α closer to 1, lower importance is given to the year criterion. Considering recent publications, the year criterion was most important for subjects such as HNVf and VES. Therefore, $\alpha = 10$ was used. In addition, IF is accounted for as a ratio of 1000, to be normalized concerning the other criteria.

Finally, to gain a deeper understanding of the relationship between the two research topics, articles that addressed both realms were thoroughly analyzed.

3. Results and Discussion

The data extraction yielded 296 documents related to HNVf research from 131 sources, with the first document published in 1997. The VES search generated 595 documents from 160 sources, with the earliest dating back to 1998 (Table 2). The most common types of documents were articles followed by book chapters in HNVf research and reviews in VES research. Despite the difference in the number of documents between the two research fields, they both showcased a similar number of authors. This indicated potential interest from scientists across various subject areas in HNVf research.

Table 2. Main information about the two research topics.

	HNVf Research	**VES Research**
Period	1997–2022	1998–2022
Documents	296	595
Articles	269	492
Reviews	8	50
Books	2	10
Book Chapters	17	43
Authors	160	159
Sources	131	160

3.1. Growth Trajectory and Geographic Distribution

The foundation stages for the exploration of HNVf and VES research originated in 1992 (Figure 2), highlighted by the Convention on Biological Diversity [83], which underscored the value of preserving biological diversity, making sustainable use of its elements, and distributing benefits resulting from the exploitation of genetic resources fairly and equally. In subsequent years, vital reports, particularly from the IEEP [84,85], emphasized the importance of conserving European farmlands known for their biodiversity richness. From 1997 to 2010, regarded as the foundation phase, both realms of research experienced a modest but steady increase in publications, with only 7% of documents produced during this period. Also, it was during this period that new and already existent frameworks and policies laid the groundwork for understanding and preserving biodiversity on agricultural land. The term HNVf, introduced by Baldock et al. [86], gained traction during this phase, with an emphasis on conservation value in Europe, especially through the continuation of low-intensity farming systems [87,88]. During the same period, the domain of VES research was boosted by key frameworks such as the Millennium Ecosystem Assessment (MEA) [89], which elucidated the economic and societal value of ecosystems. The Economics of Ecosystems and Biodiversity (TEEB) [20] report further anchored the significance of VES, emphasizing the need to integrate ecological and economic dimensions in assessing biodiversity and ecosystem services.

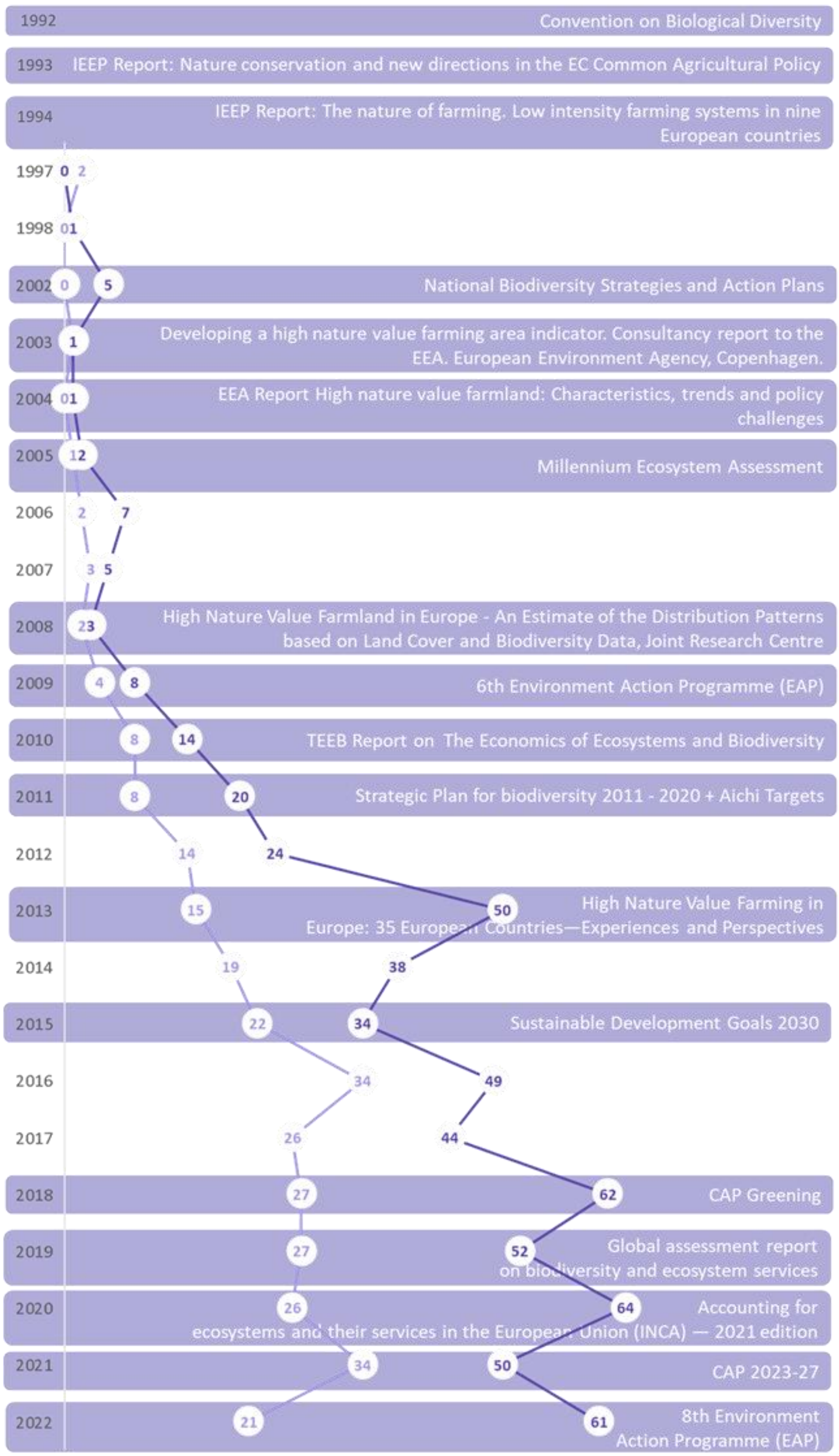

Figure 2. Publication trajectory by year and important developments, 1997–2022.

From 2011 to 2022, the research trajectory underwent a transformative phase, marked by an accentuated increase in publications (comprising 96% of documents). By 2011, both fields showed a tendency for growth in publications, with VES research showing a more pronounced increase. From 2011 onwards, VES research continued a rapid ascent, with a notable boost that might have been related to the upcoming United Nations summit for adoption of the post-2015 development agenda (the 2030 Agenda for Sustainable Development) [90]. HNVf research, meanwhile, experienced a leap by 2016, possibly spurred by strategic plans for biodiversity, including Aichi biodiversity targets, CAP Greening, and other influential documents [91–93]. From 2018 onwards, VES research maintained its dominant position, with the Global Assessment Report on Biodiversity and Ecosystem Services acting as a potential catalyst [94]. In contrast, growth in HNVf research was more measured. In 2021, while HNVf publications plateaued, VES publications surged, reflecting the drive to integrate ecosystem services into broader policy and economic frameworks, as seen with the release of Accounting for Ecosystems in the European Union by INCA [95]. By 2022, both fields displayed growth, with VES research remaining more prolific, although HNVf research showed signs of resurgence. The trends in 2022 emphasized the ongoing relevance of both areas, informed by the anticipation of policies such as the CAP 2023–27 [96] and the Environment Action Programme to 2030 [97]. In summary, both HNVf and VES research experienced significant growth over the years, shaped by global conventions, reports, and evolving research paradigms. The timeline suggests a maturing field, with opportunities for further exploration, especially in standardizing definitions, criteria, and accurate valuation methods for ecosystem services.

Regarding the geographic distribution of the published documents, 47 countries contributed to HNVf research. European countries were the most productive (97% of all publications). Among European countries, Germany, Portugal, Spain, the United Kingdom, and Italy were the top five publishing countries, contributing 56% of published documents.

Figure 3 also shows the top ten countries by the number of publications and citations. Despite having fewer documents published in the field of HNVf research, the United Kingdom exerted more influence than nations such as Portugal and Spain due to the higher total citation count. Although the latter countries had higher number of publications, they received fewer citations, implying a lower impact in the field.

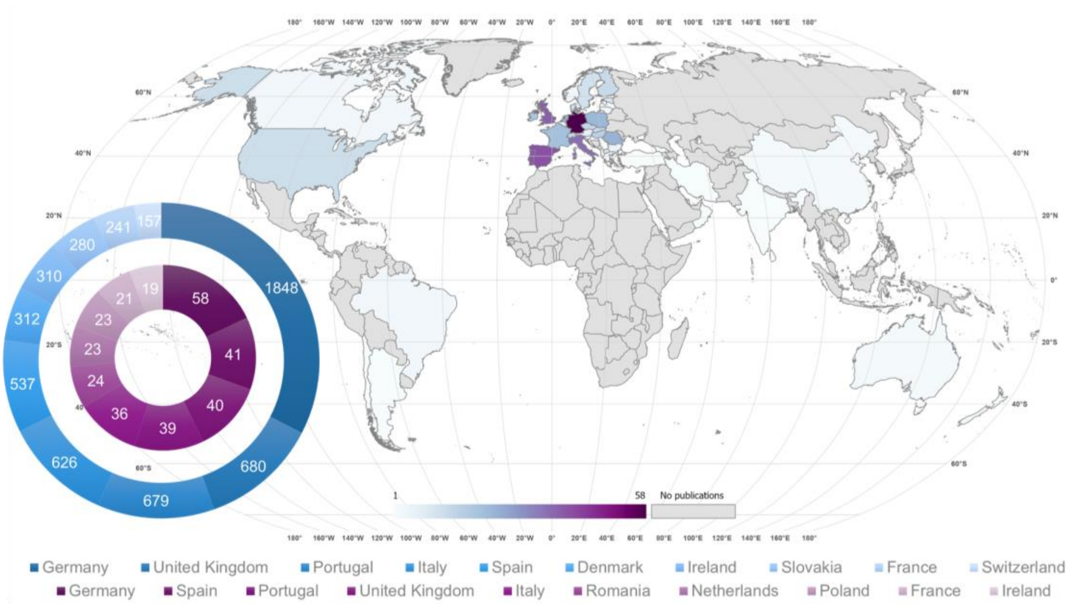

Figure 3. Academic production by country for HNVf research between 1997 and 2022 (inner circle = total of documents; outer circle = total citations).

For VES research, the distribution of published documents was wider, involving a higher number of countries, 78 to be exact. As seen in Figure 4, the most productive countries were the United States (36%), the United Kingdom (17%), China (12%), Australia (11%), and Germany (8%). However, the number of citations received by China's research did not match the highest impact of publications in the Netherlands; despite fewer studies being published than in China, research in the Netherlands received a higher number of citations.

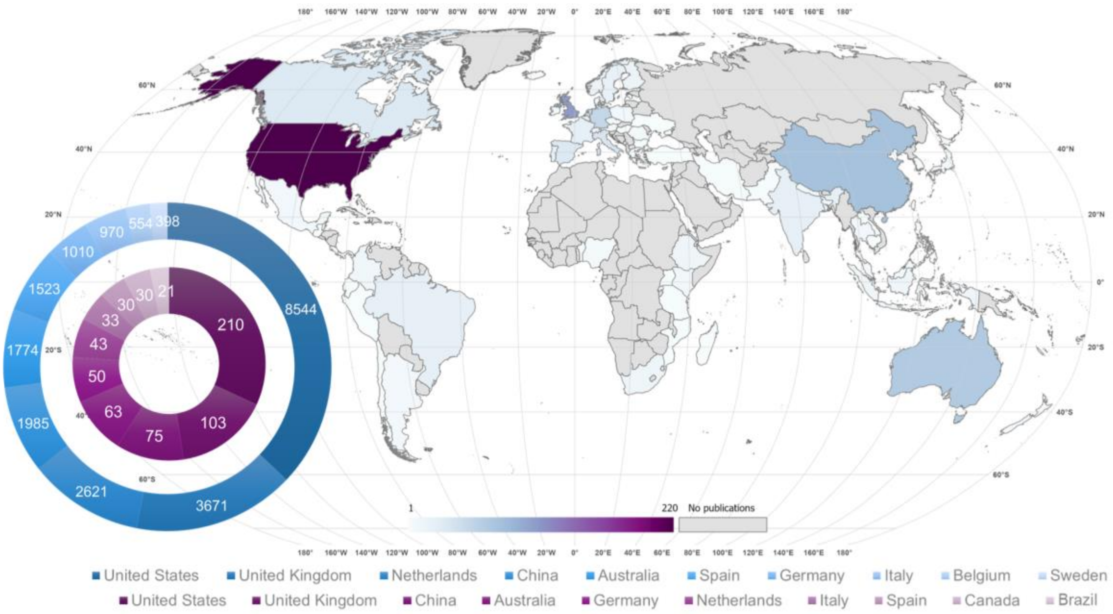

Figure 4. Academic production by country for VES research between 1998 and 2022 (inner circle = total of documents; outer circle = total citations).

Regarding collaboration between countries (Figure 5), HNVf research in Europe emerged as a focal point. Spain, in particular, stood out with consistent high-volume publications. Other consistent European contributors included Portugal, Germany, Italy, France, and Ireland. Outside Europe, the United States demonstrated research interest, particularly around 2013. Recent years also witnessed new interest in countries such as China and India, marking their presence in this research domain. The heatmap hinted at shared research trajectories. For instance, Spain, Portugal, and Germany clustered closely, indicating parallel research interests or collaborations. Similarly, the grouping of Ireland, the UK, and the USA might suggest shared methodologies or research focus. Geographically distant yet ecologically similar countries, like Australia, New Zealand, and Fiji, also clustered together, potentially pointing towards shared ecological challenges or research perspectives.

Regarding VES research (Figure 6), North America, particularly the United States, was consistently at the forefront of VES research, with high publication counts. Canada followed, with a less intense but steady contribution. In Europe, the United Kingdom, Spain, Germany, and the Netherlands displayed significant research output, emphasizing their central role in the European VES research landscape. Notably, countries with emerging economies, like China and India, exhibited a late but rapid surge in publications, indicating their growing research capacity and interest in this research domain. The dendrogram's hierarchical clustering suggested potential research affinities. For instance, Spain, Portugal, and the Netherlands clustered closely, which might signify shared research themes or collaborations. Likewise, countries such as South Korea, Indonesia, and Malaysia formed a distinct cluster, pointing towards potential regional collaborations or similar ecological contexts.

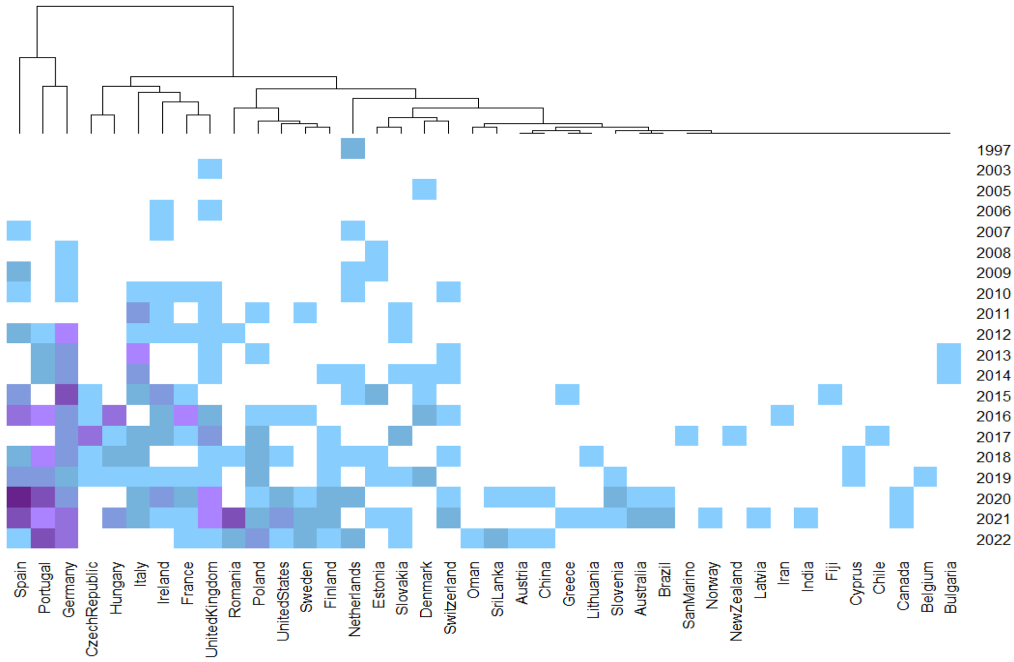

Figure 5. Heatmap and dendrogram for the number of documents per country and year of publication for HNVf research (purple = higher number of publications; light blue = lowest number of publications).

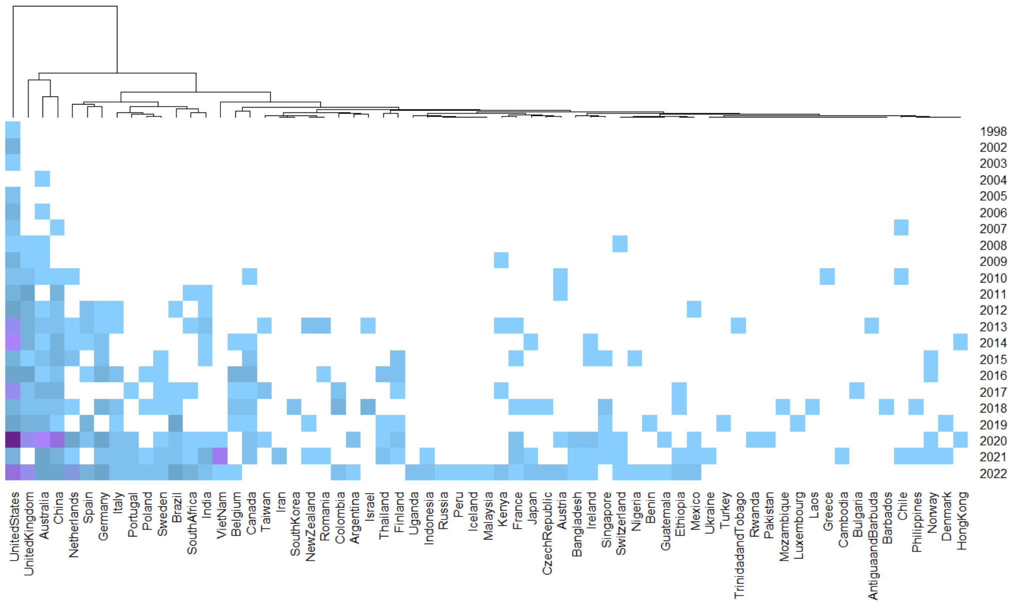

Figure 6. Heatmap and dendrogram for the number of documents per country and year of publication for VES research (purple = higher number of publications; light blue = lower number of publications).

A broad range of countries, including Mexico, South Africa, and Saudi Arabia, showed sporadic but relevant contributions over the years, highlighting the global appeal and significance of VES research.

Finally, a simple examination of publications by affiliation in both disciplines of research was carried out (Figure 7). While German institutions held greater influence in HNVf research based on the number of published documents and citations, Portuguese universities such as Évora and Lisbon Universities exhibited a higher frequency in overall studies. In the field of VES research, Stanford University stood out as the foremost institution, while Beijing Normal University and other institutions displayed a comparable frequency of contributions.

Figure 7. Institutions with the highest presence (frequency) in HNVf (**right**) and VES (**left**) research.

3.2. Intellectual Structure: Influential Authors, Publications, and Journals

This section analyses the most influential authors, publications, and journals in both HNVf and VES literature.

3.2.1. HNVf Research

The top ten productive and cited authors in HNVf research are listed in Table A1 (Appendix A). To qualify, authors needed to contribute to at least five documents. This ensured that regular contributors to HNVf research were recognized, while one-time participants in highly cited papers were excluded [98,99]. After assessment, only 13 met this criterion. The most productive authors were Plieninger T., Hartel T., and Lomba A., while the most cited were McCracken D., Plieninger T., and Dengler J.

The co-citation network (Figure 8) highlighted Beaufoy G., Plieninger T., and Baldock D. as central figures, frequently cited and anchoring the core HNVf research themes found predominantly in the red cluster. This dense cluster represented a well-established research foundation. In contrast, the isolated purple cluster pointed to niche areas or differing theoretical perspectives. Also, it is notable that some authors, the standouts in co-citations analysis, were not as prominent among the most productive or cited authors, suggesting that their broader contributions focused on the HNV knowledge base (Table A2). Overall, the HNVf literature landscape appeared to be led by influential voices, enriched by diverse topics, and marked by a dynamic, interconnected research community.

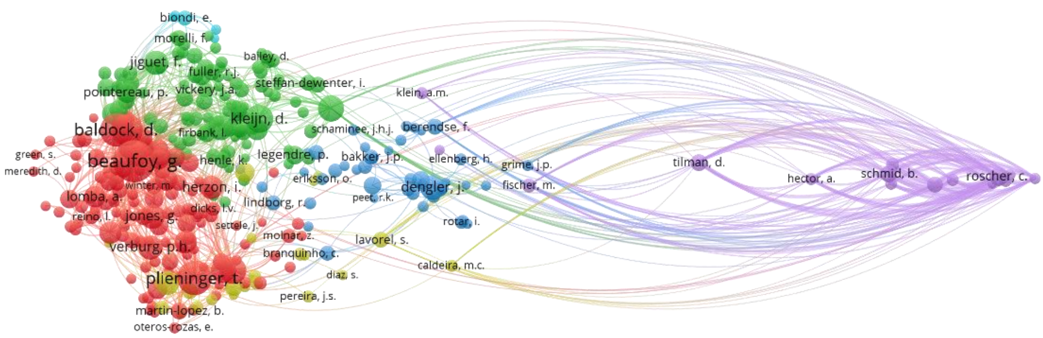

Figure 8. Author co-citation network for HNVf literature, 1997–2022 (threshold of 50 citations).

During the first period, one of the most influential publications was published [38]. In this case, the article reviewed conflicts between conservation and agricultural activities and evaluated strategies to resolve such disputes. Also, the authors approached the relationship between low-intensity agriculture and high bird species levels. In [38], the authors reviewed in which circumstances agricultural activities and interests towards economic gains clashed with conservation of biodiversity in agricultural landscapes. They identified and described three major processes responsible for creating biodiversity-related conflicts: (i) intensification of agriculture; (ii) abandonment of marginally productive HNVf; and (iii) scale of agricultural operations. Between 2011 and 2022, the rest of the top ten most cited publications in HNVf research were published. Dengle et al. [29] explored the biodiversity in a specific type of high nature value grassland and synthesized the current knowledge on the topic. This article did not explore HNVf-related topics but helped to characterize and better understand the relationship between the ES of grasslands and biodiversity. Renwick et al. [100] analyzed the potential impact of agricultural and trade policy reform on land use, focusing on land abandonment. A key finding of the article's research was that reforms widely differed in spatial impact, meaning that neglect of HNV systems occurred within the same farming systems depending on the specificity of each environment throughout Europe. The authors also pointed out that these impacts reflected the inadequacy of policies, such as the CAP's first pillar. Biondi [101] recognized the importance of HNVf for the methodological and conceptual evolution of phytosociology since the introduction of the concept praised the interactions of vegetation communities as a critical element for biodiversity levels. The article reviewed and discussed the fundamental aspects and ideas of phytosociology. Although relevant to the study of plant community sociology in HNVf areas, it did not approach HNVf-related topics in a considerable measure. The objective of the article by Halada et al. [102] was to identify the habitat types listed in the Habitats Directive Annex I that required low-intensity agricultural management. The authors identified 63 habitat types of European importance that depended on agriculture and considered delineating areas such as HNVf as a vital policy tool, leading to better-targeted application of measures to maintain habitats and species.

Next, using co-citation analysis, Figure A1 (Appendix A) depicts the influential sources with over 100 citations. The sparse connections between these sources suggested that they were rarely co-cited, possibly indicating limited interdisciplinary dialogue. The clear division between ecology and biology journals (green cluster) and those focused on environmental management and conservation (red cluster) further accentuated this observation. This distinction might signal missed opportunities for integrating biological insights with practical conservation strategies, underscoring a potential need for more holistic discussions in the literature.

3.2.2. VES Research

The most productive authors, in terms of published documents and citations in VES research, can be found in Table A3 (Appendix A). The selection criteria involved authors featured in at least five published documents. After careful evaluation, only 19 authors were found to meet the specific criteria. Hein L. stood out for significant impact with 2084 citations across five publications, indicating the profound influence of his work. Conversely, Costanza R. presented an extensive body of 16 publications but garnered fewer citations per document, suggesting specialized contributions. Barton D.N. and Bagstad K.J. struck a balance between publication frequency and impact.

Figure 9 offers a detailed visualization of the co-citation dynamics within the VES research landscape. Five distinct clusters were representative of the varied thematic concentrations within VES studies. Unlike the patterns observed in HNVf research, the top-tier authors in VES research demonstrated a balanced presence across the network, reinforcing the idea of a well-integrated research community. The notable scholars were Costanza, De Groot, and Polasky. Their prominence not only highlighted their individual contributions but also established these authors as foundational pillars in VES research.

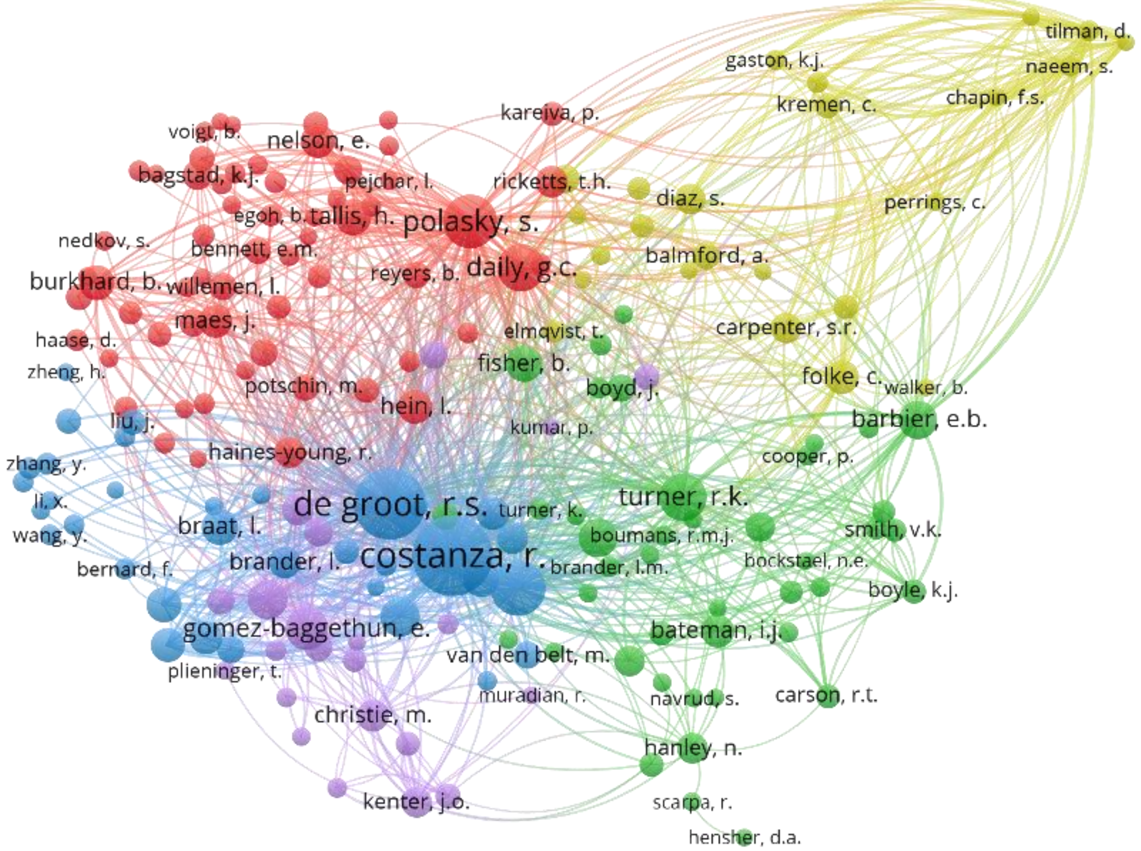

Figure 9. Author co-citation network for VES literature, 1998–2022 (threshold of 50 citations).

Table A4 (Appendix A) showcases the most influential VES literature between 1998 and 2022. The most referenced work was the piece by De Groot R. S. [25] on the challenges of integrating ecosystem services into landscape planning, reflecting the complexities of the field. This was closely followed by the article by Power A.G. [56], which unraveled the juxtaposition between ecosystem services and agriculture, illuminating the trade-offs and synergies. The topics spanned from urban planning insights by Gómez-Baggethun E. [103] to the exploration of cultural ecosystem services by Milcu [50]. Notably, Farber's work [104] remained significant, underscoring its enduring relevance. A tight citation count among the mid-ranked papers suggested thematic overlap or contemporaneous publishing. Practicality was emphasized, with works by Crossman and Troy focusing on tangible VES applications. Daw's research [105] introduced a nuanced, human-centric perspective, highlighting the evolving holistic approach in the field. Collectively, these works illustrate the dynamic interplay between theoretical and practical advancements in VES research.

Figure A2 (Appendix A) illustrates the densely interconnected co-citation network for VES research, signifying its multidisciplinary nature. This contrasts with the simpler network observed for HNVf research. Distinct clusters emerged within the VES field: the green cluster emphasized environmental economics and management, the blue delved into core ecological and biological principles, while the red embodied a transdisciplinary approach, focusing on evaluative strategies for ecosystem services. Notably, even within these clusters, there were discernible gaps, suggesting nuanced thematic variations and sporadic co-citations among closely related sources.

3.3. The Conceptual Structure

A co-occurrence analysis of text data, focusing on titles and abstracts, was employed to identify prominent concepts in HNVf and VES research. Co-word analysis, a technique used across various domains, is adept at capturing robust associations between textual elements [98,99]. This approach not only discerns prevailing tendencies in a domain [98] but also tracks shifts in dominant themes as new research findings emerge [66]. Temporal word co-occurrence maps offer visual insights, showcasing thematic relationships and their prominence over time [68].

3.3.1. HNVf Research

The network of word co-occurrence showed three generic clusters with very similar sizes and shapes (Figure 10). The separation between the blue and red clusters from the green cluster suggested a weaker correlation. This implied that the green cluster publications delved into distinct topics compared to those in the blue and red clusters. The blue cluster encompassed terms associated with methodologies for identifying and analyzing HNVf. In contrast, the red cluster pertained to the theoretical significance of HNVf and its associated policies. Notably, this cluster incorporated the term ES, underscoring the emphasis on considering these in policy formulation. Meanwhile, the green cluster centered around biodiversity research. Given the terminologies present in this cluster, it can be inferred that species richness served as a prevalent indicator for HNVf identification. However, given the noticeable distance between the red and blue clusters from the green cluster, there was a clear delineation between documents centered on species richness and diversity and those emphasizing HNVf monitoring and identification methodologies.

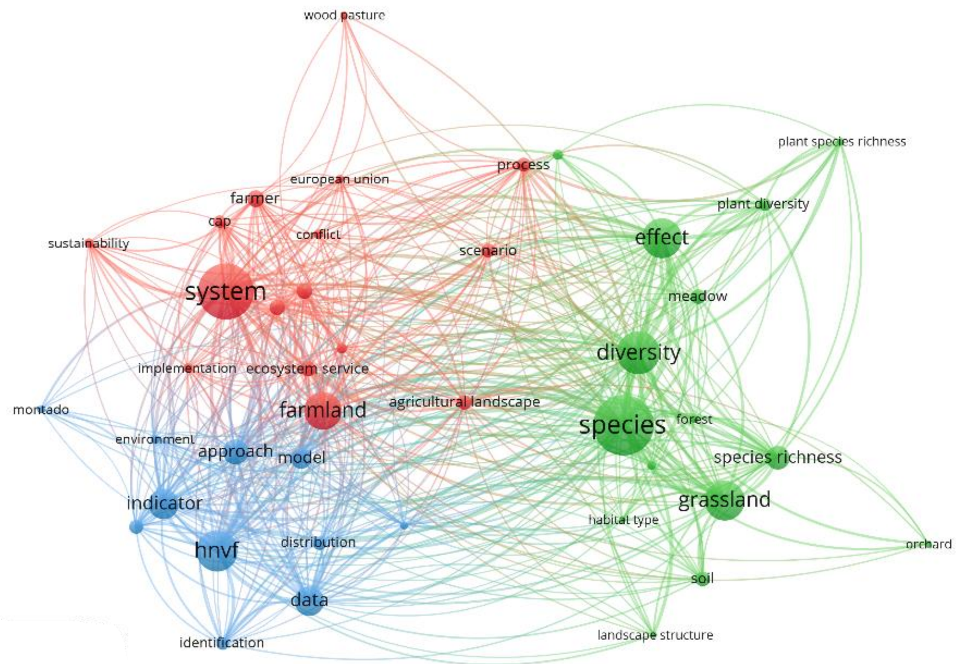

Figure 10. Network of word co-occurrence for HNVf research, 1997–2022 (threshold of 20).

Figure 11 illustrates the evolution of HNVf research from 1997 to 2022. During the initial phase (purple), the predominance of larger nodes associated with terms like “species”,“system”, “effect” and “farmland” suggested that foundational inquiries were oriented towards understanding the very essence of HNVf landscapes—their intrinsic characteristics, the species they harbor, their systematic role in broader agriculture, and the tangible or intangible effects they might have on the surrounding environment. Transitioning into the later phase (yellow), larger nodes associated with terms such as “grassland” “HNVf”, “diversity”, and “indicator” hinted at the field’s progression. The pronounced frequency of “grassland” and, more recently, “montando/wood pastures” and “orchards” suggested that recent research was zooming in on specific ecosystems within the broader HNVf category, reflecting a more granular understanding of these environments. Concurrently, the emphasis on "diversity" showcased the continuous focus on biodiversity conservation within these farmlands. The heightened frequency of "indicator" underscored a current inclination towards refining tangible, measurable metrics to monitor and evaluate HNVf health, status, and dynamics. This shift from broader concepts to nuanced specifics can be viewed as a natural maturation in many scientific domains. The initial foundational knowledge paved the way for more targeted, detailed exploration. Advanced methodologies in the later phase might have been facilitated by the evolving policy landscape and feedback from implementations like the CAP.

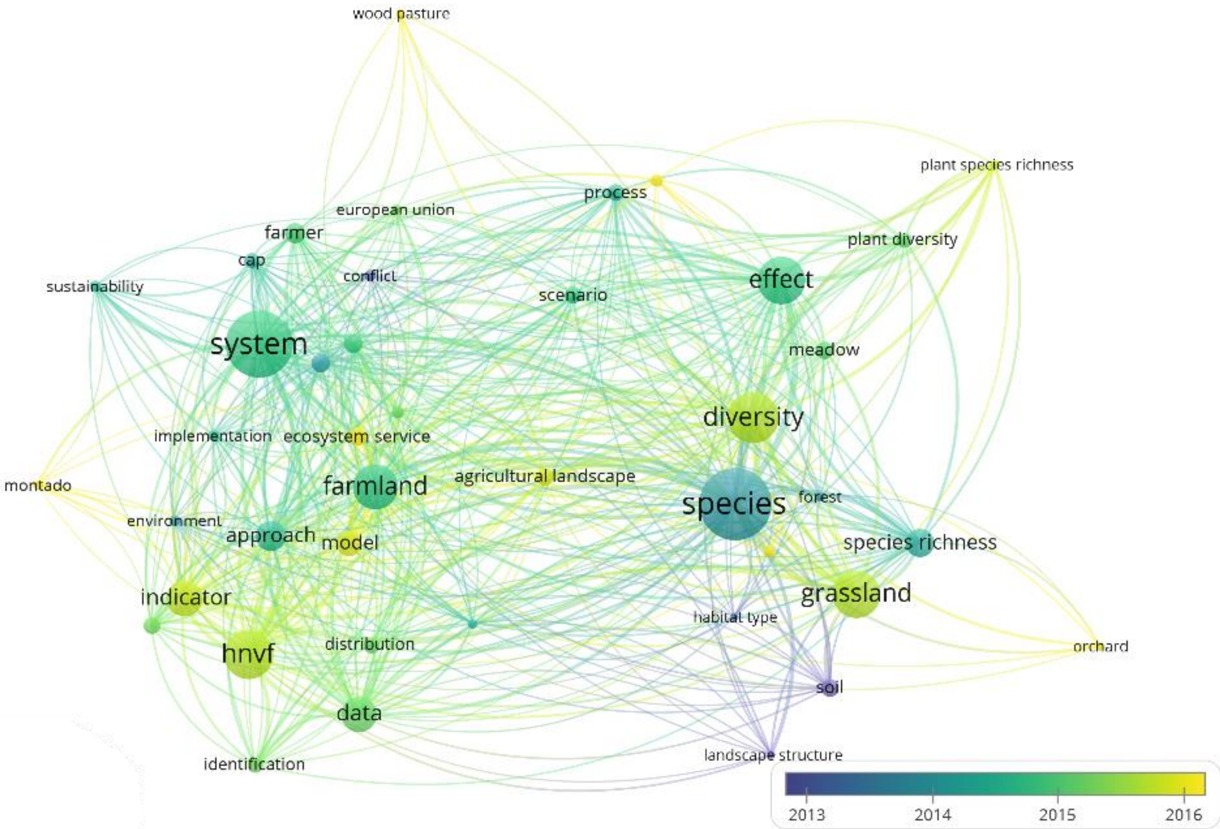

Figure 11. Temporal network overlayed on word co-occurrence map for HNVf research, 1997–2022 (threshold of 20).

3.3.2. VES Research

In examining the network of word co-occurrence for VES research (Figure 12), the overall shape of the map suggested that most published documents delved into more interconnected topics. The red cluster emphasized analytical rigor, focusing on quantifying and modeling ES using data, estimates, and scenarios. It hinted at the research's predictive and data-driven facet, with foundational terms like "natural capital" as the base of these studies. The blue cluster dove into the environmental context, highlighting how ES manifest in and impact specific landscapes, especially regions like wetlands. It underscored the dynamic nature of these services and their tangible environmental effects. The yellow cluster corresponded to the economic dimension of the research. Here, the interplay between weighing the trade-offs of VES and integrating it into policy decisions was evident, emphasizing the monetization and economic implications of these services. Finally, the green cluster, rooted around the core term, offered a holistic view. It explored the challenges in understanding and conserving ES, the intrinsic link to biodiversity, and the pivotal human-stakeholder interactions that shape their existence and restoration.

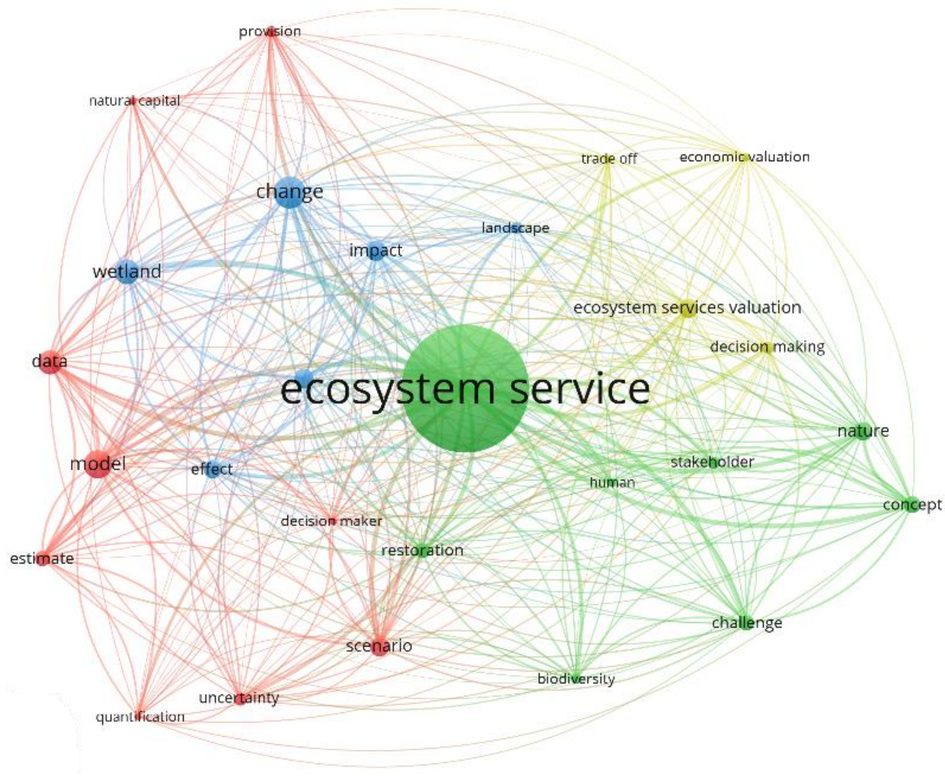

Figure 12. Network of word co-occurrence for VES research, 1998–2022 (threshold of 20).

In Figure 13, the color and size of the term "ecosystem services" suggested that the term was consistently a focal point, bridging earlier concepts with more recent discussions.

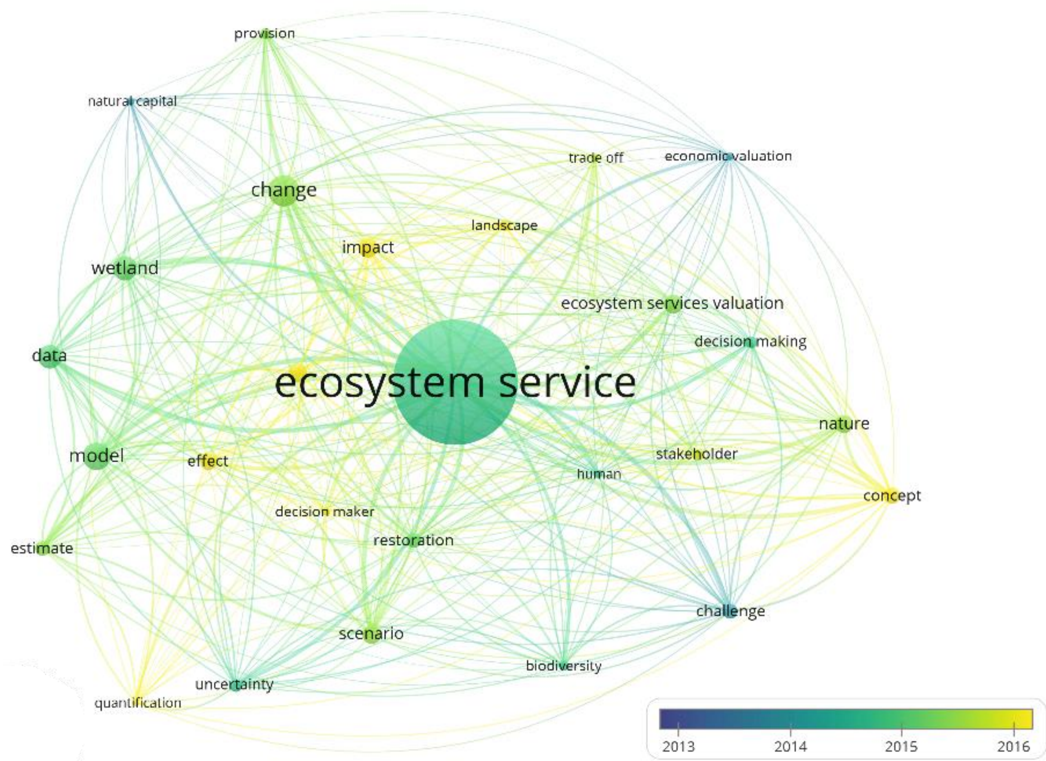

Figure 13. Temporal network overlayed on word co-occurrence map for VES research, 1998–2022 (threshold 20).

More recent terms, such as “effect”, “impact”, “concept”, and “quantification” indicated a shift in research towards understanding the direct implications of ES in various environmental and socio-economic dimensions. There was growing interest in not only conceiving but also quantifying these services’ tangible and intangible consequences and effects. Also, somewhat recent terms like “data”, “change”, “ecosystem services valuation,” “model,” and “uncertainty” suggested that as the field evolved, there was a growing emphasis on collecting empirical data, observing, and predicting changes in ES and attempting to value them. The presence of “model” hinted at efforts to create predictive or interpretive frameworks, while “uncertainty” underscored the challenges or ambiguities researchers grappled with during this phase.

Among the earlier terms, we found “natural capital,” “economic valuation,” and “challenge”. This implied that initial forays into ES research were grounded in tying the environment (“natural capital”) to economic paradigms. There was a clear endeavor to economically value the environment, underpinning the early days of ES as a concept. The term “challenge” suggested that these early efforts were fraught with complexities, both conceptual and methodological.

Despite the temporal shifts in thematic priorities, most terms maintained a similar node size, suggesting that while the focal points of research evolved, many of these themes remained consistently relevant, each contributing a pivotal piece to the holistic understanding of ES.

4. Connections between Research Topics

HNVf represents a critical intersection of agriculture and biodiversity conservation, emphasizing farming practices that maintain and enhance a diverse array of species and habitats. On the other hand, VES provides a framework for understanding and quantifying the benefits, both tangible and intangible, that ecosystems, including HNVf, deliver to humanity. As HNVf promotes sustainable agricultural practices that safeguard biodiversity, it invariably contributes to the maintenance and enhancement of ES. Valuating these services not only underscores the economic implications of sustainable farming but also offers a persuasive argument for the preservation of HNVf landscapes [19,106].

4.1. HNVf Ecosystem Services

HNVf provides a diverse array of provisioning services, ranging from a variety of crops and livestock, which are characterized by unique nutritional, cultural, and ecological attributes. Notably, traditional breeds demonstrate adaptability and resilience, often flourishing without intensive chemical interventions. Beyond providing sustenance, HNVf yields products such as fibers and regional medicinal herbs, all integral to local traditions and yet possessing global commercial significance. In terms of regulating services, HNVf systems offer numerous benefits. Their diverse cropping patterns and reduced reliance on chemicals contribute to soil health, thereby promoting fertility and controlling erosion. The dense vegetation inherent to these landscapes acts as a natural filter, enhancing water quality. Furthermore, the biodiversity they support is essential for pollinators vital to various crops. Intrinsic practices like agroforestry not only regulate local climates but also contribute to carbon sequestration and broader climate change mitigation strategies. Culturally, HNVf stands as a repository of local traditions and practices, encapsulating generational knowledge. The biodiversity and scenic beauty of these landscapes facilitate recreational activities and promote ecotourism, marking them as centers of cultural heritage and regional identity. From a support perspective, HNVf landscapes are biodiversity hotspots, offering habitats for numerous species and underlining their significance in conservation efforts. These ecosystems, replete with myriad symbiotic interactions, are pivotal in nutrient cycling, a service often underappreciated due to its intricate and multifaceted nature [107–112].

4.2. Bibliometric Insights

The synergy between HNVf and VES is an intricate subject. When it comes to research in both topics, the only bridging article found was "Valuation of Ecosystem Services for Implementing Innovative Clean Technology" [113]. The article emphasized the potential harmony between HNV areas, not specifying farmland, and VES, while retaining ecological integrity. Also, it is worth mentioning that one of the most cited articles in VES research was related to ecosystem services and agriculture [56].

Regarding consistent contributors in both fields, authors such as Plieninger T., Pinto-Correia T., Lomba A., Regos A., Moreno G., and Azeda, C. demonstrated a pronounced interest in HNVf and ES. Yet their focus was not on valuation. Both Lomba A. and Plieninger T. emerged prominently, with each having authored four pieces, one of which they co-authored.

When analyzing the dataset on HNVf and ES research (33 documents), two articles, surpassing 70 citations each, deserve particular attention. The first [19] investigated the varying perceptions of farmers and nonfarmers towards ES. It unveiled farmers' profound awareness of these services and their agricultural implications, whereas nonfarmers were more inclined towards quality food production and the cultural essence of ecosystems. The subsequent article [107] investigated HNVf's adaptability amid socioeconomic flux, proposing possible futures and accentuating the crucial nature of sustainable farming methods for these precious lands. Table A5 (Appendix A) shows the remaining articles that correspond to the top 10 most cited articles in HNVf and ES research.

On a geographical note, Portugal stood out with the highest number of publications, narrowly outpacing Germany. These studies were comprehensive, discussing topics from ecosystem metamorphosis, differential farming strategies to ES, and intricate HNVf management practices, to the employment of advanced high-resolution data techniques throughout Europe. Some also explored fire-resilient farming approaches, geocaching as a cultural ecosystem metric, psychographic-driven willingness-to-pay evaluations for ES, and a specific probe into soil organic carbon dynamics across European HNVf.

However, it is essential to note a discernible gap: collaboration between HNVf and ES research remained sparse, often narrowed down to niche subjects without delving deeper into HNVf's holistic qualities and the encompassing ES. This disparity widened when juxtaposed against VES studies.

4.3. Challenges and Pathways

Despite its significant ecological and societal importance, integrating HNVf and its ES into policy and practice still presents a multitude of challenges. Firstly, many regions suffer from a lack of formal recognition of HNVf, as evidenced by the geographic distribution of relevant research. This absence of official acknowledgment can hinder these areas from receiving the necessary targeted support or protection. Concurrently, there is a frequent deficiency in the collection of comprehensive and consistent data on HNVf. This gap makes it difficult to craft tailored policies or evaluate the effectiveness of existing ones.

For a long time, many existing agricultural policies, driven by economic motivations, tended to favor high-intensity and industrial agriculture. These often offered subsidies that might inadvertently undermine HNVf. However, there is an emerging trend of policies providing incentives for environmentally friendly practices [63]. Another concern is the fragmented approach towards HNVf conservation, wherein related policies are dispersed across various sectors like agriculture, environment, and rural development. This dispersion can result in a lack of coordination and at times, even lead to conflicting goals.

On the ground, local communities, indigenous groups, and farmers are pivotal in managing these ecosystems. Yet there is a noticeable gap in the effective involvement of these stakeholders in decision-making processes19]. Additionally, while HNVf can contribute to broader environmental goals, such as climate change mitigation, water management, and soil conservation, current policies often overlook such integrative approaches [114]. Financial constraints also present a barrier [115]. The conservation and promotion of HNVf demand financial backing, especially to remunerate farmers for the ecosystem services they offer. The absence of clear frameworks for dedicated funding can deter the preservation and promotion of these vital lands. Furthermore, in specific regions, challenges arise due to unclear land ownership or tenure, complicating the initiation of conservation and management strategies. There is also a discernible gap in the transfer of knowledge. Mechanisms or platforms to disseminate best practices, research outcomes, or innovations for these systems are often lacking. At a broader level, the scale at which policies are crafted might not always align with the unique needs of localized systems. Lastly, external factors such as global market demand and price oscillations can exert economic pressures on farmers, potentially deterring them from adopting HNV practices [116–118].

Addressing these challenges requires an integrated approach, focusing on collaboration among stakeholders, improved data collection, and alignment of economic incentives with conservation objectives. Moreover, acknowledging the multifunctional role of HNVf, not only in biodiversity but also in cultural, societal, and economic terms, is crucial for its effective integration into policy frameworks. Nevertheless, numerous mechanisms and policies are currently being implemented to address these challenges. The European Union's Common Agricultural Policy (CAP) stands out as a significant shaper of agricultural practices. A pivot in the CAP towards conservation [96], especially through the environmentally aligned initiatives in its second pillar, can serve HNVf's cause. In parallel, the EU Biodiversity Strategy [94], formulated under the European Green Deal with a 2030 horizon, encapsulates objectives that are harmonious with conserving HNVf [93]. Moreover, the expansive EU initiative for nature conservation, the Natura 2000 Network [119], offers an ideal setting for HNVf to be a strong conservation focus. The Water Framework Directive (WFD), which acknowledges HNVf's integral role in water management, is another policy conduit through which integrating HNVf management can amplify water quality and support aquatic ecosystems [120]. On a similar note, rural development programs, both at national and regional levels, can be utilized to extend financial and technical support for the stewards of HNVf [121]. Countries can leverage national biodiversity strategies and action plans (NBSAPs) to define specific goals tailored for HNVf. Regarding climate, it is crucial to weave HNVf into overarching strategies like the EU's Climate Law, given its contribution to carbon sequestration and fostering climate resilience. The agri-environment-climate measures (AECM), part of the CAP's second pillar, provide incentives for eco-friendly farming and can be refined to spotlight HNVf systems. Instruments such as the European Landscape Convention can serve to accentuate HNVf's cultural and landscape significance [87]. Lastly, the UN's Sustainable Development Goals, particularly goals 2, 13, and 15, can provide the backbone of national policies, championing the ideals and protection of HNVf [90].

Moving to mechanisms and approaches, the payment for ecosystem services (PES) system provides direct recompense for those enhancing ecosystem services from their lands [122]. Tailoring these incentives to accentuate HNVf-centric practices can further fortify crucial ecosystem services. Natural capital accounting offers a lens to monetize and appreciate the ES of HNVf, steering policymakers towards informed decisions. Ecosystem-based adaptation strategies, acknowledging escalating climate challenges, can be designed around HNVf to bolster resilience. Finally, biodiversity offsets, meant to offset biodiversity deficits, can rejuvenate both biodiversity and the accompanying ES if shaped with HNVf as a priority, especially in areas marred by intensive farming or development [123].

4.4. Future Directions

Recent advancements have broadened the monitoring and quality assessment of HNVf and its ES with a multidimensional approach, emphasizing the importance of blending ecological, economic, and socio-cultural insights [48,108,124–127]. A pivotal challenge lies in harmonizing localized, hands-on knowledge of HNVf with expansive global metrics. Climate change adds further to this challenge, demanding predictive modeling to discern the potential impacts on HNVf and VES [128–130]. Technological developments, especially in artificial intelligence and remote sensing, promise transformative capacities in HNVf monitoring, but they need to be anchored by solid methodologies [119,131–143]. Concurrently, an in-depth exploration of policy efficacy, legislative structures, and market-based mechanisms is still needed to align conservation with economic objectives [143]. In essence, the future of HNVf research calls for an integrated, technologically informed and culturally attuned approach to address the complexities of these landscapes [100,115].

5. Conclusions

Our bibliometric review revealed a dominant preference for VES over HNVf research. This preference was evident across a variety of disciplines and geographical regions. As research into VES flourishes, HNVf has attained a plateau in interest. The reasons for this may include the shift in research methodologies that prioritize ES for characterizing landscapes and assessing their ecological health. Additionally, the concept of HNVf has become ingrained in policymaking, which could account for a perceived decrease in novel research.

While tremendous progress has been made in understanding HNVf and VES, notable gaps remain in both research domains. In HNVf research, a critical step is the expansion of its geographical scope. A more comprehensive, global perspective offers insights into the challenges and opportunities that different regions present. Additionally, as we delve deeper into HNVf assessment, there is a need to include diverse metrics that not only quantify but also qualify the conditions found in this type of ecosystem; methodologies should be designed to integrate and prioritize ES, ensuring that we capture the essence of HNVf's potential. On the other hand, when considering VES research, we must acknowledge the limitations of traditional assessment methods. These methods often miss the nuances necessary for informed policymaking that genuinely values ecosystems. A solution lies in blending biophysical knowledge with economic valuation techniques, which would provide a clearer and more actionable understanding of ES.

Science mapping, while offering quantitative insights, is not without limitations. It often demands prior domain expertise and may not always deliver in-depth findings analogous to traditional reviews. Our bibliometric approach is a starting point, a foundation upon which deeper, more intricate analyses can be built. This research sets the stage for comprehensive studies that dissect the complex relationship between HNVf and VES, with a focus on standardized links. Future investigations should delve deeper into spatial modeling of HNVf and valuation of respective ES methodologies, which will further elucidate their practical implications.

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Appendix A

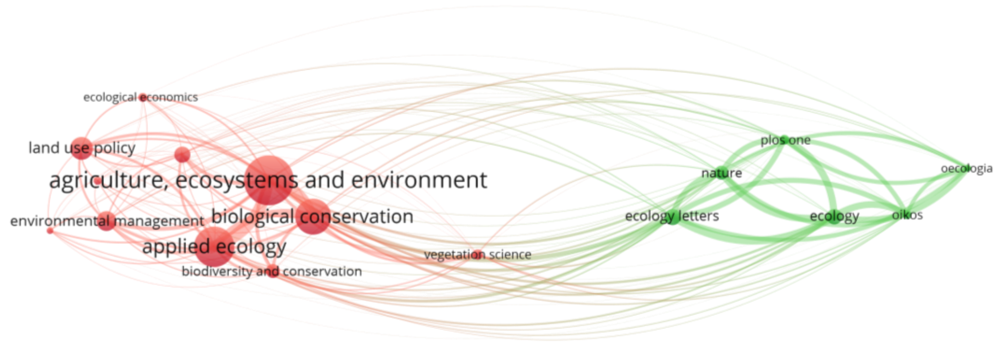

Figure A1. Source co-citation network for HNVf research from 1997 to 2022.

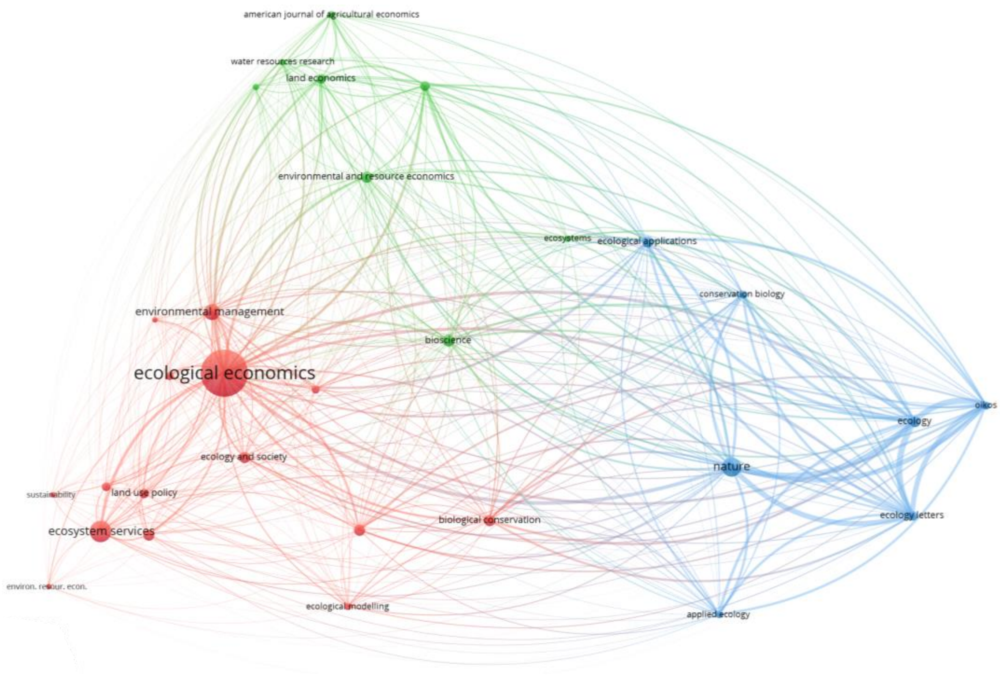

Figure A2. Source co-citation network for VES research from 1997 to 2022 (threshold of 100 citations).

Table A1. Ten most productive and influential authors in HNVf research, 1997–2022 (>5 documents).

Author	Nº of Documents	Nº of Citations
McCracken D.	5	914
Plieninger T.	11	548
Dengler J.	5	501
Hartel T.	10	383
Lomba A.	9	298
Moran J.	8	205
Moreira F.	7	203
Pinto-Correia T.	7	180
Finn J.A.	7	163
Sullivan C.A.	6	155

Table A2. Ten most influential documents in HNVf literature, 1997–2022.

1st Author (Year)	Document Title	Nº of Citations	*IO* Rank	Reference
Henle K. (2008)	Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe-A review	500	460	[38]
Dengler J. (2014)	Biodiversity of Palearctic grasslands: A synthesis	380	400	[29]
Renwick A. (2013)	Policy reform and agricultural land abandonment in the EU	304	314	[100]
Biondi E. (2011)	Phytosociology today: Methodological and conceptual evolution	223	213	[101]
Halada L. (2011)	Which habitats of European importance depend on agricultural practices?	219	209	[102]
Weisser W. (2017)	Biodiversity effects on ecosystem functioning in a 15-year grassland experiment: Patterns, mechanisms, and open questions	219	269	[144]
Plieninger T. (2015)	Wood-pastures of Europe: Geographic coverage, social-ecological values, conservation management, and policy implications	191	221	[145]
Wesche K. (2012)	Fifty years of change in Central European grassland vegetation: large losses in species richness and animal-pollinated plants	181	181	[146]
Sutcliffe L. (2015)	Harnessing the biodiversity value of Central and Eastern European farmland	176	206	[32]
Levers C. (2018)	Spatial variation in determinants of agricultural land abandonment in Europe	142	202	[147]

Table A3. Ten most cited authors in VES research, 1997–2022 (>5 documents).

Author	Nº of Documents	Nº of Citations
Hein L.	5	2084
Barton D.N.	7	1285
Bagstad K.J.	8	776
Barbier E.B.	5	639
Brander L.	10	626
Sutton P.C.	6	500
Costanza R.	16	344
Fisher B.	7	207
Polasky S.	6	148
Gómez-Baggethun E.	6	89

Table A4. Ten most influential documents in VES literature, 1998–2022.

1st Author (Year)	Document Title	Nº of Citations	*IO* Rank	Reference
De Groot R. S. (2010)	Challenges in integrating the concept of ecosystem services and values in landscape planning, management, and decision making	1524	1504	[25]
Power A. G. (2010)	Ecosystem services and agriculture: tradeoffs and synergies	619	599	[56]
Gómez-Baggethun E. (2013)	Classifying and valuing ecosystem services for urban planning	527	537	[103]
Farber (2002)	Economic and Ecological concepts for valuing ecosystem service	439	339	[104]

Table A4. *Cont.*

1st Author (Year)	Document Title	Nº of Citations	*IO* Rank	Reference
Bullock (2011)	Restoration of ecosystem services and biodiversity: Conflicts and opportunities	361	351	[58]
Milcu (2013)	Cultural ecosystem services: A literature review and prospects for future research	359	369	[50]
Crossman (2013)	A blueprint for mapping and modeling ecosystem services	295	305	[52]
Bagstad J. K. (2013)	A comparative assessment of decision-support tools for ecosystem services quantification and valuation	284	294	[23]
Troy (2006)	Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer	280	220	[24]
Daw (2011)	Applying the ecosystem services concept to poverty alleviation: The need to disaggregate human well-being	278	268	[105]

Table A5. Ten most cited articles that approach HNVf and ecosystem services as the research topic, 2011–2022.

1st Author (Year)	Document Title	Nº of Citations	Reference
Bernués A. (2016)	Agricultural practices, ecosystem services and sustainability in High Nature Value farmland: Unraveling the perceptions of farmers and nonfarmers	78	[19]
Lomba A. (2020)	Back to the future: rethinking socioecological systems underlying high nature value farmlands	72	[107]
Plieninger T. (2019)	Perceived ecosystem services synergies, trade-offs, and bundles in European high nature value farming landscapes	59	[106]
O'Rourke E. (2016)	High nature value mountain farming systems in Europe: Case studies from the Atlantic Pyrenees, France and the Kerry Uplands, Ireland	53	[148]
Ferraz-de-Oliveira M.I. (2016)	Management of Montados and Dehesas for High Nature Value: an interdisciplinary pathway	44	[149]
Lomba A. (2017)	Making the best of both worlds: Can high-resolution agricultural administrative data support the assessment of High Nature Value farmlands across Europe?	36	[150]
Pais S. (2020)	Mountain farmland protection and fire-smart management jointly reduce fire hazard and enhance biodiversity and carbon sequestration	33	[151]
Rodríguez-Ortega T. (2016)	Psychographic profile affects willingness to pay for ecosystem services provided by Mediterranean high nature value farmland	32	[152]
Varela E. (2020)	Targeted policy proposals for managing spontaneous forest expansion in the Mediterranean	30	[153]
Gardi C. (2016)	High nature value farmland: Assessment of soil organic carbon in Europe	26	[109]

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Decoupling Relationship between Industrial Land Expansion and Economic Development in China

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Abstract: Economic expansion has caused increasingly serious land resource problems, and the decoupling of urban industrial land expansion from economic development has become a big topic for intensive development. The current research has mainly concerned industrial land efficiency, a single, static indicator, compared to a decoupling model, which takes into account two variables and gives a full expression of the spatio-temporal dynamic characteristics. However, little attention has been paid to the relationship between industrial land expansion and economic development in China from the perspective of decoupling. Based on a combination of Tapio's decoupling model and spatial analysis methods, this paper investigates the decoupling relationship between industrial land expansion and economic development in Chinese cities from 2010 to 2019. On that basis, we divided the study area into three policy zones and made differentiated policy recommendations. In addition, based on the decoupling model, we obtained the decoupling indices of the cities and grouped the cities into eight decoupling types. After the spatial autocorrelation analysis, we further verified the spillover effect of decoupling with the results of urban spatial differentiation. This paper draws the following conclusions: (1) Urban industrial land expansion and economic development exhibit marked and increasingly significant spatial heterogeneity and agglomeration. (2) Industry and economy are in weak decoupling in most cities, but there are a growing number of cities in negative decoupling. (3) Decoupled cities are shifting from the southeast coast to the middle and lower reaches of the Yellow River and Yangtze River, while negatively decoupled cities keep spreading from northeast and south China to their periphery, with clear signs of re-coupling. (4) It is necessary to develop urban industrial land supply and supervision policies according to local actuality and to implement differentiated control of industrial land for cities and industrial sectors with different decoupling types. To some extent, this paper reveals the evolution dynamics, performances, and strategies of industrial land, providing a decision basis for industrial land management policies and industrial planning in China and other countries at similar stages.

Keywords: industrial land; economy; decoupling model; China

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1. Introduction

Industrialization and urbanization are the driving forces of global modernization and also an inescapable topic of economic development. North America, Europe, and other developed regions have experienced the complete process of "industrialization–deindustrialization–reindustrialization" [1,2]. Industrial land serves as the carrier of industrialization, and the sustainable development of the economy is inseparable from its intensive utilization [3]. The expansion of industrial land not only supports economic development [4], but consumes huge amounts of resources and farmland, threatening food and ecological security [5,6]. In the process of urbanization, urban land encroaches on surrounding land [7], creating many problems of underutilization of resources and unbalanced development. As the core factor of urban land, the issue of intensive and efficient use of industrial land has received widespread attention worldwide.

China has a large amount of industrial land, and its industrial economy is becoming more influential in the world economy, making it an increasingly important player in the world economic system, quite typical in the world. According to the China Bureau of statistics in 2019, the area of industrial land was 11,478.8 km^2 [8], and the industrial added value exceeded $5.6 trillion [9]. China has been active in promoting its external investment strategy since the beginning of the 21st century, which has strengthened its own international ties [10] and has contributed to the flourishing of industrial sectors such as energy, finance, and utilities [11], as well as to its economic strength and international competitiveness. Moreover, the global command-and-control function of Chinese cities is rising [12,13], as evidenced by Beijing and Shanghai, which have catapulted themselves to alpha-level international cities [14]. In addition, China is undergoing a transition from an incremental economy mode to a stock economy mode, which is typical for the study. In the context that China is transforming its economy from the industrial sector to the service-oriented sector, the development of the service industry promotes intensified and high-end industrial development, pushing industrial land to the stage of stock optimization, and even reduction and contraction [15]. To date, industrial land in some big cities [16] has undergone the change from "incremental expansion" to "stock optimization" [17]. However, industrial land expansion is still part and parcel for economic development in most cities [18], so there is an urgent need for a method for the rational allocation of industrial land that allows the economy to be gradually decoupled from industrial land expansion while maintaining stable development.

The relationship between industrial land and economic development has received increasing attention in academic circles, and a variety of research directions have been derived. Silva [19], Vandermeer [20], Louw [21], and Folmer [22] all have evaluated and compared the spatial differences of industrial land and its production efficiency, finding that it is related to factors such as development intensity, policy control, and habitat. Langer [23], Chen [24], and Ustaoglu [25] have all focused on industrial land expansion in urban agglomerations and have found that the impact of industrial land expansion on urban economies is significantly spatially heterogeneous and time-lagged and that such expansion has more negative than positive effects for most small cities. Shih [26] and Ouoba [27], from an industrial perspective, have both found that industries at different stages of development vary in adaptability to policies with different impacts on society, economy, and ecology and argued that both the renewal and iteration of production modes contribute to the efficiency of industrial land and the promotion of industrial development and social environment improvement. Some scholars have focused on the expansion of industrial land experienced by China since the beginning of the new century and have found that industrial land is characterized by significant agglomeration [28] and a spillover effect [29] in spatial distribution and economic benefits. There are also some different views on the impact of industrial land expansion on the economy. Some scholars believe that the spread of industrial land inhibits economic development [30–32], while others believe that spillover expansion has a better effect on promoting economic efficiency than enclave expansion [33,34].

There are two gaps in the current research. The first is that, from the perspective of topic focus, the studies available have mainly concerned the economic value of industrial land while ignoring the match between economic development and industrial land. Adequate consideration of the change rules of economic development helps to judge the land–economy relationship in a more comprehensive manner. The second is that, from the perspective of research methods, most of the current studies have been conducted on one-dimensional indices, such as land development intensity and output efficiency. However, one-dimensional indices are often composed of many factors, making the physical meaning of the results abstract, with no significant practical guidance. Only by fully considering the physical meaning of evaluation factors can an evaluation method guide practice more accurately. Worthy of note is that decoupling analysis methods have begun to emerge in land-use research. For example, Li [35] and Zhao [36] both have studied the decoupling relationship of construction land and service land with economic development and analyzed the decoupling state of the provinces in China, finding there is significant spatial heterogeneity in the decoupling states of cities. Nevertheless, few scholars have conducted specific studies on industrial land in China. Therefore, it is of great theoretical significance and practical value to study the decoupling relationship between industrial land expansion and economic development.

Based on a case study of 287 cities in China, this paper explores the relationship between economic development and industrial land expansion from the perspective of decoupling with the help of a new view of decoupling, a new method of measuring decoupling models, and a research framework oriented to policy formulation to help achieve scientific allocation, as well as the intensive and efficient development of industrial land. This paper focuses on three questions: What are the spatio-temporal evolution patterns of industrial land expansion and economic development in China? What are the characteristics of the decoupling relationship between urban industrial land expansion and economic growth? How are differentiated land management policies for cities with different decoupling types made?

2. Literature Review

The topic of the relationship between industrial land expansion and economic development has received much attention from the fields of economics [37,38], resource science [39,40], and environmental science [41]. Research methods to explore the relationship between industrial land expansion and economic development are becoming increasingly diverse, including multi-index integrations, coupling analyses, and regression analyses. These three methods provided an important theoretical and methodological basis for this paper. In view of the drawbacks of research using multi-index models and coupling models, this paper employed a decoupling model to measure the relationship between industrial land expansion and economic development and used a spatial autocorrelation model to determine the spatial characteristics of the decoupling model using a spatial regression model.

Most studies have been based on multi-index integrations, such as the Global Non-Radial Directional Distance Function (GNDDF) and the Stochastic Frontier Model (SFM). Xie [42] measured industrial land efficiency based on the GNDDF, finding that industrial efficiency was highest in east China and that the gap between the central and western regions was narrowing. Liu [43] measured the green economic efficiency of industrial land based on SFM, arguing that the level of regional scientific research and technology was positively correlated with economic efficiency. However, for GNDDF and SFM measurements, a variety of land and economic indicators are used, and they are taken as factors in the index calculation. These models dilute the physical meanings of the factors, making the obtained indices abstract and not very instructive for practice.

Some studies have been based on coupling analysis methods, and the more common coupling analyses include the DEA Model and the Coordination Degree Model. Xie [44] compared the urban industrial land use efficiency and the urban industrial land's total factor productivity of six major urban agglomerations in China based on a DEA-SBM model and found that improving the quality of the industrial economy and the intensity of land use in urban agglomerations could increase the land use efficiency. Liu [29] measured the coupling status of industrial land and economic development in Jilin based on a coupling model and found that Jilin showed a decreasing spatial pattern of population–industry–town coupling degree from the center of the city to the periphery, and this pattern was highly correlated with the urban population density. Coupling models also have some drawbacks. The results of their measurements are one-dimensional indices, and the classification of cities is based on the segmentation of these one-dimensional indices. However, the index segmentation does not allow for a precise classification of city types. Therefore, a more objective classification of city types can only be achieved by determining the development statuses of cities based on a variety of relevant indices together.

Regression models have been used in some studies, but the choice of variables has varied among scholars. Xu [45] performed a regression analysis of land scale and a variety of economic indices and found that the relocation of foreign-owned factories tended to lead to industrial land expansion. Zhou [46] and Huang [47] each directly regressed the land scale on economic output to analyze the differences in the responses of different cities in China to industrial land use policies and conducted spatial correlation analyses using autoregression. They both found that cities at different socio-economic levels have large differences in response to industrial land policies, while the supply of industrial land shows characteristics of a high level in the eastern coastal region and a low level in the western inland region. Regression models focus on measuring the degree of influence of industrial land efficiency factors and can only determine the average degree of influence for all the cities while ignoring the specific situation of each individual city. However, a spatial regression model also takes into account the associations between cities, providing a methodological basis for this paper to determine the associations between the decoupling states of the cities.

The approach of studying the relationship between land resource consumption and economic development based on decoupling models is favored by an increasing number of scholars. However, as a new method for the integrated analysis of land use change and its performance, it still has less support from the literature today. Most papers have now discussed the decoupling relationship between construction land and economic development. For example, Li [48] studied the decoupling relationship between construction land, economic development, and carbon emissions in China, finding that the economic output of land was the main source of carbon emissions and arguing that controlling construction land expansion could effectively decouple the economy from carbon emissions. Zhang [49] analyzed the relationship between economic development and land use in the Three Gorges reservoir area based on an ecological footprint model and a decoupling model, finding that the increase in land use was decoupled from the total economic volume and believing that the current sustainable land use was not yet able to support economic development. Nevertheless, construction land can be divided into a variety of functions, and the demand for land varies widely across functional industrial sectors [50]. Industrial output accounts for a significant share of the economic volume, and industrial land is a type of construction land with huge resource consumption [51] and a high input scale [52] that is more closely linked to the economy [53]. Therefore, it is necessary to explore the relationship between industrial land expansion and economic development using a decoupling model.

In the existing research methods on the relationship between industrial land expansion and economic development, the calculated results are often highly complex and static, and they cannot meet the government's demand for dynamic, concise, and actionable evaluation results. First, complex evaluation results are prone to a decrease in the explanatory power of the indices, and results that indirectly reflect the land–economy relationship are less liable to be used as an intuitive basis for policy making. Models such as DEA, UILUE, and UILTFP, for example, are complex in operation mode, often requiring the selection of differentiated indices based on the industrial structure of a city, and they are not suitable for large-scale popularization due to the difficulty in explaining the final results. Second, most of these models calculate points in time, making it hard to reflect the dynamic characteristics of the land–economy relationship over time. What is calculated by them is carried out, in general, in year-by-year units, but it takes 3–5 years or more for an investment in land to gain economic returns, a slow process of achieving gains from investment. The results obtained from a decoupling model fully consider the two indices to reflect both the point-in-time characteristics and the state of the relationship within the period, making it more accurate and comprehensive to present the land–economic development relationship. However, decoupling models have not been used systematically and comprehensively to study the relationship between industrial land expansion and economic development in Chinese cities, thus leaving great research potential.

3. Material and Methods

3.1. Study Area

The study was conducted on 287 cities at prefecture level and above in China (Figure 1). Given the availability of data, prefecture-level cities in the Taiwan Province, the Hainan Province, and the Tibet Autonomous Region, as well as autonomous prefectures, counties under provincial-level control, and county-level cities, were not included. The reasons were as follows: (1) different statistical calibers of different district types made it difficult to acquire complete data; and (2) they was not suitable for direct comparison due to the difference in the administrative levels and development capacities of provincial counties, county-level cities, and autonomous regions from those of prefecture-level cities. The study period was chosen to be from 2010–2019 in this paper for the following reasons: (1) China's economy has continued to slow down after 2010 and has entered a new normal of 6–7% growth. (2) China's central government proposed a new goal of supply-side structural reform and innovation-driven development in 2013, which was fully implemented during the 13th five-year-plan period (2016–2020), marking China's entry into a state of transformational development. (3) The outbreak of COVID-19 caused the global economy to stagnate in 2020, with no exception to China, so that year of abnormal economic development was not included. China was at a critical stage of transition from high-speed economic growth to high-quality development during the decade from 2010 to 2019 [54], and thus, that time period was the focus of this paper.

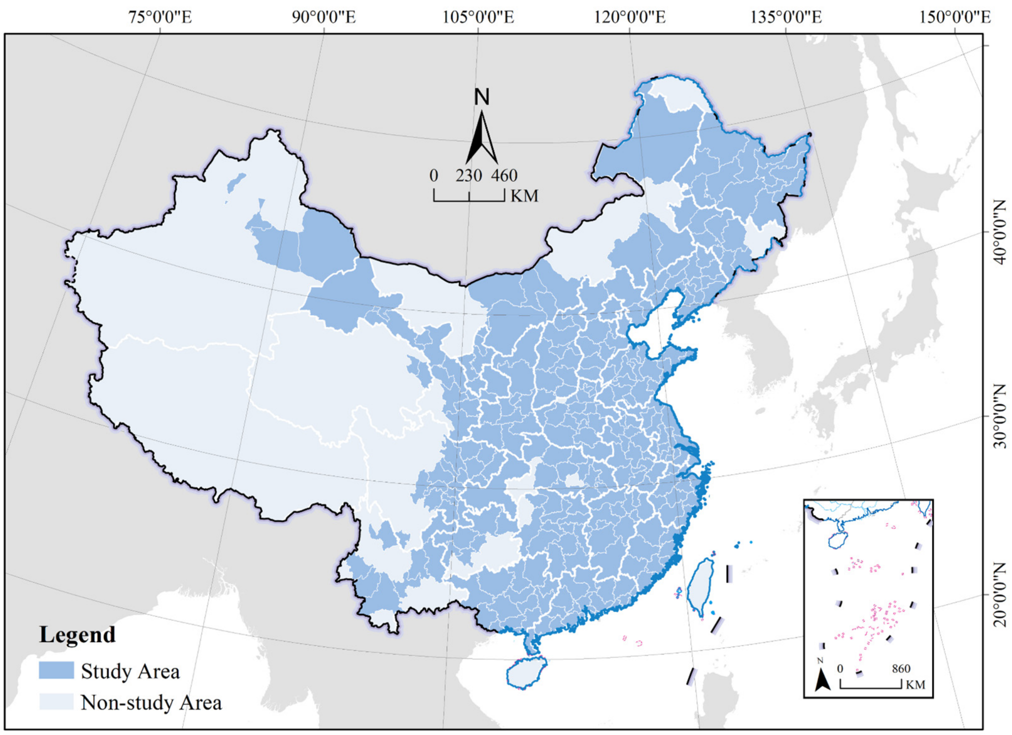


Figure 1. Study Area. The approval number of the national boundary of China is GS (2020) 4628, which comes from the standard map service system undertaken by the Ministry of Natural Resources of China: http://bzdt.ch.mnr.gov.cn (accessed on 23 June 2022).

3.2. Method

The OECD (Organization for Economic Cooperation and Development) was the first to put forward the decoupling model to promote the decoupling between economic growth and environmental damage [55]. Later, Tapio classified 8 types of decoupling based on the combination of decoupling models and elasticity coefficient methods [56]. These decoupling types were, from best to worst: strong decoupling, weak decoupling, expansive coupling, expansive negative decoupling, recessive decoupling, recessive coupling, weak negative decoupling, and strong negative decoupling. The improved method has been widely used in the fields of economics [57,58], resource science [38,59,60], and environmental science [61–63].

This paper analyzed the relationship between urban industrial land expansion and economic development with the help of the Tapio decoupling model. With α used to denote the decoupling index between industrial land expansion and the economy, the decoupling index equation can be expressed as:

$$\alpha = \frac{\Delta LAND}{\Delta GDP},\ \Delta LAND = \sqrt[n]{\frac{LAND_{i+n}}{LAND_i}} - 1, \Delta GDP = \sqrt[n]{\frac{GDP_{i+n}}{GDP_i}} - 1 \tag{1}$$

where, $\Delta LAND$ represents the average annual growth of industrial land; $LAND_i$ and $LAND_{i+n}$ represent the scales of industrial land in year i and year $i+n$, respectively; ΔGDP represents the average annual growth of economic-development-related indices; GDP_i and GDP_{i+n} represent the annual values of the economic indices in year i and year $i+n$, respectively; and n represents the study interval of time.

The Tapio decoupling model classifies decoupling into 8 types using 0.8 and 1.2 as classification thresholds (Figure 2). Strong decoupling is the best state, indicating that the economy is growing despite the contraction of industrial land. Cities in weak decoupling have an economic growth slightly faster than land expansion, indicating that the expansion of industrial land promotes economic development. The expansion of industrial land in cities in expansive coupling grows simultaneously with the economy, and according to Gan [64], it is inferred that most of these cities are at the incremental development stage in the state of city–industry integration. Expansive negative decoupling indicates that both industrial land and economic output are growing, but land is being consumed at a faster rate. Cities in recessive coupling experience the expansion of industrial land simultaneously with economic contraction in a state of urban contraction that produces disconnectedness [65]. Recessive decoupling and weak negative decoupling stand for terrible states to show that both industrial land and the economy are contracting, with the difference that the land is contracting faster in the former state, while the economy is contracting more severely in the latter state. Strong negative decoupling is the most terrible state, indicating that industrial land expansion comes with continued economic contraction. According to the method of Zhang [66] for assigning decoupling types, the decoupling types are assigned as 4, 3, 2, 1, −1, −2, −3, and −4 from the best to the worst. A larger value assigned indicates a better decoupling state and a lower level of dependence of the industrial economy on land.

3.3. Research Steps and Data Resource

The study included three stages, as the Figure 3 shown, corresponding to the following three questions. What are the spatio-temporal evolution patterns of industrial land expansion and economic development in China? What are the characteristics of the decoupling relationship between urban industrial land expansion and economic growth? How are differentiated land management policies for cities with different decoupling types made?

The decoupling study involved two perspectives. The first was to study the decoupling relationship of INL–SAV, which represented the economic output efficiency directly brought by industrial land expansion and visualized the decoupling relationship between industrial land and the economy. INL was derived from the industrial land section in the 2011–2020 *China Urban Construction Statistical Yearbook*, and SAV was derived from the municipal district section of industrial structure in the 2010–2019 *China Statistical Yearbook*. The second was to study the decoupling relationship of INL–GDP, which comprehensively showed the interaction between industrial land expansion and economic development. As industry is in close cooperation with service and agriculture in part, the development of industry boosts the output efficiency of other sectors, thus promoting the intensive and efficient use of land. The GDP data were obtained from the municipal district section of GDP in the *China Statistical Yearbook* for 2010–2019.

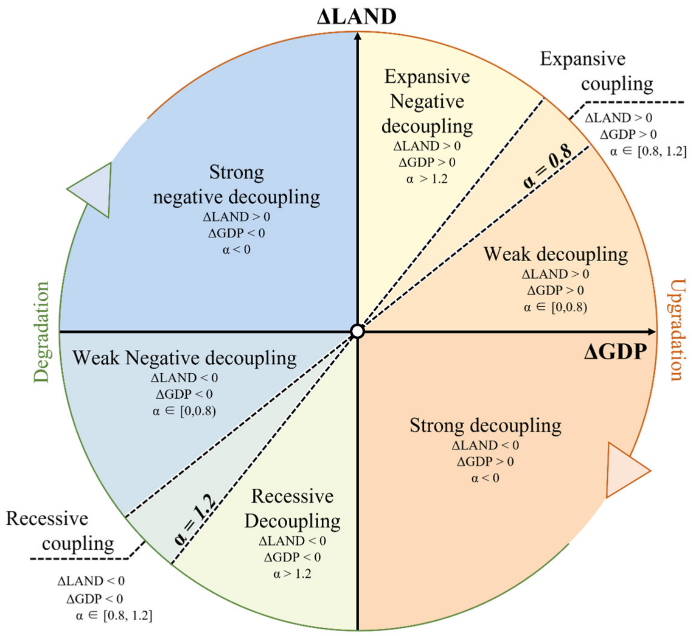


Figure 2. The decoupling relationship between industrial land (ΔLAND) and economic development (ΔGDP).

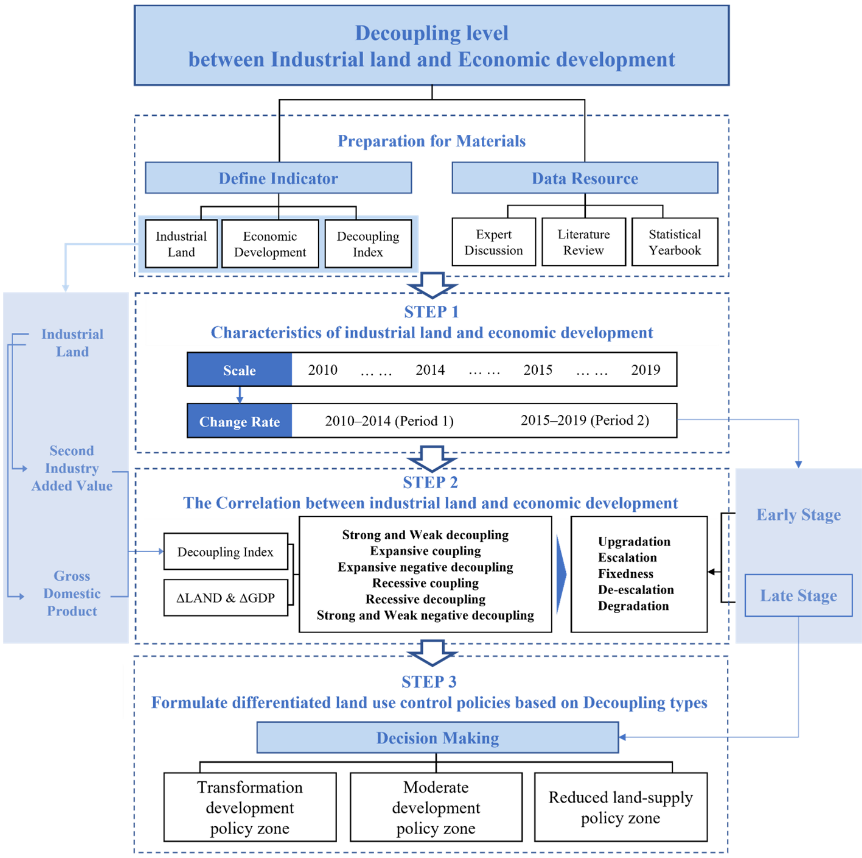


Figure 3. The research framework of decoupling degree to evaluation.

In the first step, we analyzed the scales and changes of land and economy around their spatio-temporal evolution pattern. As 2015 was a watershed year for two five-year-plan periods with different development goals, we divided 2010–2019 into 2010–2014 and 2015–2019 and recorded them as Period 1 and Period 2, respectively. To calculate the rate of change between the two 5-year periods more concisely, we analyzed the rate of change of the indices in Period 1 and Period 2 based on the data of four critical years: 2010, 2014, 2015, and 2019. In this study, we used the area of the industrial land (INL) to represent the characteristics of industrial land, and we used two variables to represent the characteristics of economic development, which were second-industry added value (SAV) and gross domestic product (GDP).

In the second step, we analyzed the types of decoupling and their changing characteristics in cities around the relationship between industrial land expansion and economic growth using the decoupling model. Based on the calculation the decoupling indices of INL–SAV and INL–GDP, we classified 287 cities into 8 categories according to the model criteria and analyzed the spatial pattern and evolution characteristics of the decoupling states of Chinese cities under Period 1 and Period 2 through geo-visualization. Then, we compared the decoupling types of the cities between the two periods and analyzed the change characteristics of the decoupling states.

In the third step, we made policy recommendations concerning the land-use policy controls for cities with different decoupling types. First, we took the least favorable state of the two decoupling types of INL–SAV and INL–GDP in Period 2 as the basis for the decoupling policy making in each city in line with the least favorable principle. After that, we divided the cities in the study area into three types of policy zones and proposed differentiated industrial land-control policies for different policy zones.

In addition, we supplemented missing yearbook data for some years through averaging and trend extrapolation in this paper. For missing data in year N, with no data missing in years $N-1$ and $N+1$, an averaging method was applied. For example, for the missing 2018 INL data of Zhuhai, the average of the 2017 and 2019 values was taken as the scale of its industrial land for 2018. Trend extrapolation was applied when data for year N were missing and data for year $N-1$ or $N+1$ were also missing. For example, for the missing 2019 SAV data of Jilin, the trend was extrapolated based on the 2016–2018 data, and the output value for 2019 was then obtained.

4. Results

4.1. Pattern of Relationship between Industrial Land and Economy

4.1.1. Scale of Industrial Land and Economy

From the perspective of industrial land, the scale of the land showed a trend of gradual decrease from the eastern coast to the western inland areas, but it steadily increased in the eastern region and continuously expanded in the western region, while showing obvious weakness in the northwest and southwest. High-scale areas developed in a belt-like pattern, mainly concentrated early in the northeast, the eastern coastal, and southern economic development areas, with a small number in Sichuan and Chongqing. These western economic areas, having developed mainly relying on the preferential policy of western development, together with central and western regions such as northern Guizhou (western Hubei having developed later), grew into complete, high-scale agglomeration areas along the Yangtze River. The marginal regions of most provinces were medium-scale areas, and their scales fluctuated. Some southeast regions, including Jiangxi and Fujian, developed from low-scale areas. Relatively stable, medium-scale areas included Guangxi, Anhui, and Hebei, while the northeastern regions, such as Inner Mongolia, were contracted to medium-scale areas from high-scale areas. Low-scale areas were relatively stable and increasingly concentrated in the northwest and southwest regions. Figure 4 shows the results of the clustering distribution of industrial land scale in 2010 and 2019.

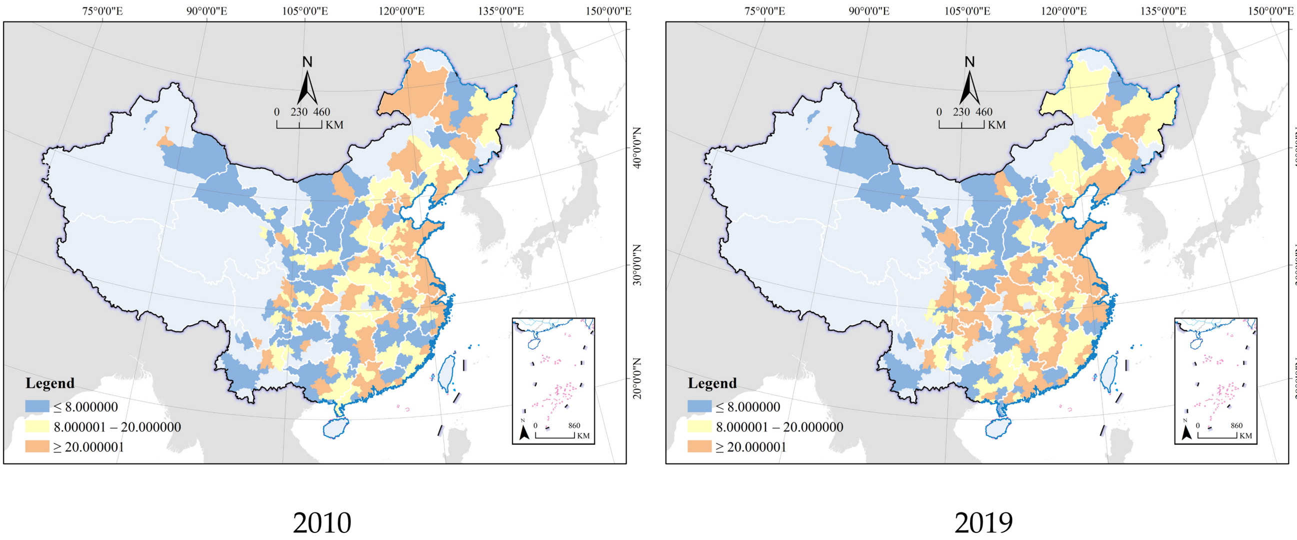


Figure 4. Distribution of industrial land scale.

From the perspective of economic development, SAV and GDP shared roughly the same spatial differentiation, with high-output areas mainly in two types of regions, that is, the eastern coastal zone and the central city of each province. Low-output areas were mostly concentrated in the border areas of provinces, showing a cluster-like development pattern. With the increase in output value, the eastern coastal cities basically reached a high level of production, especially in Jiangsu, where the production reached a high level in the domain and overflowed outside, showing a significant agglomeration characteristic. Most of the medium-output-value areas developed from low-output areas and gathered around high-output areas, especially in southern Guangdong, Guangxi, Hebei, Henan, Sichuan, Guizhou, north China, and Chongqing. Low-output areas were widely distributed throughout the country in the early days, except for north China and the eastern coast, and were then mostly replaced by medium-output areas. The remaining low output cities in the southeast, north China, and south China regions were mostly in the margins of the provinces, except for in northeast and northwest China, such as Heilongjiang, inner Mongolia, Jilin, and Gansu.

4.1.2. Growth Rate of Industrial Land and Economy

China's industrial land and its economic development indices were characterized by significant spatial heterogeneity and agglomeration, with the differences between land-use indices decreasing, while economic indices increased, as shown in Table 1. A larger coefficient of variation indicated higher degrees of dispersion and variability characteristics, and according to the study, when the degree of variation was greater than 0.36, there was significant heterogeneity between variables [67]. The observation of the index coefficients for the first and second five-year periods showed that the coefficients of variation of SAV and GDP were much larger than 0.36 and were growing larger.

Table 1. Statistical analysis of average annual growth rate.

Index		Max.	Min.	Mean	COV	Moran's I
2010–2014	INL	128.55	−39.39	1.18	13.56	0.035
	SAV	110.20	−46.39	12.75	1.30	0.050
	GDP	61.88	−10.40	13.23	0.59	0.109
2015–2019	INL	68.10	−39.14	3.18	4.14	0.042
	SAV	37.50	−36.00	4.09	2.39	0.215
	GDP	32.93	−22.41	8.42	0.92	0.330

The Global Moran's I of industrial land change in China is a positive value, while the significance is lower than the spatial autocorrelation index of economic development, indicating that industrial space is agglomerative, but constrained by regional characteristics. The Global Moran's I values of SAV and GDP in 2010–2014 and 2015–2019 were 0.05, 0.11, 0.22, and 0.33, respectively, and they passed the significance test of 0.01 and above, indicating that the economic development indices generated by industrial land showed a significant agglomeration characteristic at the spatial level and became more concentrated.

By analyzing the positive and negative characteristics of the change rates of industrial land and economic development in the early and late periods, we obtained the results in Figure 5 It was obvious that the fluctuating growth of industrial land in China's cities over the past decade has not stopped the negative economic growth that is growing worse. Negative growth was also spatially clustered to some extent, mainly distributed in the northeast. There were 32 and 10 cities with negative growth of SAV and GDP, respectively, in the early period, and the numbers increased to 82 and 35, respectively, in the later period. According to the spatial clustering analysis, it was found that cities with negative growth were mainly concentrated north of the Yellow River, especially in the northeast region.

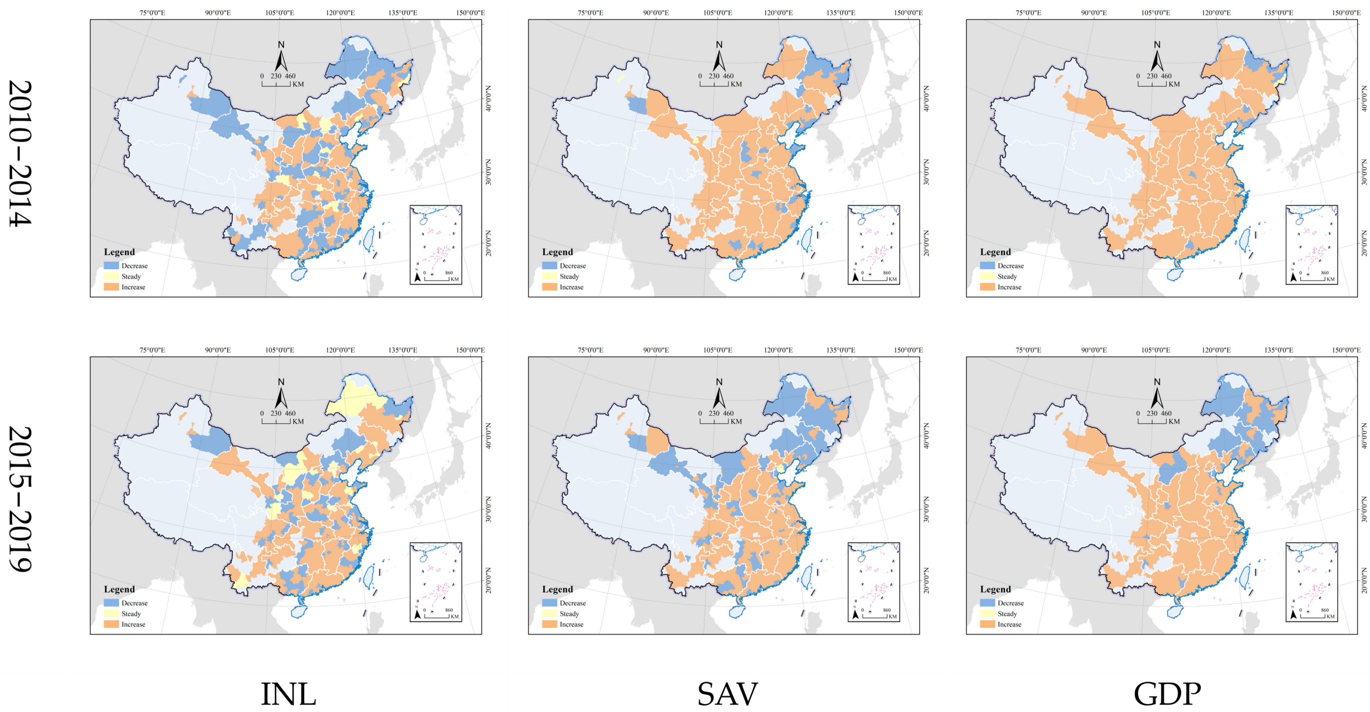


Figure 5. Distribution of industrial land and economic change rate.

4.2. Decoupling Relationship between Industrial Land and Economy

4.2.1. Relationship between Industrial Land and Second-Industry Added Value

According to the Figure 6, there were seven types of INL–SAV in the early stage, and most cities were in the states of strong and weak decoupling, accounting for about 74.22% of the total. As recessive coupling emerged in the later period, the cities in strong and weak decoupling states reduced to 47.39%, while those in strong and weak negative decoupling states increased up to 23.3%. From the perspective of spatial clustering, cities in strong and weak negative decoupling states were mainly concentrated in some pockets of northeast China in the early period, but they spread to the whole northeast and northwest of China later, even involving some parts of north China; in the later period, cities in the expansive negative decoupling state formed east–west belt clusters in Guangxi, Hunan, Jiangxi, and Fujian.

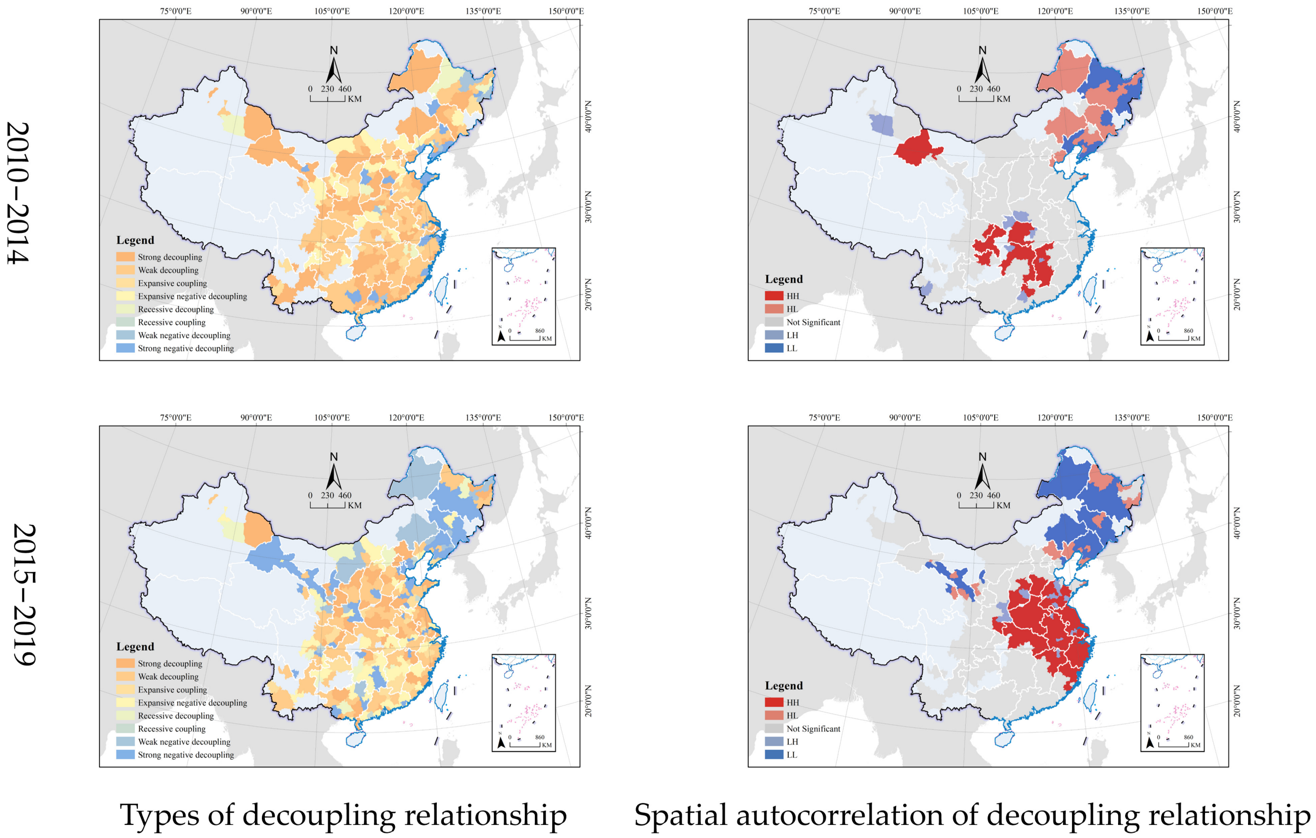


Figure 6. Decoupling type and spatial autocorrelation of industrial land and second-industry added value.

According to the spatial correlation analysis using GeoDa, different cities were categorized into five characteristic spaces of HH, HL, No Significant, LH, and LL. There were many cities well-decoupled around HH cities, while HL cities were in good decoupling states but were surrounded by those in poor decoupling states. Different from HL cities, LH cities were in poor decoupling states but were surrounded by cities that were well-decoupled. LL cities were surrounded by those also in poor decoupling states. No Significant meant that the decoupling states of these cities were average, and there were no significant agglomeration characteristics.

According to the spatial correlation analysis of INL–SAV, it was found that HH cities were concentrated and distributed in the central regions of Chongqing, Hubei, Hunan, and Jiangxi in the early period, while LL and HL cities were in the northeast region. In the later period, the spatial agglomeration of HH and LL cities increased significantly. The former was mainly found in the middle and lower reaches of the Yellow River, the Yangtze River Delta, and its inland hinterland, while the latter was mainly in the whole northeast region and some northwest regions.

The changes in decoupling of the two periods showed that the decoupling state of INL–SAV was severely degraded in most cities in the northeast and northwest, followed closely by the Pearl River Delta and its inland hinterland. Upgraded cities were mainly concentrated in regional central cities and two provinces. These two provinces are Shaanxi and Shanxi, both of which are major provinces of raw material production and processing. Cities with stable development were mostly along the Yangtze River economic belt.

4.2.2. Relationship between Industrial Land and Gross Domestic Product

INL–GDP shared the same decoupling type as INL–SAV in the early period, but about 79.80% of the cities were in strong and weak decoupling states. The cities in strong decoupling states declined to two-thirds of the previous state in the later period, and some transformed into the states of strong and expansive negative decoupling. From the perspective of spatial cluster analysis, the cities of strong and weak negative decoupling in the early period were mainly in northeast China, especially in Liaoning, and they spread to the whole northeast in the later period.

From the spatial correlation analysis, as the Figure 7 shown, the HH cities were mainly concentrated and distributed in Hunan, Guangdong, Jiangxi, and other south China areas in the early period, with a small number distributed in the eastern coastal region in a band, while HL cities were mainly concentrated in the northeastern region and LL cities were also scattered in the northeastern region, indicating a sign of slowing economic growth in the northeastern region. In the later period, the spatial agglomeration of LL and HH cities was further enhanced, with the former having spread from a few cities in the northeast to the entire northeast and the latter being widely distributed from south of the Yellow River to north of the Yangtze River, covering the western economic zone and including Sichuan, Chongqing, Gansu, and Shaanxi, the north China economic zone (including Henan and Shandong), and the entire middle and lower reaches of the Yangtze River. However, it should be noted that LH cities were still widely dispersed in the provinces of HH cities and showed the same spatial characteristics as those found in the northeast in the early period.

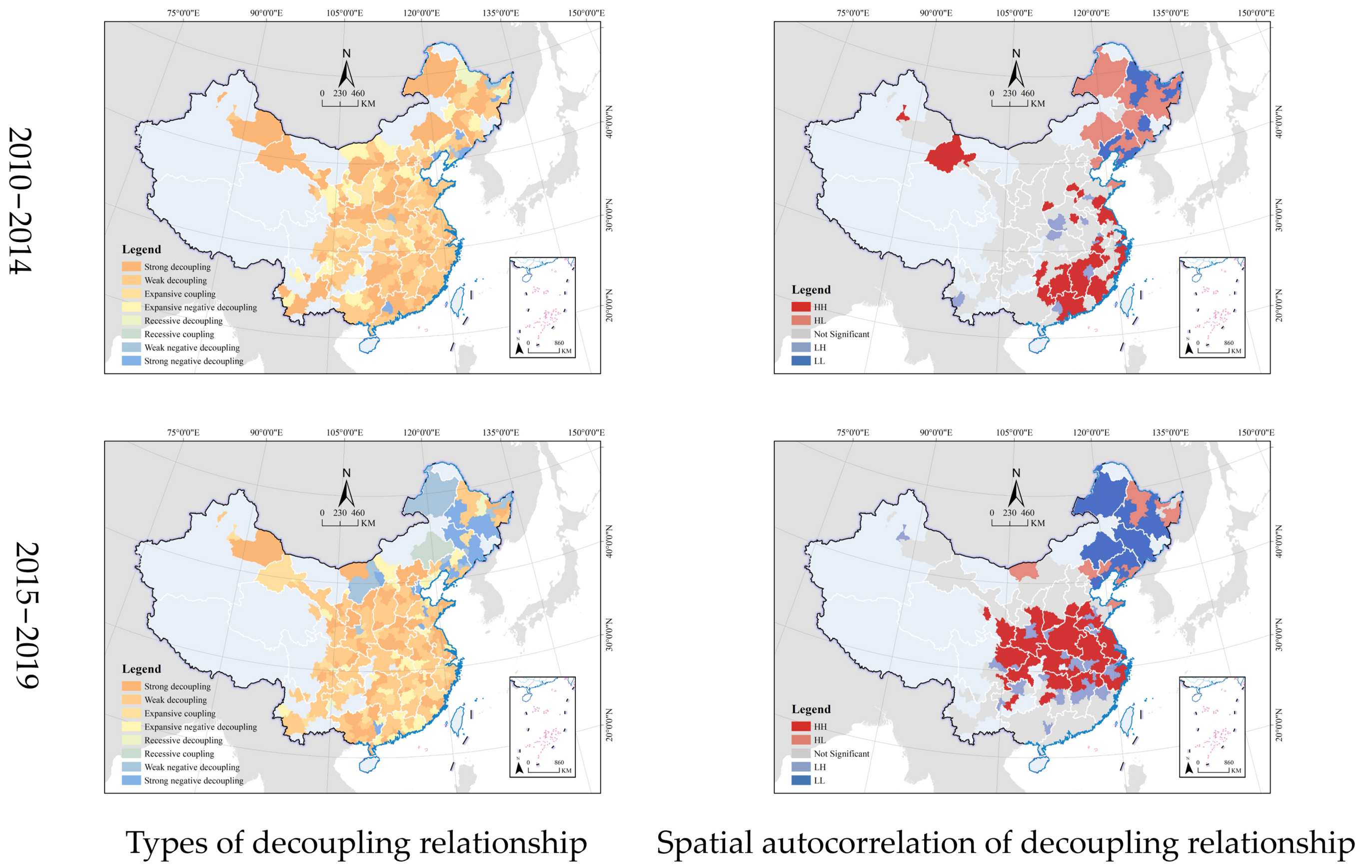
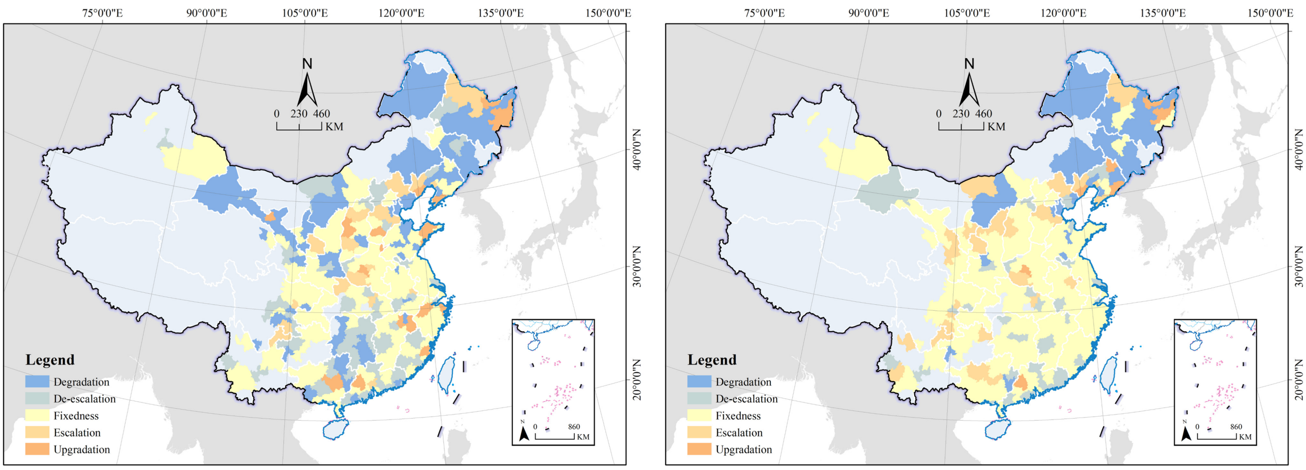


Figure 7. Decoupling type and spatial autocorrelation of industrial land and gross domestic product.

As the Figure 8 shown, the decoupling state of INL–GDP was similar to the results of INL–SAV, with most cities in northeast and northwest China severely degraded, followed by the Pearl River Delta and its inland hinterland. However, the degradation of the Pearl River Delta was much slower because of its richer industrial structure. The upgraded cities were also scattered around the severely degraded cities, reflecting from the side that the neighboring cities had learned from the old industrial structure of the formerly developed industry in the northeast. The cities with stable development were widely distributed in the Yellow River and Yangtze River basins.



INL-SAV INL-GDP

Figure 8. Distribution of decoupling changes between industrial land and economic development.

5. Policy Suggestion

Since the decoupling states varied widely among cities, a one-size-fits-all approach to the development of the stock economy could not be applied to all cities [68]. The results acquired based on the decoupling model reflected the matching degree between urban industrial land expansion and economic growth, enabling an accurate reflection of urban development.

In the first step, we superimposed the results of the INL–SAV and INL–GDP decoupling types of cities in China from 2015 to 2019 and obtained the combination results of the decoupling types under two conditions. INL–SAV measured the economic benefits brought by industrial land expansion and directly reflected the industrial and economic conditions of the cities. INL–GDP indicated the contribution of industrial land expansion to the economy and indirectly showed the rationality of the city's industrial structure. The urban industrial structure includes the agricultural, industrial, and service sectors, which are complementary to each other. The industrial sector drives the development of agriculture and services, which in turn contributes to its own development. A city could only be considered economically healthy when it was in good decoupling under both conditions of INL–SAV and INL–GDP. Therefore, according to the least-favorable principle, the inferior result from the two perspectives of each city was taken as the final decoupling type. The specific results of each combination are shown in Table 2.

In the second step, we grouped the eight decoupling types of cities into three policy orientations, as shown in Table 3. The demand for land from economic development was the basis for land supply, and the land-supply strategy was the feedback for the economic performance of the city. According to the relationship between the supply and demand of land, cities could be divided into three types of balance between supply and demand, short supply, and oversupply. Cities in strong decoupling, weak decoupling, and expansive negative decoupling states were generally considered as cities with balanced supply and demand of land. Their economic development rarely relied on land expansion, and they basically achieved sustainable economic development, with a focus on transitioning to an innovation economy in the future, so their policy orientation should be focused on the transformation development of land. Cities in expansive coupling and recessive decoupling states were mainly those in short supply of land. Their economic development often depended heavily on land expansion to create economies of scale, so the policy orientation of these cities should be mainly focused on the moderate development of land. Cities in recessive coupling, weak negative decoupling and strong negative decoupling states were basically those with an oversupply of land. For them, the supply of land led to a serious waste of resources instead of stopping their continued economic slowdown. These cities should implement reduced land-supply-oriented policies to end the vicious cycle of land–economic relations. We finally obtained the transformation development policy zone, the moderate development policy zone, and the reduced land-supply policy zone, as shown in Figure 9.

Table 2. Statistical analysis of average annual growth rate.

		INL–GDP							
		A [1]	B	C	D	E	F	G	H
INL–SAV	A	55 [2] (A [3])	0 (B)	0 (C)	0 (D)	0 (E)	0 (F)	0 (G)	0 (H)
	B	0 (B)	79 (B)	1 (C)	0 (D)	0 (E)	0 (F)	0 (G)	1 (H)
	C	0 (C)	14 (C)	5 (C)	2 (D)	0 (E)	0 (F)	0 (G)	1 (H)
	D	0 (D)	13 (D)	10 (D)	24 (D)	0 (E)	0 (F)	0 (G)	0 (H)
	E	9 (E)	0 (E)	0 (E)	0 (E)	2 (E)	0 (F)	0 (G)	0 (H)
	F	2 (F)	0 (F)	0 (F)	0 (F)	2 (F)	0 (F)	0 (G)	0 (H)
	G	2 (G)	2 (G)	0 (G)	0 (G)	0 (G)	2 (G)	8 (G)	0 (H)
	H	0 (H)	17 (H)	4 (H)	13 (H)	0 (H)	0 (H)	0 (H)	19 (H)

[1] A–H represent eight decoupling types of cities, which are strong decoupling, weak decoupling, expansive decoupling, expansive negative decoupling, recursive decoupling, recursive coupling, weak negative decoupling, and strong negative decoupling, respectively. [2] The numbers represent the number of cities in each combination of decoupling types of INL–SAV and INL–GDP; for example, 55 means there were 55 cities in the combination of A–A. [3] The letters in brackets represent the final decoupling type of cities; for example, A means the final type of cities in the combination of A–A was strong decoupling.

Table 3. Statistical analysis of average annual growth rate.

Decoupling Type	Development Status	Policy Orientation
Strong decoupling, weak decoupling, and expansive negative decoupling	Healthy development with less dependence on land expansion	Transformation development
Expansive coupling and recessive decoupling	Basic equivalence between urban development and land expansion	Moderate development
Recessive coupling, weak negative decoupling, and strong negative decoupling	Urban development does not need as much land, and the excess supply of land leads to waste of resources	Reduced land supply

5.1. Transformation Development Policy Zone

The transformation development policy zones covered Beijing, Shanghai, Shenzhen, and most cities in Henan, Jiangsu, Anhui, Shanxi, and other regions, mainly concentrated around the middle and lower reaches of the Yellow River and the Yangtze River economic belt as the front-runners of industrial land governance and economic development in China. These cities, due to the continued increase in economic growth despite the reduction of industrial land and the low dependence of economic development on industrial land expansion, should implement the transformational development policy. First, they should withdraw inefficient industrial land in an orderly and moderate manner, control the total land use area when ensuring stable and sustainable economic development, and stop the withdrawal of industrial land when the total land use area is reduced to the bottom line of land required for industrial development indices. Second, they should transform land-preferring policies into innovation-encouraging policies, increase financial support for innovation-based enterprises and talents, promote innovation-driven development, and reduce land waste. Third, they should enable the flexible transformation of existing land and change the pattern of land use that mainly hosts innovative industries and facilitates the transition from inefficient to efficient land use, for example, promoting the use of M0 land. M0 land is a type of urban land belonging to Class M by China's urban-land-use classification standard. Class M also includes M1 land, M2 land, and M3 land, which are classified by their impacts on the surrounding environment. M1 land has the least impact on the surrounding environment, while M3 land may cause serious pollution. M0 land was put forward for the first time in Shenzhen's urban planning for the purpose to promote urban innovation activities. M0 land integrates innovative industrial functions such as research and development, creativity, design, pilot testing, and pollution-free production. It mainly carries zero-pollution plants and research and development houses, while serving as commercial, dormitory, municipal, and transportation facilities.

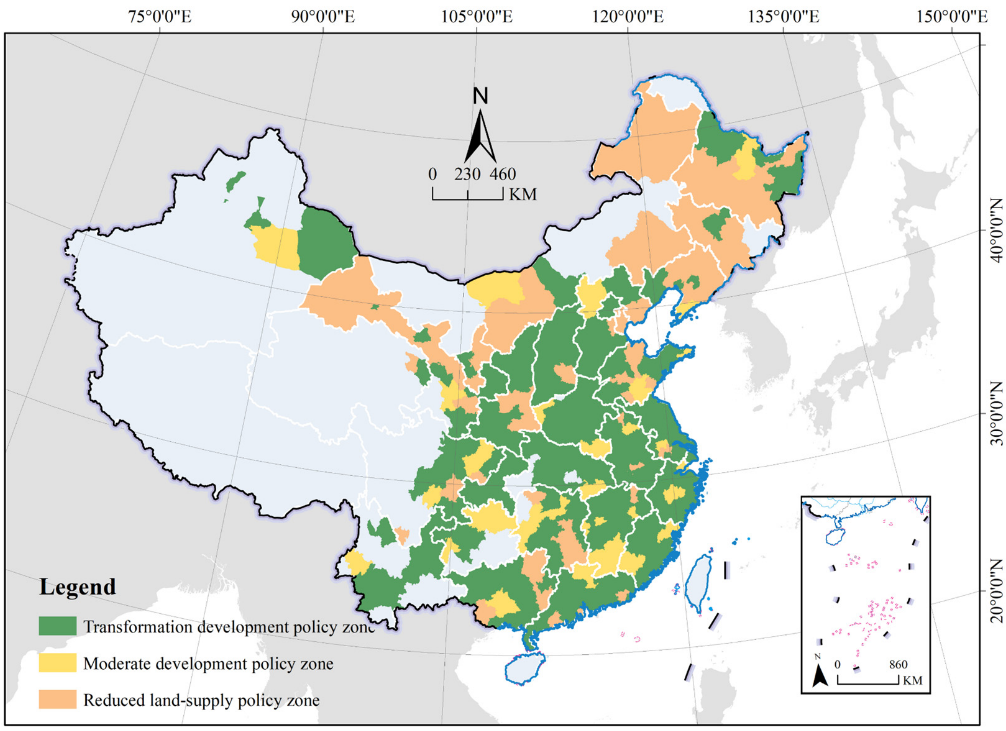


Figure 9. Distribution of policy zones based on INL–SAV and INL–GDP.

Finally, we formulated differentiated control policies for the three policy areas in terms of total control, land supply, usage criteria, and regulatory standards to improve the relevance and effectiveness of policy control and promote the intensive use of industrial land.

5.2. Moderate Development Policy Zone

Moderate development policy zones were scattered throughout the country, mainly around the central cities of the provinces, including Yangzhou, Jiaxing, and Zhangjiakou. Industrial land expansion in these cities has brought considerable economic development, and since these cities are in a critical period of development and are highly dependent on industrial land expansion, a high-quality supply of industrial land should be maintained. First, industrial land should be supplied within the development boundaries of the towns. Careful consideration should be given to industrial land application, approval, and site selection without breaking the red line of the land. Second, an efficient, enterprise-friendly, land-preferential policy should be constructed. Enterprise efficiency assessment standards should be developed to reduce the land use and operating costs of efficient enterprises, and certain financial subsidies should be provided according to the efficiency rankings of enterprises. Third, policies to promote the transformation of inefficient industrial land should be established. The transformation of M2 land to M1 land should be encouraged to introduce advanced technical talents and equipment to improve the efficiency of industrial-intensive production.

5.3. Reduced Land-Supply Policy Zone

Reduced land-supply policy zones covered cities in Heilongjiang, Jilin, Liaoning, inner Mongolia, and Gansu and were mainly concentrated in northeast and northwest China, as well as south China. These cities have invested large amounts of industrial land, but they have encountered a continuous slowdown in economic growth, resulting in great land waste. Therefore, the withdrawal of industrial land should be strictly implemented, and policies should be developed in line with the principle of transforming inefficient land through efficient enterprises and the orderly withdrawal of inefficient land. First, the supply of industrial land should be compressed, and the application threshold for enterprises should be raised. The efficiencies of industrial enterprises applying for land should be assessed, and the scale of land use should be strictly limited for enterprises with high consumption and low output. Second, land-use standards and costs should be raised. Differentiated land application thresholds should be designated according to industrial sectors to increase their tax shares and land-use costs. Third, existing or potentially inefficient industrial land should be strictly withdrawn. Unused industrial land approved should be revoked, and enterprises that need industrial land should give priority to the reconstruction of existing industrial land. Furthermore, efforts should be made to enhance the dynamic monitoring of the decoupling states of cities, and the land–economic decoupling states should be precise to the year to ensure the stable and efficient use of land on a yearly basis, to force the transformation and upgrading of land use and economic development methods, and to prevent further slippage toward negative decoupling.

6. Discussion

6.1. Theoretical Value

This paper found significant spatial heterogeneity and agglomeration characteristics in the relationship between industrial land expansion and economic development in Chinese cities, which agrees with the conclusions of the previous literature. Kuang [69] found large regional differences in industrial land expansion and its economic development, showing a significant spatial pattern, with the fastest in the coastal region and the slowest in the northeast. Yang [70] found that there were great differences in industrial development between the north and south of Anhui. With the shift in policy orientation, there has been an increasingly significant variability between regions, which further suggests that industries differ in their resilience to policy in different regions and stages [67,68]. Jiang [71] each analyzed the efficiency of industrial land in different countries, and both found a significant spatial agglomeration. Xu [72] found that technology-intensive industrial land in the Beijing–Tianjin–Hebei region was increasingly concentrated in Beijing. Zhang [73] found significant spatial heterogeneity and spillover effects in Guangxi, which were significantly associated with the spatial agglomeration effect of urbanization levels.

In the analysis of the decoupling stages of cities, it was found that different decoupled cities also had significant agglomeration and heterogeneity in spatio-temporal distribution, with the first decoupled cities mostly distributed in the southeast coastal area, while the later ones were mainly in the middle and lower reaches of the Yellow River and Yangtze River. Most cities were in weak decoupling states, but there were still about 20% in strong decoupling states. This is largely consistent with the findings of the decoupling analyses of construction land and economic development by Liu [74], Wang [75], Huang [76], and Bai [77]. It should be noted that there were more and more cities in negative decoupling states. In contrast, Wang [78], when studying the decoupling relationship between urban land expansion and economic growth in Shandong from 2001 to 2016, found that more and more cities were strongly decoupled, and fewer cities were negatively decoupled, a conclusion that diverges from the one reached in this paper due to the differences in the study population and the study period. China's economy has seen a series of major shifts since 2013, including supply-side structural reforms. In analyzing the land–economy decoupling relationship from 2015 to 2019, this paper found marked recoupling in the evolution of the decoupling states between the former and latter periods, and the cities with recoupling were mostly concentrated in northeast, northwest, and south China. In the context of slowing economic growth, we should be alert to recoupling and reduce the possibility of decoupling cities into the negative decoupling state. These empirical results are the original and new findings of this paper, which have not been mentioned or foreseen in other papers and provide a complement to the theory of urban industrial land development.

The text proposes differentiated land policies based on the decoupling results, and these policy-zoning strategies conform to the findings of the industrial land policy study. Dong [79] argued that adequate land supply and development momentum helped push the upgrading of urban industries. In this paper, cities in both the transformation development policy zone and the moderate development policy zone generally had good development momentum, and they could promote economic development by means of scientific land management. Zheng [80] and Needham [81] each found that labor-intensive enterprises were more sensitive to land policies than technology-intensive enterprises, and reasonable land management approaches could contribute to enterprise upgrading, similar to the development foothold of the reduced land-supply policy zone in the text.

6.2. Limitation and Future Implications

The methods and conclusions used in this paper are applicable not only to China, but also to India, Turkey, Pakistan, and other countries for the following two reasons. First, these countries are all in a stage of transformation from rapid industrial development to high-quality development with an industrial development similar to that of China. Second, they are developing, populous nations with a great need to establish a closed-loop industrial input–consumption–output system, and industrial land control plays a key role in the construction of such a system.

There are some shortcomings in the study of this paper due to the limitation of data. For example, as for the choice of indices, further optimization is needed. The GDP does not all come from industry, but its sources include agriculture and services. However, due to incomplete data on the industrial total output, we only used the GDP as an alternative. In addition, industrial land and economic development are in a complex relationship, and it was difficult to analyze the influencing factors of the two in-depth with the decoupling model alone, leaving the influencing mechanism of the decoupling relationship to be further studied.

7. Conclusions

The "decoupling" of economic development from land expansion has become a key topic in the exploration of intensive economic models. China is transforming from incremental expansion to stock optimization, which is typical in global industry. Based on Tapio's decoupling model, this paper investigated the decoupling relationship between industrial land expansion and economic development in Chinese cities from 2010–2019 and concluded the following.

In terms of spatial distribution, the changes in urban industrial land showed significant spatial heterogeneity and agglomeration, and cities with high growth of land were decreasing and tended to agglomerate in Sichuan, Chongqing, and the area south of the Yangtze River, while cities with low growth were agglomerating to the northeast and northwest. In terms of evolution characteristics, the development of urban industrial economy was characterized by significant, cluster-like agglomeration, and cities with high SAV and high GDP growth were concentrated in the lower reaches of the Yangtze River, the middle and lower reaches of the Yellow River, and the western economic zone, while cities with low growth stayed concentrated in northeast and northwest China for a long time. In addition, HH cities were mainly concentrated in the Yangtze River Delta and its inland hinterland, Chengdu–Chongqing urban agglomeration, and the eastern coastal areas, while LL and HL cities were mainly in the north of China, especially in the northeast. In terms of the decoupling effect, or the type of decoupling between urban industrial land expansion and economic development, most cities were in a state of weak decoupling, but there was an increasing number of cities in the negative decoupling state. Cities of different types of decoupling showed obvious agglomeration and differentiation in the spatio-temporal distribution, with decoupled cities shifting from the southeastern coastal region to the middle and lower reaches of the Yellow River and Yangtze River, while negatively decoupled cities were mainly concentrated in the northeastern and southern regions of China and were continuously spreading to the peripheries, showing an obvious sign of recoupling. In terms of policies, it was recommended to develop differentiated industrial land-supply and supervision policies based on decoupling evaluations and to apply differentiated land management to cities and industrial sectors of different decoupling types to force the transformation and upgrading of land use and economic development methods and to guard against the recoupling of land–economy relationships.

The conclusions of this paper apply to most developing countries with flourishing industries. The use of decoupling models to analyze the relationship between industrial land change and economic growth is still in the exploratory stage, and we also call on more scholars to join us to find more generalizable conclusions through case studies and empirical research in different countries and regions or to further explore the driving forces behind decoupling development.

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Article

Obstacles to the Development of Integrated Land-Use Planning in Developing Countries: The Case of Paraguay

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Abstract: Land-use planning identifies the best land-use options by considering environmental, economic, and social factors. Different theoretical land-use plan models can be found in the literature; however, few studies focus on its practical application and particular challenges in different contexts, especially in the Global South. We use expert surveys to explore the feasibility and relevance of integrated land-use planning and data acquisition in developing countries using Paraguay as an example. We identify the challenges of developing land-use plans and strategies to navigate these barriers to speed up its implementation. The results show that it might be difficult to develop an integrated land-use plan in the context of developing countries, mainly due to data availability, lack of political will, lack of stakeholder engagement, and insufficient financial and human resources. We also highlight examples of creative ways in which previous land-use planning projects and studies navigated these challenges, including stakeholder consultations, use of simpler models that required less data, prioritization of data collection, and engagement of decision makers throughout the process. We provide crucial information to improve land-use planning processes in Paraguay and across the Global South in areas with similar contexts and challenges that aim to develop in a more sustainable way.

Keywords: land-use planning; Paraguay; sustainable development; obstacles; developing countries

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1. Introduction

Anthropogenic activities transformed about a third of the lands worldwide over the last six decades [1]. Land-use changes can lead to environmental and human well-being impacts, and many of these changes occur without any planning [2–4]. Land-use planning can help identify the best options to allocate terrestrial resources based on environmental, economic and social factors [5] and navigate the trade-offs that may arise [6,7]. Several studies have explored the potential contribution of land-use plans to promote sustainable development [8–12] and prevent unplanned land-use changes that impact ecosystem functioning [13]. This becomes even more relevant in a climate change context, where planning is key to develop adaptation strategies [14]. Different countries adopted land-use planning to work towards their sustainability goals [12,15–17]. However, various land-use plan practices used worldwide do not include all dimensions of decision making (i.e., environmental, social, and economic), which prevents sustainability from being effectively addressed [17–20].

Integrated land-use planning considers all three dimensions, and has the potential to positively impact decision-making processes, reduce land-use conflicts, promote stakeholder dialogues, and identify areas where changes in land-use may have minimal impact on the environment and human well-being [21–23]. Despite the perceived relevance of integrated land-use planning models, scholars and practitioners have identified several challenges to fully develop and implement these plans. However, to our knowledge, none of these studies have used expert surveys to gather this information. Some of the challenges identified in land-use plans include weak political will and lack of institutional support [24,25], as well as lack of tools to support land-use planning processes [26]. Additionally, although land-use planning models incorporate complexity, there have been few practical applications of these models in the context of the Global South [22,24,27]. The challenges of acquiring the necessary data and the complicated nature of the models themselves have inhibited their application [22,23,27]. Many projects and studies that used an integrated model in developing countries were carried out in Asia. For example, one study in Malaysia conducted a community-based participatory land-use planning to support forest conservation [16]. Another study in Iran used a quantitative method to prioritize land-uses considering the ecological and socio-economic characteristics of the region [28]. There are fewer studies using integrated land-use planning models in Africa and South America. One study in Morocco combined stakeholder preferences and multi-criteria analysis to support land-use planning [29]. Another study in Argentina included stakeholders to ensure that the three dimensions of sustainability were considered [30]. The fewer number of studies may be due to data limitations or a lack of systematization of the ongoing land-use planning processes in these regions [22,23,27]. Previous studies defined different land-use planning models and a wide range of data needed to account for each dimension, but to our knowledge, not many focus on the existing challenges and feasibility to develop land-use plans and obtain the required data using a bottom-up approach (e.g., expert surveys) in developing countries. Thus, it is important to assess and understand the use of these models, as well as to identify and address the existing challenges, including data collection, that exist to broaden their development and implementation [17,18,31].

Several international agencies have promoted the development of land-use plans to achieve sustainable growth. Some examples include the use of land-use planning processes to advance the 2030 United Nations' sustainable development goals [7], and the development of village land-use plans by the African Wildlife Fund and World Wildlife Fund (WWF) [32]. In response to this, during the last two decades, many countries also advanced the agenda for implementing land-use planning policies and regulations [16,33–38]. We have focused on Paraguay, a developing country that has made progress in land-use planning in recent years, as it is identified as a key element in achieving its strategic country objectives [15]. Indeed, this is a crucial strategy for a country experiencing economic growth at the expense of its natural resources [39]. Though some guidelines exist in the country, land-use planning is very incipient [40]. This provides an opportunity to build a sound model that integrates all three dimensions to enable sustainable growth, ensuring most stakeholder's objectives and interests are included to reduce land-use conflicts [11,41].

We explored the feasibility and relevance of integrated land-use planning models and data acquisition by implementing a survey with experts from Paraguay to inform current efforts. We identify challenges of developing land-use plans and strategies to navigate these barriers and speed up its implementation. This study will inform future plans and research on the application and viability of implementing land-use planning models in Paraguay, and how they can be applied in other regions of the Global South with similar data limitations and context.

2. Land-Use Planning in Paraguay

Land-use planning is very incipient in Paraguay, and even though part of the framework is in place (Table 1), its operation and enforcement are needed [40]. Paraguay has a National Framework for Development and Land-use Planning which aims to define actions, regulations, and instruments to allocate land uses in the territory [42]. Land-use planning is also included as one of the strategies to achieve the goals of the 2030 Paraguay National Development [15]. Additionally, Paraguay, through a municipal organic letter (Law 3966 of 2010), requires each municipality to have two instruments in place: (1) a sustainable development plan, which ensures harmonious urban and rural development taking into consideration environmental and societal protection and economic growth, and

(2) an urban and territorial land-use plan, which guides land-use and occupation, and is in line with the sustainable development plan. There is also a legal resolution that requires all properties located in the Western region to prepare a plan that guides their land-use changes to ensure sustainable development [43]. Paraguay has made progress in recent years. In 2016, the Secretariat of Technical Planning and Economic and Social Development (STP), the United Nations Development Programme (UNDP) and the Japanese International Cooperation Agency (JICA) developed the Guidelines for the Sustainable Development Plan for municipalities [44]. In 2018, STP, UNDP, and the Secretary of Environment and Sustainable Development created the Guidelines for Land Use Planning [45]. More recently, the government of Paraguay is working towards a national law on land-use planning to define specific criteria for its operation [46]. However, the challenge is to align all the existing frameworks to ensure compliance and correct implementation.

Table 1. Land-use planning framework in Paraguay.

Framework	Scale	Year	Description
National Framework for Development and Land Use Planning	National	2012	Define actions, regulations and instruments to organize the territory, in order to have basic conditions to enable productive economic development, population's quality of life, institutional political development, and environmental sustainability [42].
2030 National Development Plan	National	2014	Define the axes and strategic objectives, policy priorities and action lines for inclusive and sustainable development in Paraguay. It has three action lines: poverty reduction and social development; inclusive economic growth; and Paraguay's better insertion into the world to increase investments. It consists of four cross-cutting strategies: equal opportunities; efficient and transparent public management; land-use planning and development; and environmental sustainability [15].
Law 3966/2010-Municipal Organic Letter	Municipal	2010	Municipalities will establish a municipal planning system that will have two instruments: (1) sustainable development plan for the municipality to promote a balanced urban and rural development with its natural resources and ensuring collective well-being (Art. 225). (2) urban and territorial land-use planning (Art. 12 and 224) to guide land use and occupation in urban and rural areas to reconcile them with the natural environment. It is a technical and management tool to define territorial objectives and strategies in line with the Sustainable Development Plan (Art. 226) [47].
Resolution 224/2001-Land use plan	Property	2001	It is a tool that provides information on the best land-use allocations based on ecological, social, and economic aspects. The main goal is to guide land-use changes to ensure sustainable development [43]

The land-use planning process in Paraguay is defined by the guidelines mentioned above that were developed by STP and UNDP. These guidelines consist of six stages: (1) identification of the general project conditions which include political consensus, mobilization of financial resources, workplan, and technical team formation; (2) generation of spatial data which consist of compilation of existing data and creation of new data; (3) assessment of the territory to understand its dynamics; (4) development of the territorial strategy based on the existing sustainable municipal development plan and stakeholders' consultations; (5) design of the urban and territorial land-use plan; and (6) creation of legal documentation including a zoning plan and municipal ordinances [45]. This process is led by each municipality and is accompanied by STP. It also includes a multi-stakeholder platform to ensure the participation of relevant actors such as local and indigenous communities, farmers, decision-makers, and private companies depending on the main activities of each region. Some of the land-use planning processes in Paraguay are funded by NGOs.

3. Materials and Methods

3.1. Study Site

Paraguay is located in the heart of South America, neighboring Argentina, Bolivia, and Brazil (Figure 1). Its population in 2012 was estimated at 6.4 million in an area of 406,752 km^2 [48]. The Paraguay river divides the country into two regions, the Eastern region which has a humid subtropical/tropical climate, and the Western region which has a drier climate with less rainfall [40]. Paraguay is very rich in biodiversity and comprises six ecoregions which include the Pantanal, Dry Chaco, Medanos (part of Dry Chaco), Humid Chaco, Atlantic Forest, and Cerrado [49,50].

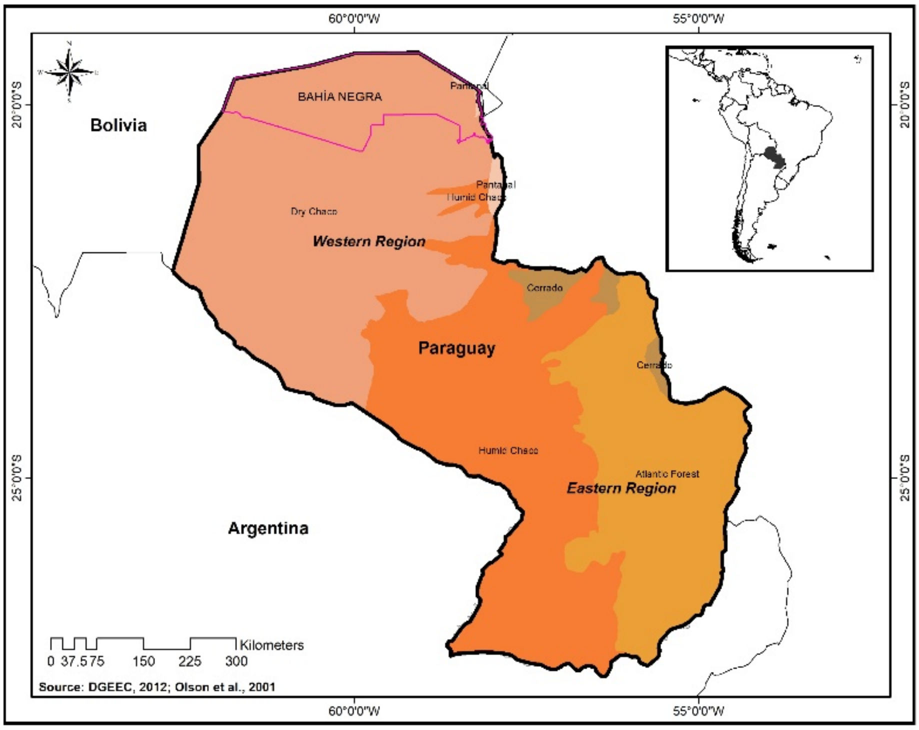


Figure 1. Location of Paraguay in South America, its two regions: Eastern and Western, and its ecoregions.

Paraguay is classified as a developing country [51], and in the last few years, has experienced economic growth above the regional average. However, this growth was at the expense of the country's natural capital [39]. The main economic activities include agriculture and livestock production. Paraguay has one of the highest deforestation rates in the world (among the top 11 countries) [39], and most of this deforestation occurred in the Western region of the country (Chaco) [52]. The deforestation caused changes in ecosystem services, habitat destruction and fragmentation, and biodiversity loss [53,54]. It also affected indigenous communities which are at risk given their livelihood dependence on forests [55].

As such, Paraguay is a good case study for this research as it has many land-use conflicts (e.g., nature conservation and livestock production), high deforestation pressure, limited data on social-environmental systems, and a great diversity of stakeholders. Paraguay still has many gaps of information in several areas to conduct research e.g., [56]. Additionally, environmental problems are the result of poor enforcement of environmental laws and lack of land-use plans [40]. This country has low production costs for agriculture and livestock when compared to other countries from the region. Low production costs are considered an advantage, but at the same time, increase the risk of over-exploiting natural resources [39]. Potential solutions may include strategies to balance conservation and development. In recent years, many policies, including land-use planning, have been developed in the country under the leadership of the Secretariat of Technical Planning and Economic and Social Development (STP) [45].

3.2. Survey Design, Implementation and Analysis

We designed a survey to determine the feasibility of developing integrated land-use planning tools and the viability of acquiring the required data in the context of Paraguay as a developing country (Supplementary Materials). We conducted the survey to explore challenges, including data access and availability, to broaden the development of these plans. We extracted the most required data needs for land-use plans models from previous studies and used this information to create our own data list. We used this list to ask experts about their perspectives on the feasibility to collect these data. For this research, we defined an expert as someone with comprehensive knowledge in a specific area (e.g., environmental, social, and economic) and work experience in the country for more than a year. We then developed and implemented an online survey, using Qualtrics, a cloud-based platform following standard guidelines for designing and implementing web questionnaires [57]. The survey was conducted in Spanish. We refined the survey instrument through a pre-test with 15 survey design experts and other respondents to evaluate comprehension of the questions [57]. We recruited potential participants using a combination of a pre-established professional network as two of the authors previously worked in the country, and a snowball sampling method [58,59]. We contacted 15 experts in the first round and asked each respondent to provide at least three names of experts who could complete the survey. We stopped adding experts when the same people already surveyed were mentioned several times, which means that our sample was exhausted [58]. Seeking representation from different sectors, we targeted experts who work in academia, government institutions, non-governmental organizations and environmental associations, independent consultants, and private companies. A total of 27 experts from Paraguay completed the survey during November–December of 2019. The University of Arizona (UA) Institutional Review Board (IRB) reviewed and approved this study to ensure the protection of human research subjects.

We defined five categories to determine the level of difficulty in collecting data for land-use plans: very easy, moderately easy, neither easy nor difficult, moderately difficult, and very difficult. We included a description for each of the categories to ensure all respondents used the same criteria. We grouped the specific data needs identified in previous studies for the three dimensions and provided definitions and examples for each to improve their understanding (Table 2) [57]. Experts also had the option of writing in other data needs for each dimension. Additionally, participants ranked data from the most to the least important for developing land-use plans in Paraguay following the method proposed by Darvill and Lindo [60].

In the first section of the survey, participants responded to questions to determine how familiar they were with the concept of integrated land-use planning. We also asked about the difficulty in developing this type of land-use planning tool in Paraguay and the primary limitations that exist based on a pre-determined list extracted from existing literature and previous knowledge of the region. The respondents also had an option to add other limitations that they considered important. Then, experts identified their area of expertise choosing environmental, social, and economic based on their relevant experiences. The respondents only completed those sections that reflected their expertise. In the last section, the survey collected information on the demographics and professional backgrounds of the respondents. The results of the survey were analyzed using qualitative analysis for open questions, and quantitative analysis for closed-ended questions [60,61].

Table 2. Definitions provided for each data needs in the survey.

Dimension	Required Data	Definition
Environmental	Ecosystem services	It refers to the quantity of specific ecosystem services delivered. Ecosystem services are the benefits people receive from nature (e.g., recreation, water regulation, carbon sequestration, agricultural production, among others).
	Updated land-use and land cover maps	These maps define different categories to show the physical land type and how people use the land (e.g., vegetation types, distribution of landscapes, agricultural areas).
	Biodiversity	It determines the diversity among living organisms in terrestrial and aquatic ecosystems (e.g., wildlife populations, number of tree species).
	Habitat preferences for some species	The likelihood of a habitat being chosen by some species, if other habitats are offered on an equal basis (e.g., one of the habitat preferences of jaguars are forests).
	Environmental policies	It refers to national, regional, and local policies related to the conservation and sustainable use of natural resources (e.g., Law 422-Forestry which refers to 25% of forest as reserve).
Social	Social impact assessment	This includes identification and analysis of land-use problems and conflicts from key stakeholders' perspectives.
	Social value	It determines the non-economic value of natural ecosystems based on the importance to stakeholders. For example, use of forest for religious purposes.
	Land-use preference	This includes the preference that a certain stakeholder has regarding the possible uses of the land. For example, one stakeholder prefers to conserve the forest and another stakeholder prefers to carry out agricultural activities.
Economic	Ecosystem service values	This includes the monetary value of ecosystem services. Ecosystem services are the benefits people receive from nature such as carbon sequestration, recreation, among others. Some examples include the cost of carbon sequestered per hectare, the cost of clean water provision, cost of food production from agricultural systems.
	Cost of conservation actions	It includes the economic cost of implementing a conservation action in the field. For example, stewardship or land acquisition, forest restoration, forest conservation, biological corridor establishment.
	Opportunity costs	It refers to the costs that we do not receive since we have chosen another alternative. For example, the cost of forgone agricultural production for selecting forest conservation.
	Land price markets	The cost of acquisition of lands (e.g., cost per hectare).
	Marginal value	The marginal value refers to the amount that people are willing to pay to access to an extra unit of the service or the price that people would pay to avoid losing one unit (e.g., scarce ecosystem services will have higher marginal values).
	Economic returns	This includes the money made or lost on an investment over some period. For example, economic return for a crop, forest, and cattle ranching activity.
	Economic policies	It refers to national, regional, and local policies related to the economic development of each country. For example, government policies, subsidies.

4. Results

4.1. Participants' Profile

The survey was conducted in Paraguay. We reached 38 experts at the beginning; however, our final sample consisted of 27 experts (71.05% response rate) on environmental, social, and economic topics. Of these, 93% answered questions on environmental topics, 52% on social, and 30% on economic. Most of the survey respondents self-identified as female (61%), male (39%), and none of them as other genders. Of our respondents, 37% held a master's degree and 70% of them had more than 7 years of working experience in Paraguay. Of our respondents, 48% worked in the non-governmental organization (NGO) sector, 22% in academia and research, 15% in government institutions, 4% in private companies, and 11% were independent consultants.

4.2. Integrated Land-Use Plans in Paraguay: Challenges and Opportunities

We asked experts if Paraguay has integrated land-use planning processes, and the majority responded affirmatively to this question. Most of them (73%) mentioned the land-use planning process conducted in the Municipality of Bahia Negra (Western Region) in 2016 as an example of integrated models. According to the experts, this plan was not yet fully approved as of December 2019. One expert highlighted that this process might need to include some additional information such as maps to assess ancestral territories and high-value conservation areas. When we asked how difficult it might be to develop these integrated plans in Paraguay, the overwhelming consensus among respondents was that developing these plans was difficult; 71% thought that it would be moderately difficult and an additional 21% thought it would be very difficult (Figure 2). However, a strong agreement was expressed by experts regarding the importance of these plans, 93% of the respondents agreed that Paraguay would benefit from having integrated land-use plans.

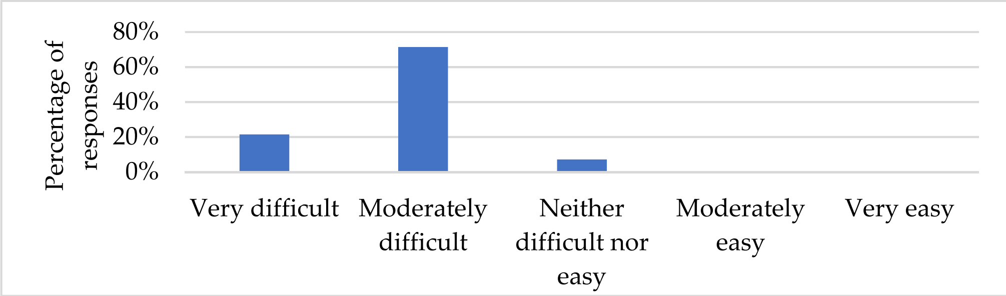
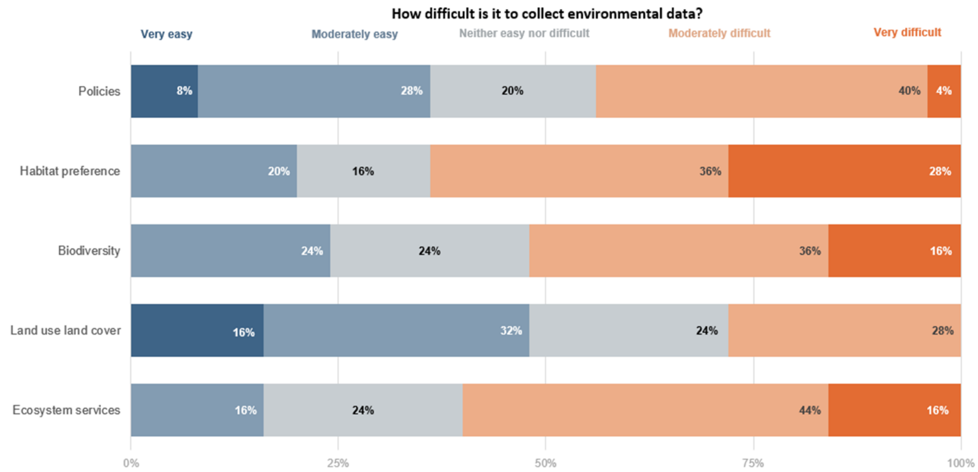


Figure 2. Difficulty to develop integrated land-use plans in Paraguay from the expert's perspective.

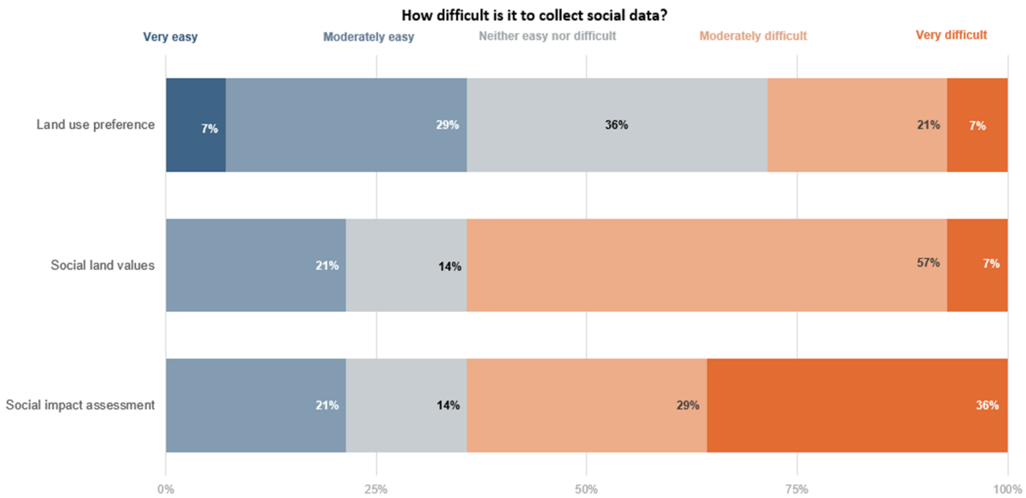
4.2.1. Challenges for Land-Use Planning in Paraguay

Our questionnaire asked respondents to select from four main barriers to developing integrated land-use plans in Paraguay. Lack of data was cited by 70%; 63% cited lack of resources to collect data; over half (53%) cited lack of expertise in collecting data, and approximately 50% of respondents thought that lack of interest in developing integrated land-use plans was a contributing factor. Of the 10 respondents who wrote in additional challenges, 2 identified the difficulty of engaging stakeholders in the process and the capacity to reach consensus among them. The quality of the existing data was also identified as a challenge. More specifically, different institutions produce geographic data for specific regions; however, there was little data consistency and these different data sets did not overlap geographically. Therefore, meta-data to ensure accuracy were limited, making their use for geographical analysis problematic. One person also noted that the cost to generate data was extremely high and financial resources were not available. Other challenges mentioned were the lack of political will, lack of coordination or cooperative work among institutions, and the absence of data/information sharing among institutions as there was a lack of central repository for all the data generated. Other respondents mentioned that several planning initiatives were funded by non-governmental institutions which posed a risk to the sustainability of these processes, in terms of continuation beyond the project. One respondent mentioned that the development of land-use plans depended exclusively on the political will of the authorities and if they did not consider it a priority, it would not be included in the budget. Another respondent mentioned that, in general, land-use planning processes were not participatory and local governments were not included.

Experts identified lack of data as the most important barrier to develop land-use plans in Paraguay. Therefore, we used the survey instrument to identify how difficult it was to collect environmental, social, and economic data in Paraguay to fill these gaps. We had five specific data needs for the environmental dimension, including ecosystem services, land-use/cover, biodiversity, habitat preference for species, and existing environmental policies. Based on the results, habitat preference were the most difficult data to collect; 28% of the respondents indicated this response, and the easiest was land-use/cover with 16% of respondents identifying this as easy (Figure 3a). Some respondents expanded the list provided in the survey and identified more data needed, including protected area boundaries, agroecological zones, biological corridors, and studies on fauna and flora.



(**a**)



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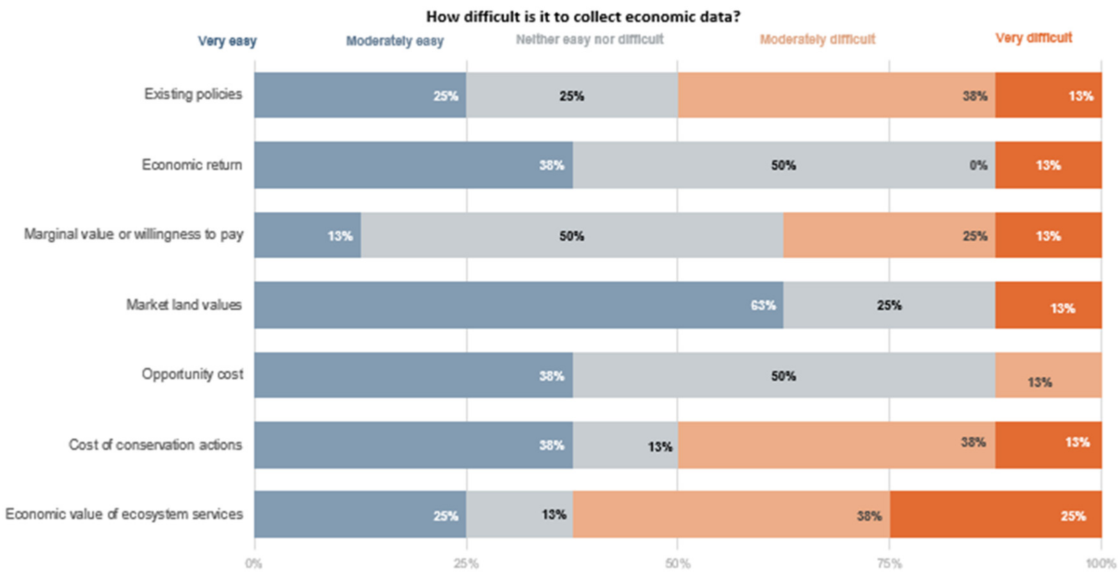
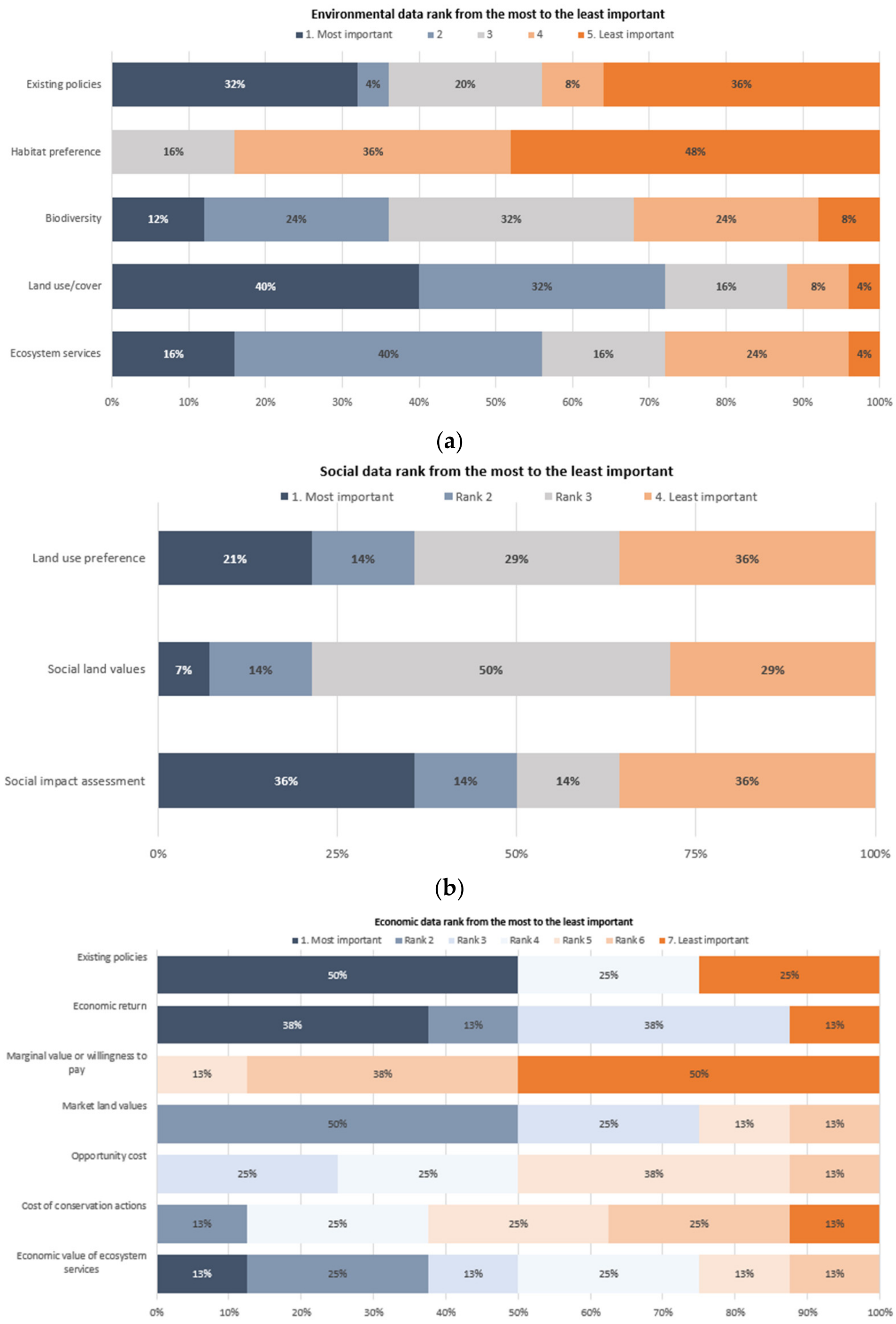


(**c**)

Figure 3. Difficulty to collect data in Paraguay. (**a**) Environmental data (total of 25 responses). (**b**) Social data (total of 14 responses). (**c**) Economic data (total of 8 responses).

We asked the participants to determine how important it was to obtain this data in case prioritization was needed. Participants ranked each data from most to least important. Experts determined that land-use/cover was the most important environmental data in a land-use planning model with 40% (Figure 4a). Habitat preference for species was never listed as number 1 (most important) or 2 by the respondents; however, it was listed as number 3 (16%), number 4 (36%), and number 5 (48%).



(c)

Figure 4. The most to least important data needs for land-use planning identified by experts. (**a**) Environmental (total of 25 responses). (**b**) Social (total of 14 responses). (**c**) Economic (total of 8 responses).

The social dimension included the following three criteria: social impact assessments, social land values, and stakeholder's land-use preference. Experts identified that the most difficult social data to collect in Paraguay was the social impact assessment with 36% of the responses. The respondents also mentioned that social land values are moderately difficult to get with 57% of the responses. However, they indicated that land-use preference was neither easy nor difficult to collect (Figure 3b). When asked to add additional data needs to the list, some experts emphasized the difficulty of having or accessing social data in the country based on the list provided in the survey. One respondent also stated that there are few publications in the country, so it can be assumed that data systemization is minimal. Another respondent also mentioned that these data are moderately expensive to collect. Experts ranked social impact assessment as the most important data needed to include in an integrated land-use planning process with 36% of the responses. However, the social impact assessment was also identified as the least important with 36%. Another least important factor listed was land-use preference with 36% (Figure 4b).

For the economic dimension, we asked experts about the difficulty and importance of the economic value of ecosystem services, cost of conservation actions, opportunity costs, market land values, marginal value, or willingness to pay to access an additional unit of a service, economic return, and existing economic policies. The results showed that the economic value of ecosystem services was very difficult to estimate with 29% of the responses. Moreover, responses indicated that costs of conservation actions and existing economic policies were moderately difficult to collect with 25% for both. None of the data were identified as very easy to collect and market land values were defined as moderately easy with 63% (Figure 3c). One respondent wanted to emphasize that academia has made some progress towards data on the economic valuation of ecosystem services; but it might be necessary to work on the legal framework and include the concept of natural capital in planning activities.

Experts ranked existing economic policies as the most important data needed to develop an integrated land-use plan (50%). Existing policies include those related to the economic development of a specific region. Moreover, they identified market land value as the second most important with 50% (Figure 4c). Only existing economic policies, economic return, and economic value of ecosystem services were listed as most important. Opportunity costs, market land values, and economic value of ecosystem services were never listed as least important (selected as number 7).

4.2.2. Opportunities for Integrated Land-Use Planning in Paraguay

There are challenges for Paraguay in developing land-use plans, but there are also many potential opportunities with using an integrated model. As previously mentioned, most of the survey respondents (93%) agreed that Paraguay would benefit from having an integrated land-use planning model. The survey respondents mentioned many opportunities or advantages including the proposition that land-use planning could facilitate more organized urban and rural development in the country by balancing the available natural resources and their sustainable use. Moreover, a theme among responses was that an integrated model can support the effective allocation of forest reserves and biological corridors and prioritize conservation activities and ecosystem services. One respondent also mentioned that the land-use plan would allow a more balanced development that would safeguard resources for future generations, especially considering the need for new scenarios resulting from climate change. Additionally, this respondent mentioned that with proper planning there would be no issues of water availability in certain parts of the country; otherwise, considerable conflicts could arise between the different sectors (e.g., agriculture, population in general). This respondent also added that it is known that some cities will grow in Paraguay, and therefore it would be better to engage in planning to prepare for this growth.

One expert sees land-use planning as a legal tool to manage the territory, promote decentralization of public functions if local governments are included, and improve law enforcement. Additionally, this respondent mentioned that land-use plans can guide investments, as it might provide information on the best location for different land-use options to reduce environmental and social risks. Another opportunity is that the model could help to standardize the land-use planning process in all the municipalities of Paraguay. Moreover, this model could ensure inter-institutional data sharing to lay the foundations for the development of a national database. The respondents also highlighted some important advances in the country regarding more participatory land-use planning processes (i.e., the Municipality of Bahia Negra), and the publication of guidelines to develop land-use planning e.g., [45].

5. Discussion

Many governments worldwide have committed to develop in a more sustainable way; however, global tendencies are still far from achieving sustainability. Land-use planning arose as a strategy to achieve sustainability, but many challenges still remain to develop and implement these plans across the Global South. This paper explored the feasibility of developing integrated land-use planning by engaging with experts, planners and implementers thorough a survey built on criteria in the literature and implemented in Paraguay. Most experts mentioned that Paraguay will benefit from having integrated land-use plans to promote sustainable development, among other aspects. This finding aligns with previous studies in China, Spain, and Tanzania among others, stating that land-use planning might play a key role in achieving sustainable development goals [8–12,15]. Yet to achieve this, land-use plans need to integrate the environmental, social and economic dimensions of sustainability during the process [12]. Several studies have highlighted the importance of integrating all three dimensions into one model [27,62–64]. However, political will and institutional challenges also play relevant roles and can compromise the success of these policies, especially in developing countries [24]. Experts expressed some of the advantages of having land-use plans which correspond to studies in West Africa and Paraguay that discussed the identification of synergies and trade-offs among the different dimensions in complex landscapes to find a balance between conservation and development [23,56]. An integrated approach might determine the right allocation for different land-use options and anticipate and minimize potential conflicts [27,65].

5.1. Challenges to Develop Integrated Land-Use Plans

According to our results, land-use planning processes face challenges that affect their broader application in Paraguay, as in many other developed and developing countries e.g., [18,31,66]. These challenges need to be identified and addressed to move forward with implementing land-use plans. Our results highlighted some of the existing obstacles or challenges to fully develop and implement land-use plans in Paraguay, and these might be used in other developing countries with a similar context, such as Argentina and Bolivia, which share the Gran Chaco region with Paraguay [30,67,68]. Several challenges were identified by our experts, and we focused our discussion on the lack of data, political will, stakeholder engagement, and insufficient financial and human resources.

5.1.1. Lack of Data

Most of our respondents mentioned that lack of data was one of the main challenges in Paraguay. Choosing one model or another is influenced by the data required for them [31]. Given the complexity of land-use planning, most of the data needed and the models for integrated plans may be very difficult to obtain in developing countries of the Global South [18,41]. These challenges are also faced by Global North countries; however, Global South countries have fewer financial, technological, and human resources to overcome these challenges e.g., [69]. It has been shown that simpler models can be used in planning. For example, Von Bertrab et al. [70] described a six-step approach to developing plans that consider aspects related to both nature and development, including tradeoffs, opportunities, and potential risks that may exist between the two. This approach has been successfully implemented in Mexico, Jordan, Brazil, Cote D'Ivoire, and Colombia.

The participants also indicated that data validity is a problem, which corresponds with other studies that state that lack of relevant and valid data is an issue for land-use planning processes and for making informed decisions [71]. For example, Sallustio et al. [72] mentioned that Europe still lacks national harmonized datasets to classify marginal lands. We also find that there is lack of coordination or of joint work among institutions. Some authors also note that this lack of cooperation among local and regional data, efforts, and actions can cause delays in the processes [33,38,73]. The lack of data is an important issue for Paraguay and many other developing countries. Therefore, data collection and prioritization strategies would be recommended to fill the gaps. It is also important to identify existing studies that can support land-use planning processes in Paraguay [74], especially when the required data to develop integrated land-use planning is not easy to obtain. This is consistent with the results of a study by Naidoo and Rickets [56], who conducted a spatial cost-benefit analysis for conservation planning and found that the availability of relevant data was limited for their study region in Paraguay. Another study in Paraguay mapped multiple benefits of REDD+ to support land-use planning and faced challenges due to the lack of available information on the forest conditions and location of degraded forests in the country [74]. A study in Africa stated that data limitation was an issue when using some land-use planning models and that some data had to be dropped because of this [11]. To address this challenge, we also need to better understand why data are so difficult to collect. Here, we discuss some of the most difficult data to collect and provide some potential solutions.

More specifically, our survey results show that most respondents identified land-use/cover maps as important for land-use planning, and as the easiest to collect. Land-use/cover maps play an important role in understanding land dynamics for implementing a multifunctional landscape planning approach [75,76]. Satellite remote-sensing data can provide consistent land-use/cover maps with investment in data acquisition, processing, and analysis [52]. Regarding habitat preference for species, a high percentage of responses consider these data very difficult to collect due to the complexity of these data, the need to have them for each species of interest, and the pattern of land-use, species-habitat associations, and species range [77]. These data might not be available in some regions; our respondents also identified these data as the least important.

Respondents stated that it is very difficult to collect social impact assessment data, which require the identification and analysis of land-use conflicts among stakeholders that are usually carried out using stakeholder consultation methods [37,78]. It might be difficult to collect these data because conflicts are very sensitive and land conflicts played a significant role in the history of Paraguayan economic development, social stratification, and international relations [79]. We assume that this may limit the collection of these data in the country. In general, most conflicts involve disagreements over values and objectives, as well as power differences, and issues about property rights [36]. However, as social impact assessment was also referred to as the most important issue (36%), specific methods need to be developed to generate this information despite the challenges, or a similar indicator might still need to be identified to account for this social dimension. For example, one study from Tanzania assessed land-use conflicts and used a participatory analysis to identify land users and social groups [18]. Social impact assessment was also identified as the least important data (36%), indicating that the experts' opinions were polarized, and this might be the result of different approaches or methods used to conduct this assessment.

Regarding the economic dimension, the most difficult data to collect are the values of ecosystem services. The ecosystem services approach in Latin America is still difficult to implement into governance. Involving multiple and diverse stakeholders with power differences and contrasting interests makes incorporation of this approach particularly challenging [80]. The concept still creates confusion and there is a lack of knowledge on how to connect it with planning and policy [81,82]. In addition, the ecosystem services approach requires testing and validation, which is not yet well described [81]. In some cases, ecosystem services can be undervalued, as discussed in a study case conducted in Hungary [83]. Another study conducted in the United States mentioned that there is much uncertainty about ecosystem service values that make it difficult for integration [84]. However, some scholars have focused their efforts on trying to make the concept more usable for decision making by offering frameworks to connect ecosystem services and land-use planning policies [82,85], as well as lessons from previous experiences including more iterative science-policy process and empowerment of experts with technical tools that can help them in gathering and analyzing data [86]. Experts identified existing economic policies as the most important information to take into account. Pourebrahim et al. [64] used data from existing policies (e.g., the National Ecotourism Plan for Malaysia) to set the objectives for the development of the region, which is essential before initiating any land-use planning processes. Attention to these policies can determine which land uses might need to be prioritized, taking into consideration the sustainable development of the region.

Lack of data might not necessarily be a limitation for decision makers or planners to develop land-use plans and make decisions [71]. Some studies have navigated the lack of data by integrating local stakeholders into participatory land-use planning processes which can have a dual benefit, such as gathering the required information and promoting more transparent decision making [16,18]. This engagement can empower local stakeholders/communities to make their voices heard and facilitate the process of building trust and sharing knowledge which will benefit the implementation of land-use planning [87]. Another study in Paraguay used different data/indicators to fill in gaps of information [74]. This paper presents several examples that could be adapted to different contexts to overcome some of the existing challenges.

5.1.2. Lack of Political Will

Our respondents stated that political will was a key challenge to moving forward with the development and implementation of land-use plans. The lack of political support was a major threat to planning processes [23], and this was beyond the scope of scientists [22,23]. The will to develop land-use planning would need to come from the government and several issues needed to be addressed [88]. Some studies have shown how land-use planning benefits when government authorities are engaged by providing access to data and/or participating as key stakeholders in workshops or interviews [16,29,89]. Conflicting interests and policies among institutions are issues that can slow down the development of land-use plans [31]. For example, the land-use planning process might be led by certain political interests that might differ on what is appropriate for the land and stakeholders [28,29,90,91]. A study conducted in China mentioned that the government wanted to invest more funds in one region to develop the economy there over other regions [92]. In a study in Peru, planners were not granted access to data to develop ecological and economic zoning, as the government had previously made the decision to promote mining activities in the region. This demonstrates how contrasting political positions can influence future land and water use [34]. Additionally, some governments still lack or can improve the required regulations or legal frameworks to develop and implement land-use planning processes [4,33,38]. These regulations or models might exist, but they are not very accessible to decision makers which can make their application difficult [93]. For example, land-use planning models are often developed in an academic setting, and to implement them in the real world with public agencies can be challenging [31]. According to Sili and Avila [40], Paraguay needs to redefine its own policies and practices for land-use planning to ensure improvement of planning models, capacity development at the level of technical and political institutions, and the effective implementation of legal frameworks.

5.1.3. Stakeholders' Engagement and Insufficient Financial and Human Resources

Some respondents also referred to other challenges, including stakeholder engagement and financial and human resources availability. When land-use plans do not use participatory approaches and local governments are not included, there is a risk of developing top-down plans. This situation might lead to land-use plans that are developed by practitioners who do not fully understand the context of the region. Even if the land-use plan meets all the requirements and has the best data and analysis, if the outcome is not practical for local stakeholders, the plan will not be implemented in the field [24]. The involvement of local people is crucial since they know the dynamics of the region [94]. This is even more important in data-scarce regions, where local stakeholders could be part of participatory data and knowledge collection that can help fill existing gaps and enable more relevant decision-making [95]. However, engaging stakeholders in these processes can be challenging in Paraguay and other countries, as many of our respondents mentioned. Therefore, alternative ways to promote participation might be needed, such as assisted workshops instead of self-administered surveys e.g., [23,31]. A study conducted in Spain stated that including public participation in planning is difficult so they designed a strategy to ensure participation in every stage of the planning process [20]. The conservation strategy of the Lao People's Democratic Republic combines land-use planning with information on the needs of local communities living around or within protected areas to improve their livelihoods. This has increased communities' desire to participate in the process, as one of the main outcomes was that their land tenure would be officially recognized [96]. Additionally, land-use planning processes may benefit from promoting participation of indigenous people. In Paraguay, they account for 130,000 inhabitants (approx. 2% of the total population) [97]. Indigenous lands were not listed by the respondents as required data for an integrated land-use planning, but we wanted nevertheless to highlight the importance of considering this information as part of the process. A study carried out in the Chaco region of Argentina presents an example of how to include areas claimed by indigenous communities as one layer of information in land-use planning processes. This study categorized indigenous areas with high conservation values; however, they also emphasized the challenges in operationalizing the maps produced, as this requires political will. They mentioned that the government only accepted to identify those areas with medium conservation value, despite the communities wanting to categorize them with a higher value. The indigenous communities requested to take care of their own lands to ensure the integrity of nature and culture in their territories; however, according to the study, the re-categorization of those lands was not granted [71]. Another example was the land-use plan of the Bahia Negra municipality in Paraguay, where consultations were done with communities to identify indigenous lands. During the process, these communities identified some ancestral lands that they are claiming and as a result of the process, these lands are now included in the draft of the map.

We also found that lack of resources to generate data is a critical barrier. Developing countries often have limited financial resources and technical capacity to develop and implement land-use planning processes at the local/district level. For example in Tanzania the 1999 Land-use Planning Act has been implemented in only 13% of the villages as of 2019, largely due to dependence on funding from international organizations and some other land issues that exist in the village including illegal land transactions and tenure insecurity [18]. In Ghana, national and international NGOs (e.g., Korea International Cooperation Agency, KOICA) as well as the business community (e.g., Tullow Oil) conduct land-use planning processes and influence land-use priorities [33]. However, there are some strategies to navigate these challenges. A previous study conducted in Paraguay identified some potential solutions to secure funds for these processes, some of them included the use of the countries' royalties and/or support from cooperative agencies and public-private alliances [40]. Additionally, local experts can be trained to lead data collection and analysis [86].

5.2. Opportunities for Integrated Land-Use Planning in Paraguay

In addition to the identified challenges, there are also many opportunities with using an integrated model. This model proposes a bottom-up strategy with stakeholders playing an important and active role in decision-making processes, which can result in fewer social conflicts over land-use [25]. Fewer conflicts can lead to effective plan implementation in the long-term [7]. Our respondents also highlighted the difficulty to reach consensus; and some previous studies used tools to manage power differences among stakeholders such as empowerment and participatory exercises [36,98]. It may be that those stakeholder groups with more power can promote decisions that are only favorable to their interests [99]. Experts see land-use planning as a legal instrument to promote decentralization of public functions and enforcement; however, this would require a shift in political strategies and agenda to empower local governments [100]. This means securing financial resources and strengthening capacities of local governments [40]. Austin [94] stated that the rationale behind decentralization is that local stakeholders are the ones with knowledge about their needs, challenges and potential solutions, so they need to be actively involved in these conversations.

Our experts also referred to land-use planning as a key tool to address water availability issues in Paraguay. It is well known that land-cover changes affect ecosystem functioning and hydrological cycles [101–104]. As mentioned earlier, Paraguay experiences high deforestation rates, and this is a challenge as forests are essential for the hydrological cycle and water supply, and also to regulate atmospheric moisture fluxes and precipitation patterns over terrestrial areas [102]. Land-use planning can integrate water ecosystem services to ensure provision in the long term [105]. This integrative vision in planning allows identifying the effects and consequences of the hydrological cycle in relation to the ecosystems of the region [102]. A case study conducted in Germany explored the role of land-use planning to address water issues. They found that there are many benefits for water quality and biodiversity when water is included in development plans. However, they also acknowledge the challenges in doing so, and they recommend raising awareness among stakeholders and decision makers about the multiple benefits of including water aspects [106]. Another study conducted in the Paraguayan Chaco highlighted the benefits of conserving forest belts around lagoons to reduce vulnerability to salinization, keeping the salty water table at a safe distance from the surface [107]. This recommendation is accepted as a land-use planning component for this region [107], ensuring long-term provision of water ecosystem services in this semi-arid region. Moreover, Carter et al. [106] presented a case study to identify water-forest protective belts in Latvia. With this study, they proved that the inclusion of water issues in planning can reduce negative impacts on water pollution, reduce erosion, limit development to reduce flooding events, and protect local landscapes. Paraguay can benefit from these examples, as land-use planning is at its beginning. The country already has in place legislation that connects to land-use planning: (1) the Decree Number 9824 of the Law number 4241 of 2010 of re-establishment of forest belts of water courses, and (2) the Law number 3239 of 2007 of water management regulation. Private landowners and companies need to comply with these two laws that are part of the land-use plans that are required at the property level (Table 1). This legislation is to be included as part of the land-use planning process in the country. This might be built on existing legislation or policies to speed up the development and implementation of plans.

The use of land-use planning as a legal tool also needs some discussion. As mentioned before, Paraguay requires each municipality to have an urban and territorial land-use plan, which is supported by the municipal organic letter (Law 3966 of 2010). However, there are still many challenges to fully enforce its compliance due to the lack of political will and insufficient financial and human resources. Currently, the government has made progress by creating a national law project on land-use planning to define the principles, criteria, and rules to ensure sustainable land-use planning. This new legislation will define the different land zones suitable for agriculture and livestock, forestry, mining, and industrial activities. Additionally, it will determine which areas should be conserved and protected, it will delimit indigenous lands, and areas suitable for urban development [46]. To date, land-use planning cannot be used as a legal tool, but that does not mean that it cannot be used in the near future.

6. Conclusions

Using Paraguay as an example, this study explores the feasibility of developing integrated land-use plans in developing countries where there are challenges to their adoption including data availability and collection, financial and human resources, and political will. We assessed the challenges and opportunities by conducting a survey of experts from Paraguay. We highlighted the existing alternatives to navigate these challenges using examples from other countries. Developing and developed countries can face similar challenges in terms of data availability and quality, especially for ecosystem services and marginal land values. Developing countries are still at a disadvantage because the priorities of each country are defined according to different contexts, which in most cases includes the situation of poverty that is experienced in the South. Thus, differences also occur in terms of financial, technological, and human resources. If we acknowledge these challenges, we can develop solutions and improve the land-use planning process. The integration of the three dimensions of sustainability might help reduce land-use conflicts and ensure that all interests are taken into consideration, which is crucial for complex landscapes. If integrated plans are to be used in diverse contexts, it will be necessary to develop this integrated vision to apply in different contexts, even in places where not much data are available. Furthermore, it might be required to ensure that land-use plans are not only developed on "paper" but implemented in the field so they can meet their goals.

Our study has some practical implications. Development and implementation of land-use plans in a developing country context may require the cooperation of public entities, regional governments, and NGOs to work in concert. Our study, and the land-use planning literature generally, suggests several challenges that require consideration when applying land-use plans in Paraguay and other developing country contexts. For example, the lack of data suggests that simpler and more participatory models with bottom-up approaches that increase stakeholders' engagement and facilitate the consensus over land-uses may serve to increase the feasibility of implementing land-use plans in Paraguay and similar countries. The six-step approach proposed by Von Bertrab et al. [70] might be an alternative for developing a simple land-use planning model for a country such as Paraguay. Simpler models might still fulfill their role without sacrificing quality and validity. Additionally, it may be beneficial to centralize efforts to gather and store data and information from different institutions. The availability of a coordinated or centralized location for data may facilitate prioritizing data collection in key areas that would help to broaden the application of existing land-use planning models. Lastly, institutional support and political will are important elements for the successful implementation of land-use plans. Buy-in from decision makers helps address most of the land-use planning challenges, especially that of securing financial resources for their development. As the land-use planning framework happens at national, governmental, municipal, and property levels, aligning these tools may help to promote the same goal. These are more effective when land-use plans are being rolled out in the country. Acknowledging challenges; developing strategies to navigate these challenges; and creating a sound legal framework for land-use plans may be helpful. As we described earlier, having the enabling conditions in place might be challenging for certain regions; however, the existence of policy instruments may help to implement plans in the field successfully.

This study might serve as a stepping-stone towards a broader application of integrated land-use plans in Paraguay and other countries with similar challenges. In addition, further research might assess the effectiveness of the land-use plans to achieve sustainability and respecting the environmental, social, and economic dimensions of land-use planning.

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Article

Exploring the Effects of Transportation Supply on Mixed Land-Use at the Parcel Level

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Abstract: The interactive relationship between transportation and land use has become more difficult to understand and predict, due to the economic boom and corresponding fast-paced proliferation of private transportation and land-development activities. A lack of coordination between transportation and land-use planning has created an imbalanced provision of transportation infrastructure and land-use patterns; this is indicated by places where a high-density land-development pattern is supported by a low-capacity transport system or vice versa. With this, literature suggests that Mixed Land-Use (MLU) developments have the potential to provide relevant solutions for urban sustainability, smart growth, inclusive public transit use, and efficient land-use. Therefore, this study employed deep neural network models—Long Short-Term Memory (LSTM), and Multilayer Perceptron (MLP)—for forecasting the effect of transportation supply on the MLU pattern at the parcel level in the Jiang'an District, Wuhan, China. The findings revealed a strong relationship between the supply of public transportation and MLU. Moreover, the study results indicated that MLU is widely available in areas with high accessibility, high density, and proximity to the city center. The forecasting results from the MLP and LSTM models showed an average error of 5.55–7.36% and 3.62–4.28% for mixed use, respectively, while most of their 90th percentile errors were less than 13.73% and 10.46% for mixed use, respectively. The proposed models and the findings from this study should be useful for stakeholders and policy makers for more precise forecasting of MLU at the urban level.

Keywords: mixed land-use; accessibility; transit-oriented development; machine learning; mixed land-use index; land parcel

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1. Introduction

Mixed land-use (MLU) is a modern planning paradigm that enables compatible land used for various socioeconomic activities to be located in close proximity to each other, thereby reducing the travel distance/time between them. MLU refers to a range of functional land-uses, including residential, commercial, industrial, institutional, and transportation-related. It has been promoted as a significant component of modern urban development strategies, such as smart growth, Transit-Oriented Development (TOD), walkability, and compact development [1–4]. MLU is expected to provide numerous social benefits such as urban vitality, social cohesiveness, job generation, and efficient use of public utilities, and reduce travel distance, energy consumption, and CO_2 emissions [5]. MLU is essential for the sustainable development of large and medium-sized cities. Cities in Europe are often featured with mixed land-use areas that are efficiently connected via public transportation. In addition, it is evident from the literature that households and apartment dwellers are more willing to pay for a house in a mixed neighborhood with business services and entertainment than for a house in a segregated-land-use area [6]. Meanwhile, fast economic development, urbanization, and motorization have resulted in various negative impacts, such as traffic congestion, accidents, and air pollution [7,8]. On the other hand, urban sprawl with low land-use density mostly relies on private cars for travel, leading to traffic congestion and high travel costs [9]. Similarly, large and medium-sized cities are vigorously promoting the development of subway and ground bus networks [10,11]. Thus, land-use and transportation planners should have a thorough understanding of the dynamic connections between urban form, land-use patterns, and transportation supply. Experiences from many cities around the globe indicate that they must integrate land-use and transportation planning because the alteration of one of the two affects the other, and cities or areas with an uncoordinated land use and transportation supply are much less sustainable. Planners are unable to perform a strategic intervention to attain the desired urban shape unless they have a thorough understanding of the dynamic linkages between the two systems [12]. There is a strong association between the urban form, accessibility, and other variables such as activity distribution, employment, and land-use patterns [13]. A previous study by Jayasinghe et al. [14] shows that high-accessibility areas tend to have a high mixed-land-use density, whereas low accessibility areas have low mixed-land-use density.

TOD is a compact, mixed-use development close to transit amenities that provides a better environment for walking and cycling. It consists of office space, new residential development, and other service facilities that are within a half-mile of public transit and are easily accessible via walking or bicycle. TOD usually promotes sustainable communities by providing an inexpensive, convenient, and physically active style of living. TOD focuses on developing integrated communities with commercial clusters and recreation centers to prevent urban sprawl. The key advantages of TOD include an increase in land values, increased higher-density development, the promotion of active transportation, the improvement of business visibility, and the introduction of new prime retail areas to attract customers to businesses [15]. Transportation primarily facilitates accessibility and mobility. Accessibility refers to people's ability to access products, services, and activities, which is the primary objective of most transport activities. In addition, accessibility reflects the influence of land-use distribution and transportation system characteristics on user access. Therefore, land use and transportation are related because they allow people to participate in activities occurring in different locations [16,17]. Moreover, numerous studies have analyzed the relationship between mixed land-use and various kinds of accessibility, including network accessibility [18–20] and job accessibility [21,22]. The findings of these studies revealed that accessibility and mixed land-use have a strong relationship.

In general, land-use data are usually available at aggregate and disaggregate levels. However, the most precise measurement of mixed land-use is at the disaggregate, parcel level [23]. Likewise, traditional land-use models, such as the Lowry and MEPLAN model, forecast land-use patterns based on aggregate-level zoning policies, vacant land, and accessibility at a spatial scale of land-use zones (LUZs) or traffic analysis zones (TAZs). The land supply-and-demand markets are critical in integrated land-use transport models, but only a single type of land-use development pattern is considered, and mixed land-use has rarely been considered within those models [24]. On the contrary, disaggregate, parcel-based land-use models provide a vivid representation of land-use dynamics with a much more accurate representation of land development and much higher utility in policy analysis [25]. Presently, cities in North America have adopted mixed land-use as a primary policy, and the majority of European countries are gradually moving toward mixed land-use, motivated by the concept of a "compact city". However, existing land-use and transportation planning systems within most developing countries have not been adopted at a national level [26]. In addition, a plethora of studies have examined the effects of land use on travel patterns; most of them largely focused on their impact on traveling distance and time, while neglecting the impact of transportation supply on mixed land-use. Recent trends in transportation and urban planning are unsustainable, and it is essential to adapt transportation and MLU systems to accommodate current and future needs [27]. However, no research has been found on the effect of transportation supply on MLU at the parcel level. Therefore, this study fills the above gaps by analyzing the interactive relationship between transportation supply and the development of mixed land-use patterns using a state-of-the-art technique, i.e., deep neural networks, in an effort to have an improved understanding of the effects of transportation supply on mixed land-use.

The purpose of this study is to investigate the effects of transportation supply on MLU change at the parcel level, with a case study in the Jiang'an District, Wuhan, China, from the year 2012 to 2015. Deep neural network models such as Long Short-Term Memory (LSTM) and Multilayer Perceptron (MLP) are employed for forecasting mixed land-use patterns. The input variables such as MLU, accessibility, and space-price by space-type were used for training and testing LSTM and MLP models.

The rest of the paper is organized as follows: Section 2 presents the literature review related to land use and transportation supply; Section 3 provides the study data and methodology of this study; Section 4 presents the results and discussions; and finally, Section 5 summarizes the main findings and limitations of this study with recommendations.

2. Literature Review

2.1. History of Mixed Land-Use

The emergence of the industrial revolution and its adverse effects, due to polluting industries in the residential area, prompted the conceptualization of segregated land-use in the 19th century. Following the industrial revolution, developed countries were the first to introduce segregated land-use zoning to keep residential and industrial areas away from each other [10]. For the first time in the 1960s, the concept of segregated zoning came under severe criticism. Jane Jacobs was a leading opponent of single-use blocks [28]. Throughout that decade, it had been argued that any sort of urban zoning or planning, whether segregated or mixed-use, should be evaluated in terms of its social, economic, physiological, and aesthetic effects on its users [10]. Nevertheless, mixed land-uses were deemed a beneficial component of this decade's urban growth [28]. In the 1980s, the benefits of mixed land-use for living, working, and shopping became increasingly obvious, and urban planners started to advocate for mixed land-uses more frequently [28].

With the beginning of the 21st century, mixed-use zoning appeared as a more beneficial planning idea than segregated land-use, prompting a paradigm shift toward the abolition of single-use zoning. The researchers observed a clear adoption of MLU in modern city planning over the past two decades [10]. Mixed land-use concepts come in a variety of definitions. In general, the term "mix" refers to "a synthesis of multiple and distinct elements," a setting in which land-uses (the elements) form spatial combinations through the allocation of different types of uses to contiguous land plots [29]. MLU encompasses the functions and facilities contained and supplied by buildings. MLU provides development patterns that can enhance the vitality of cities, as shown in the literature [30,31]. Based on this modern urbanism, planners started emphasizing the importance of mixed land-uses with a high density in the urban planning process. One way to materialize this goal is with the help of TOD, which is one of the best examples showcasing the interactive relationship between land use and transportation systems; TOD effectively integrates land use, public transportation, and urban design to maximize land-use efficiency. TOD can assist cities in reducing the use of private cars for travelling, managing travel demand, promoting the use of public transportation, and enhancing the value of the surrounding land. Globally, urban planning and management practitioners and policy-makers are focusing their efforts on developing desirable mixed land-uses around a transit station rather than on individual parcels, i.e., "horizontal" neighborhood-scale mixes rather than "vertical" within-building mixes [32,33]. A strategy for promoting healthy MLU and travel modes has been proposed by Seong et al. [34]; they studied the impact of MLU on the travel-mode choice of unemployed people and homemakers in Seoul, South Korea, and found that mixed land-uses improve walking and the viability of the city. Due to the development of mixed land-uses, more residents choose to walk rather than drive. Additionally, residents opt to walk rather than drive in areas with a higher density of business firms.

2.2. Previous Research on Mixed Land-Use

Land-use patterns influence accessibility, which refers to people's general ability to access desired products, services, and activities [35]. In general, urbanized areas that have more accessible land-uses and more diverse transportation systems usually lead to a decrease in private car use and encourage alternative modes [27]. A study conducted in Nagpure, India, revealed that neighborhoods with high and moderate mixed land-use are more sustainable in terms of travel behavior. According to residents' perceptions, neighborhoods with a moderate land-use mix are more sustainable than in a low mixed land-use neighborhood [36]. Another study conducted in the Madrid region, Spain, suggests that mixed land-use and walkable neighborhoods promote environmental sustainability and discourage car ownership [3]. A similar study was conducted in Shenzhen, China, to evaluate the effect of land use on bicycle usage. The findings indicated that the percentage of green land has a strong impact on bicycle usage and mixed land-use is positively correlated with bicycling frequency [37].

Previous studies [6,38] divided land use into various sectors: residential, commercial, and industrial. The synergy and distribution of various facilities within a specific area results in a local, mixed-land-use built environment. Usually, it is primarily residential, with the remainder of the property being used for recreational or residential purposes in conjunction with retail and public organizations. Grant et al. [39] claim that mixed land-use is a straightforward model, and they proposed three conceptual levels after performing a comprehensive investigation of MLU strategies and objectives. The first level is to increase the variety of land uses, for instance, by promoting a range of housing types and tenures. This social mixing is more prevalent in North America than in Europe. The second level is to increase the diversity of uses by promoting a compatible mix. The third level is to integrate segregated land-use; this will assist in overcoming regulatory hurdles concerned mostly with environmental impacts. This mixing of residential and industrial land-uses originated in pre-World War II in European cities to allow laborers to live closer to their places of employment, primarily within industrial zones. Thus, mixed land-use enables residents to be close to work, shopping, and public services [40].

Although numerous studies have been conducted to analyze the effects of neighborhood spatial characteristics on housing prices, little is known about how two critical land-use characteristics associated with smart growth strategies—mixed land-use and job accessibility—affect housing prices and rents, respectively [21]. According to urban economic theory [41], the monocentric model argues that residential activities are determined by a trade-off between the accessibility of being close to the Central Business District (CBD) and property values. Mills [42] expanded on this hypothesis, and the concept of accessibility was quantified in terms of distance from the CBD. Nevertheless, when employment shifted away from central cities and toward suburbs, a variety of polycentric models highlighting the importance of employment subcenters were proposed [43]. The findings of a previous study suggest that numerous factors such as public facilities, environmental impact, household characteristics, and accessibility have an influence on the choice of residential location, and housing prices [44]. Several studies have evaluated the relationships between the accessibility of retail stores and housing prices within neighborhoods with mixed land-use. The results indicated that the accessibility of retail stores has a significant effect on housing prices [6,45]. The effects of MLU, job accessibility, housing prices, and rents have been observed. The results indicated that increasing job accessibility increases housing costs but not rents, while MLU decreases housing costs but increases rents. On the other hand, rent demonstrates the renter's willingness to pay for housing.

Various housing demands have prompted renters and homebuyers to pay close attention to various elements while purchasing or renting [21]. Similar studies [22,38] affirmed that housing costs are much higher in neighborhoods dominated by single-family residential land-use; however, there is a decrease in communities dominated by multi-household residential land-use. Another study [46] reaffirmed that the impacts of mixed land-use on housing prices rely on the development characteristics of the neighborhoods. In addition, a study conducted in the Rotterdam metropolitan area revealed that mixed land-use promotes housing prices [13].

Mixed land-use is highly related to sustainable development goals, such as the improvement of accessibility and social health outcomes. Shi et al. [1] proposed a new index to represent functional compatibility based on spatial segregation measurements to eliminate the inadequacies and complexities. However, Maitreyan et al. [2] developed a multi–mixed-use distribution index by combining divisional and integral indices. This index evaluates quantity, distance, and balance in land-use mixing along streets that serve as important commute corridors in Tehran, Iran. Likewise, Yang et al. [4] employed the type number index and entropy index to analyze the mixed land-use level's spatial distribution and aggregation characteristics. It was determined that the level of mixed land-use is higher in the city center and lower in the city's outskirts in Beijing.

2.3. Methods for Predicting Mixed Land-Use

Different methods have been employed to evaluate the effect of accessibility on mixed land-use. Most studies have used the entropy index (ENT), and Herfindahl–Hirschman index (HHI) to evaluate urban mixed land-use [30,47]. In addition, the mixed degree index (MDI), activity-related complementarity index (ARC), dissimilarity index (DIS), balance index (BAL), Gini index (GINI), and clustering index (CLST), were used to measure mixed land-use in a city [30]. The association between land-use changes and the corresponding impact factors is frequently nonlinear, irregular, and highly complicated. Artificial neural networks (ANN) can capture the complex nonlinear interactions between input and output data through an adaptive learning process. In addition, the application of ANN in land-use modeling and forecasting with numerous land types is an appealing option. This has been well showcased in those papers coupling ANN and Culler Automata (CA) models [48]. On the other hand, existing ANN-based CA models are limited to modeling changes in the state of individual cells as a result of stimuli in their surroundings. They failed to account for the socio-economic interactions and behaviors of various decision makers at various spatial scales. ANN has been a robust technique for projecting land-use changes [49,50]. Similarly, Liang et al. [51] proposed a mixed-cell CA framework for forecasting mixed land-use change by modeling the basic land-use grid cell with proportions of multiple land-use components. The mixed-cell CA model has shown acceptable simulation accuracy and demonstrated the viability of future mixed land-use change projections in a metropolitan area. In addition, Wu et al. [52] studied the methodological framework for simulating and forecasting changes in mixed land-use by developing a multi-label (ML) convolutional neural network CA (ML-CNN-CA) model with a multi-label learning strategy. The results indicated that the ML-CNN-CA model is an effective approach for simulating changes in the city's mixed land-use. A study used a decision tree model to analyze the effect of accessibility on mixed land-use [14]. Some previous studies have used machine learning approaches such as Logistic Regression [53], and Support Vector Machines [54] for predicting land-use changes and urban growth. Moreover, econometric models such as the Lowry model [55], MEPLAN [56], TRANUS [57], and UrbanSim [58], were used for forecasting activity location.

The current study employs the EI and HH indexes to show the MLU degree in the parcel. The EI and HH indexes are used to capture the equilibrium degree of the area or quantity of various land-use types in the parcel, while the type number index is used to reflect the richness of land-use types in the parcel. The EI and HH indexes are usually used to measure the equal occurrence degree of different functions and the diversity in a region. These indexes can, therefore, be used to measure the equilibrium degree of the area or the quantity of different land-use types in the parcel [30,47]. In addition, the current study employs Deep neural networks (DNNs)—the LSTM and MLP models—for forecasting the effect of transportation supply on MLU at the parcel level. DNN has been considered a robust technique for projecting land-use changes [49,50]. LSTM has the capability to capture information within sequential datasets such as spatial and temporal sequences [59]. DNNs are improved versions of the conventional ANN, with multiple layers. The DNN models have recently become very popular due to their excellent ability to learn not only nonlinear input–output mapping, but also the underlying structure of the input data vectors [49,50,52]. These approaches will provide a thorough understanding of the interactive mechanism between MLU patterns and transportation systems, thereby improving the scientific nature of urban land and transportation planning.

3. Study Data and Methods

3.1. Data

This study considers the Jiang'an District, City of Wuhan, China as the case study. The City of Wuhan is located at a latitude of 29°58′–31°22′ north and a longitude of 113°41′–115°05′ east. The City of Wuhan has 13 districts under its jurisdiction. As of the end of 2019, the total area of Wuhan was 8569.15 km^2, with a resident population of 11.212 million. In recent years, rail rapid-transit development in Wuhan has accelerated. The length of completed rail-transport lines expanded considerably from 2011 to 2015, from 28.68 km to 125.64 km [60]. In addition, only line 1 is within the study region; line 1, which was constructed in 2004 and then extended in 2010 and 2014, was the only elevated rail line. It follows a path parallel to the Yangtze and Han rivers [60]. The City of Wuhan has around 4.77 million employees, working in various sectors in 2012, and it had increased to 5.06 million by 2015.

The employment data were obtained from the Wuhan Transportation Development Strategy Institute (http://www.whtpi.com) (accessed on 20 May 2022). Furthermore, employment by industry type was used to develop the transport model. The total number of parcels considered for this study was 871. There were 141 and 196 bus lines in service in 2012 and 2015, respectively. In 2012, there was only one subway line with 26 subway stations; by 2015, this was increased to 28 subway stations which are shown in Table 1. In order to estimate the average space prices, the building floor space was split into four categories: residential, commercial, mixed residential–commercial, and mixed commercial–residential. The residential–commercial mix indicates that the density of residential building types is higher than commercial, while the commercial–residential mix indicates that the density of commercial buildings is higher than residential. Table 2 illustrates the total space quantity and average space price type data of the Jiang'an district between 2012 and 2015. As indicated in Table 2, the space quantity and average space price increased between 2012 and 2015. In addition, it was observed that the total space quantity of mixed commercial–residential increased by around 125,054 square meters between 2012 and 2015. The average space price of mixed commercial–residential and mixed residential–commercial increased by 29.18% and 25.63% between 2012 to 2015, respectively.

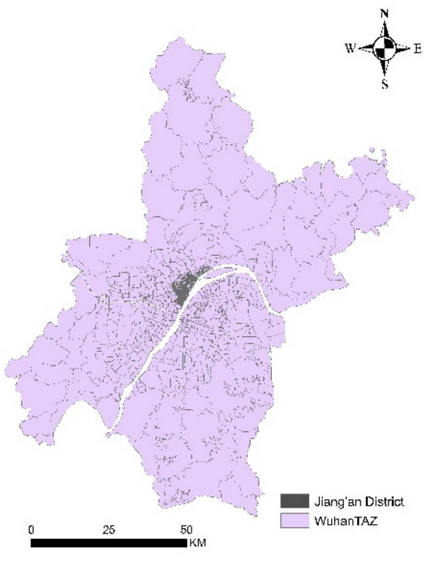
Table 1. Type study data of Jiang'an district.

Years	Bus Lines	Subway Stations	Population (Persons)	Space Quantity (Square Meter)	Parcels (Nos)
2012	141	26	921,700	36,417,232	871
2015	196	28	954,300	38,613,407	

Table 2. Total space quantity (m^2) and average space price (Yuan/m^2).

Years/Type	2012		2015	
	Total Space Quantity	**Average Space Price**	**Total Space Quantity**	**Average Space Price**
Commercial	1,804,696	1804	2,179,442	2413
Mix (Commercial–Residential)	1,888,940	1792	2,013,994	2315
Residential	13,559,658	3409	14,804,345	4319
Mix (Residential–Commercial)	19,163,936	3398	19,615,624	4269

Figure 1a illustrates the 13 Districts of the City of Wuhan and Figure 1b shows the road network, bus line, bus stations, subway line, and subway stations. Figure 1c illustrates the building data from the year 2012 by building type (i.e., residential, commercial, mixed residential–commercial, and mixed commercial–residential) of the Jiang'an District at the parcel level; however, Figure 1d depicts accessibility to residential activities in the year 2012. The range of index values of accessibility indicate: low accessibility (10.96~11.84), low–medium accessibility (11.85~13.54), medium accessibility (13.55~14.38), medium–high accessibility (14.39~14.66), and high accessibility (14.67~15.07). The MLU module was developed using building data, which contain building type and floor-space quantity by space type. Furthermore, the ArcGIS spatial intersection analysis tool was used to aggregate the building floor space to the parcel level. Usually, MLU is divided into three types: vertical mix, horizontal mix, and a combination of both. However, due to the limitation of the data, in this study, only a horizontal mix was considered. Additionally, the price of residential and commercial floor space was acquired for the years 2012 and 2015. To support this study, a multimodal transport model was developed using population and employment by type, to calculate accessibility at the parcel level. Furthermore, the multimodal transport model was calibrated to validate the model's accuracy.



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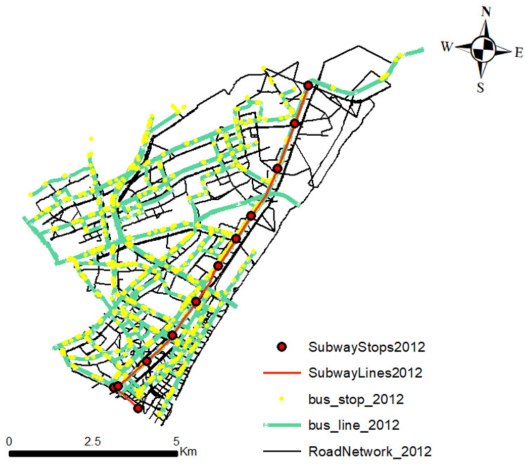

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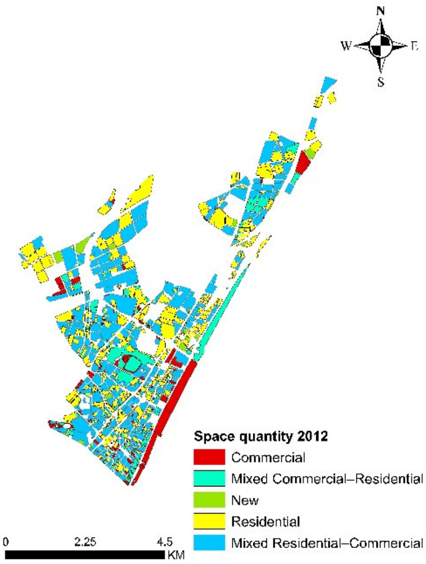
Figure 1. *Cont.*



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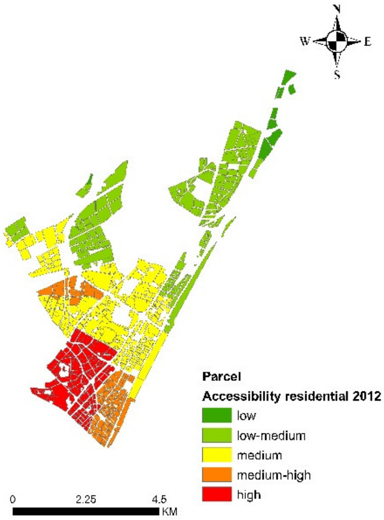


(d)

Figure 1. Various levels of study data of the Jiangan district at the Parcel level: (**a**) Wuhan district; (**b**) multimodal network of Jiang'an district_2012; (**c**) parcels by building type (2012); (**d**) accessibility to residential activities (2012).

3.2. Data Processing

3.2.1. Price of Floor Space

Residential and commercial floor-space price data for the years 2012 and 2015 were obtained from the online real-estate website (https://fang.com/default.htm) (accessed on 20 May 2022). However, the floor-space price collected covers only part of the study area. This study used a kriging interpolation method to estimate the average floor-space price for the rest of the study area. By using this method, the raster data of floor-space price were obtained. After that, the "raster to point" tool was used in Arc Toolbox to convert the raster data of floor-space price into point data. Then, the point data of floor-space price and the parcels layer of the Jiangan district were spatially connected to estimate the average floor-space price for residential and commercial using "spatial join" tool, as shown in Figure 2. For the whole study area, we used the addresses of the locations to establish the latitude and longitude of residential and commercial buildings, matching them to real estate addresses using the website batchgeo (https://batchgeo.com) (accessed on 20 May 2022); then, the coordinates were converted to the standard WGS1984 coordinate system and visualized in the ArcGIS software, as shown in Figure 3. As mentioned earlier in Figure 1c, which contains residential, commercial, residential–commercial, and commercial–residential mixed land-use at the parcel level using density. However, buildings with low density are overlapped by other building types. Most of the study area has both residential and commercial land-use, as it is an urban area. While Figure 3 shows average floor-space prices for each floor-space type. It is observed from Figure 3c,d that most of the areas with high commercial buildings show high floor-space prices. In addition, space price (Yuan/m^2) ranges are shown in Figure 3. In Figure 3a, the range of index values indicates space price: low space price (5683~6502), low–medium average space price (6503~7370), medium space price (7371~8520), medium–high space price (8521~10,070), and high space price (10,071~12,015). In Figure 3b, the range of index values indicates low space price (7673~8935), low–medium space price (8936~10,562), medium space price (10,563~12,472), medium–high space price (12,473~14,672), high space price (14,673~17,633). In Figure 3c the range of index values indicates low space price (12,928~14,883), low–medium space price (14,884~16,614), medium space price (16,615~18,988), medium–high space price (18,989~21,226), and high space price (21,227~22,518). Lastly, in Figure 3d, the range of index values indicates low space price (13,612~15,392), low–medium space price (15,393~17,879), medium space price (17,880~19,718), medium–high space price (19,719~23,292), and high space price (23,293~27,675).

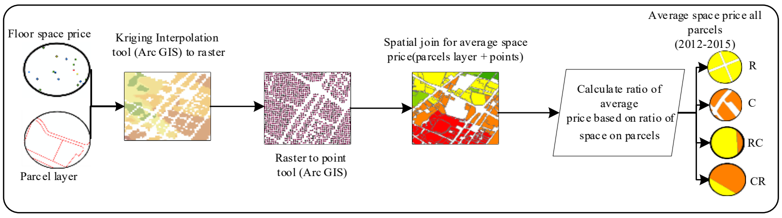


Figure 2. The process of estimating average floor-space price.

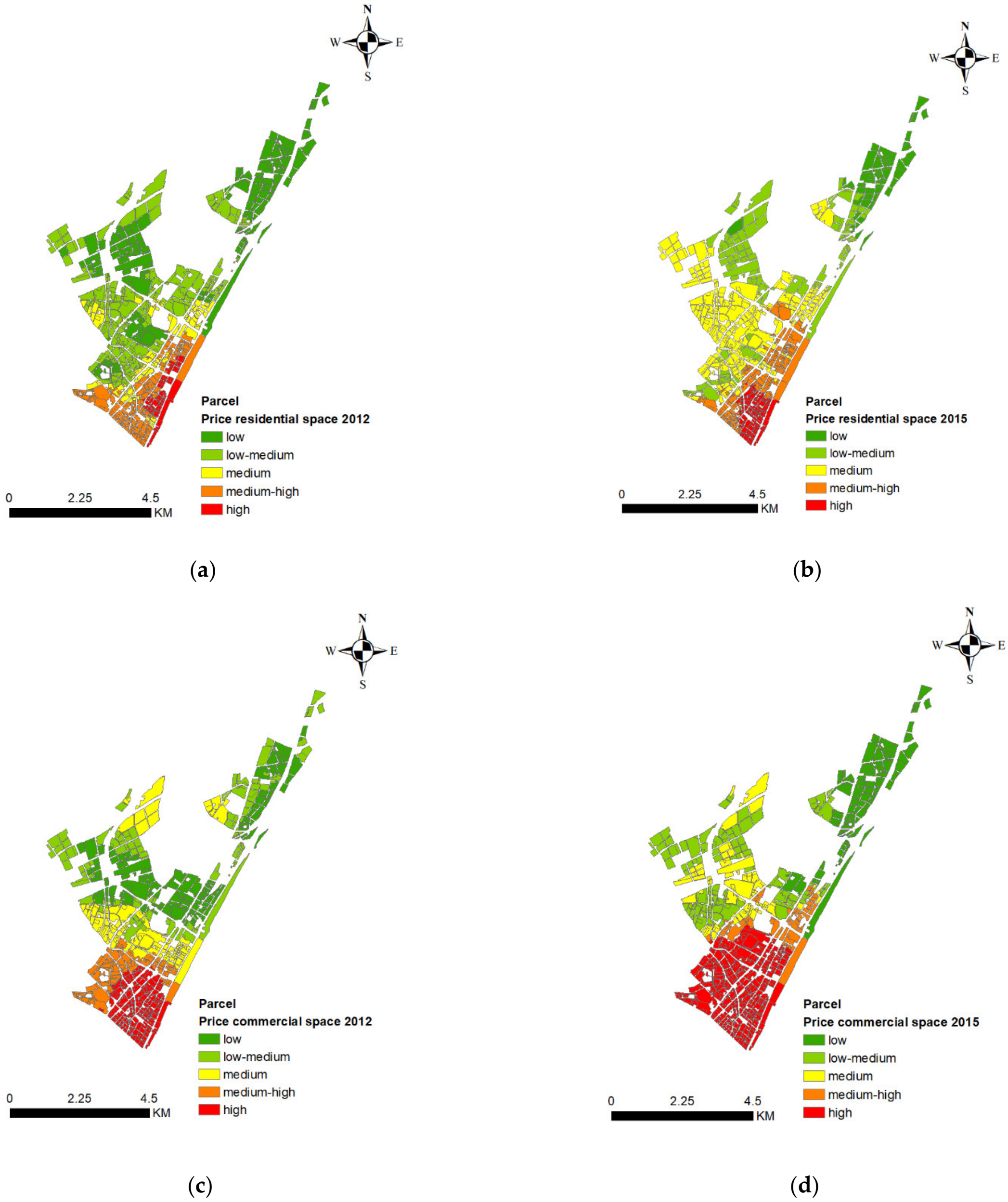


Figure 3. (**a**–**d**) Floor-space prices for residential and commercial for years 2012 and 2015 at parcel level; (**a**) average price for residential space (2012); (**b**) average price for residential space (2015); (**c**) average price for commercial space (2012); and (**d**) average price for commercial space (2015).

3.2.2. Preparation of Mixed Land-Use Data

MLU is an important tool of urban planning and spatial planning nowadays, since it introduces diverse land-uses into an area. For example, the mixed land-use strategy is regarded a key component for improving walkability in urban areas.

The building data for the years 2012 and 2015 were used to develop the model. The parcel data, which contain the building area, number of floors, and building use type, were extracted. The building uses for the years 2012 and 2015 were extracted using the data describing current land-use at the parcel level. Spatial analysis, using the intersection tools of ArcGIS, was used to extract the parcel data. Furthermore, the extracted parcel area and the number of floors in each building type were used to calculate the built space quantity by type of parcels. To determine the level of mixed land-use, the HHI and entropy indexes were used. From the output from these steps, the buildings were categorized into residential, commercial, mixed residential–commercial, and mixed commercial–residential with the mixed land-use degree, as shown in Figure 4.

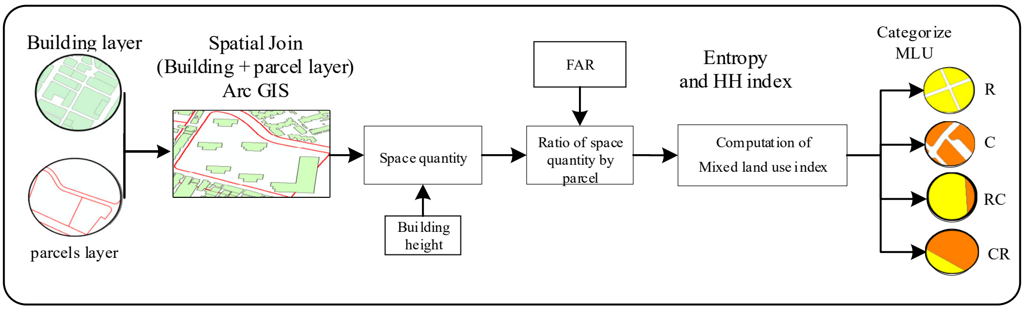


Figure 4. The process of data preparation.

The floor area ratio (FAR) is the ratio of the total floor area of the building to the size of the land on which it is constructed. It is frequently used to calculate the building-to-land ratio. It is one of the regulations in city planning to aggregate the building data and obtain the total construction area to determine the FAR of each parcel [14]. The mathematical form of FAR is shown in Equation (1).

$$(FAR) = \frac{\sum_{j=1}^{n} B_i \times F_i}{A} \tag{1}$$

— B_i represents the total floor area $\left(\mathrm{m}^2\right)$ of the building i;
— F_i represents the number of floors of the i the building; and
— A represents the area of the parcels under computation.

The maximum amount of developable space refers to the amount of space permitted by the land developer. This information is derived from developable land-use and the maximum floor area ratio. Data of each Parcel in the Jiang'an District for the years 2012 and 2015 is depicted in Equation (2).

$$MaxQ_i^p = AL_i^p \times FAR^p \tag{2}$$

— $MaxQ_i^p$ represents the maximum developable space of the p land-use type in the parcels i;
— AL_i^p represents the developable land of the p land-use type in parcels i; and
— FAR^p indicates the maximum floor area ratio of the p land-use type.

Two different mixed land-use indexes were used to analyze the data: entropy and HH indexes. The entropy index is a relative measure of an area's land-use types, with a higher entropy degree indicating a higher mixed land-use [4]. The HH index is the inverse of the entropy index, with a higher degree indicating a lower mixed land-use. The entropy index is used to quantify the mixed land-use diversity. The degree of land-use diversity within a specific area is calculated by Equation (3) as follows:

$$Entropy = -\sum_{i=1}^{k} P^i \ln P^i \tag{3}$$

where

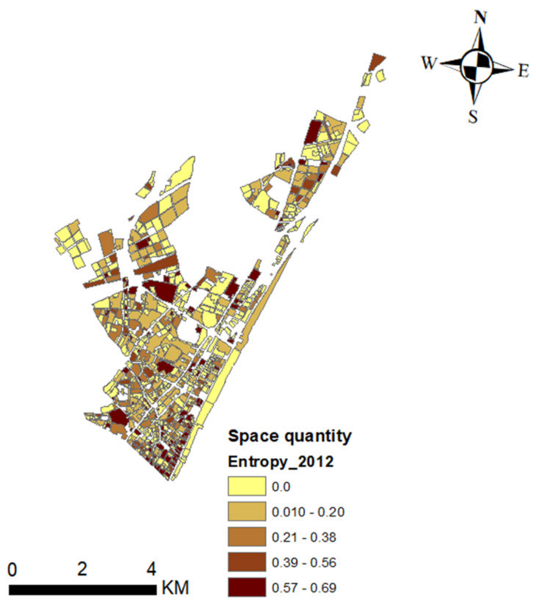
— P^i, is the percentage of each land-use type i in the area; and
— k is the total number of land-use types.

The HH index relates to mixed land-use status and is applied to the situation of market concentration in economics [30]. The HHI is calculated using Equation (4).

$$HHI = \sum_{i=1}^{k} \left(100 \times P^i\right)^2 \tag{4}$$

— P^i is the percentage of land-use i in the given area; and
— k is the number of land-use types in parcels i.

Figure 5a,c show the entropy index for the years 2012 and 2015. A value of 0.057–0.69 and 0.58–0.69 from 2012 and 2015, respectively, indicates a high degree of mixed land-use patterns; a value of 0.21–0.38 and 0.22–0.39 indicates a medium degree of mixed land-use patterns; and a value of 0.010–0.20 and 0.010–0.21 indicates a low degree of mixed land-use patterns. The results from the entropy index depict that most parcels show a high level of mixed land-use patterns. Moreover, Figure 5b,d depict the HH index for the years 2012 and 2015. A value of 50–57 and 50–58 from 2012 and 2015, respectively, indicates a high level of mixed land-use, while a range of 84–99 indicates a low level of mixed land-use patterns. In addition, an entropy value of 0.0 and an HHI of 100 indicate that a parcel only contains one land-use pattern. As indicated by the HH index values in Figure 5b,d, most parcels have a high level of mixed land-use.



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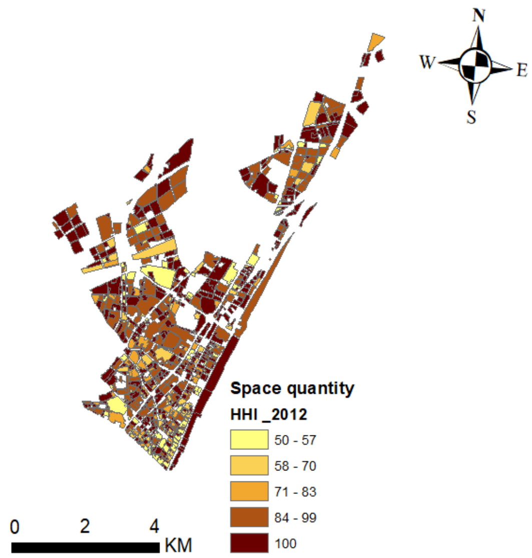

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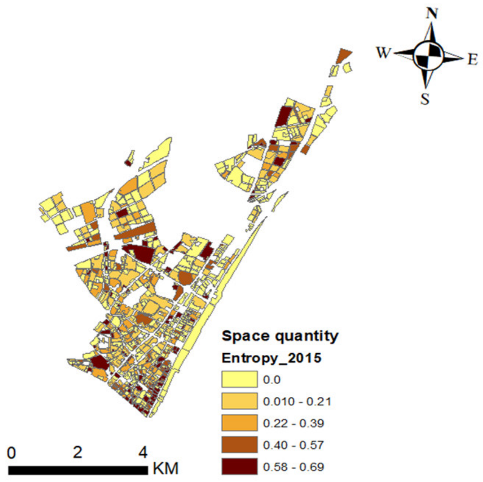

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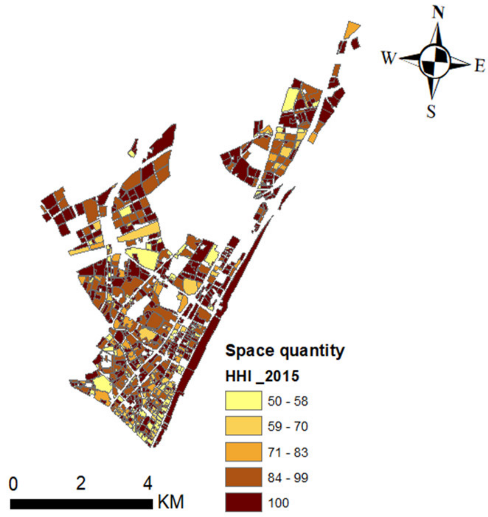


(**d**)

Figure 5. (**a**–**d**). An entropy index and HH index for the years 2012 and 2015: (**a**) entropy index 2012; (**b**) HH index 2012; (**c**) entropy index 2015; and (**d**) HH index 2015.

3.3. Methods

A deep neural network (DNN) is an ANN with multiple hidden layers between the input and output layers. DNNs can solve complex nonlinear relationships. ANN is a robust technique that receives a set of inputs, performs progressively complex calculations on them, and outputs results to solve real-world problems such as forecasting and classification. Thus, in this study, DNN, including MLP and LSTM, were used to analyze the effect of transportation supply on mixed land-use. The workflow is depicted in Figure 6. The primary steps are as follows:

(1) The data for the models representing transportation supply (road network, bus stops and lines, subway lines and stops, and others), floor-space price (by type), and land-use data (construction area, developable land, floor area ratio, building, and other land-use data) were prepared;

(2) The developed multimodal transport model was used to calculate accessibility to residential, commercial, and mixed land-uses at the parcel level for the years 2012 and 2015;

(3) Due to the data limitation, the average floor-space prices were estimated using the Kriging interpolation tool at the parcel level;

(4) The mixed land-use data were prepared at the parcel level in ArcGIS using the "spatial join" and "intersection analysis" tools, and the Entropy and HH indexes were used to quantify the degree of mixed land-use;

(5) Deep neural networks (MLP and LSTM) were used to forecast future years of mixed land-use types at the parcel level. Moreover, the change in space quantity due to transportation supply and floor-space price changes between 2012 and 2015 were analyzed;

(6) Finally, the accuracy of the developed MLP and LSTM models were compared.

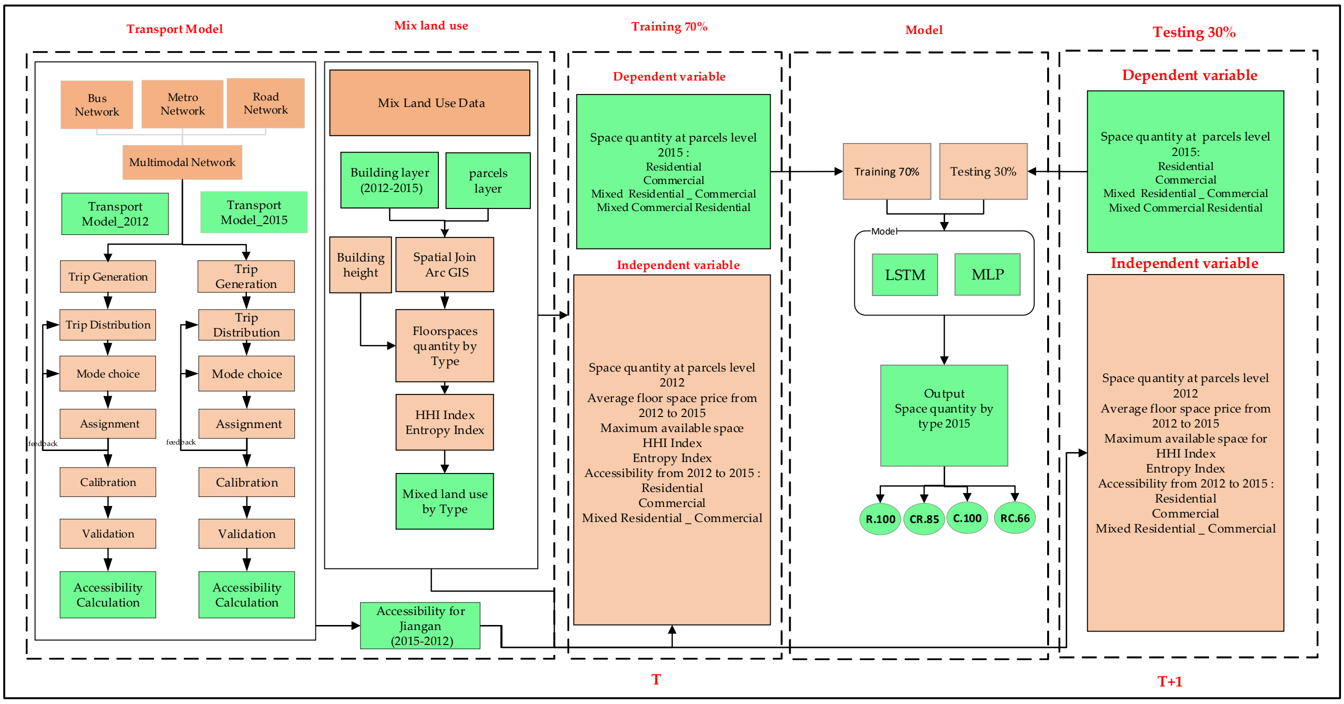


Figure 6. The workflow of the proposed model.

The model examined the effect of transportation supply on MLU patterns at the parcel level in the Jiang'an District using MLP and LSTM. The models developed for this study are presented as follows.

3.3.1. Transport Model

The transport model was developed and then used to calculate utility-based accessibility measures at the parcel level from 2012 to 2015. This model was developed using a multimodal network approach to represent the interactions between all transportation modes. As mentioned in the data Section 3.1, various datasets were adopted and several steps were taken, which enabled the calculation of accessibility measures for the residential, commercial, mixed residential–commercial, and mixed commercial–residential land-uses at the parcel level. These accessibility measures were used as the input to the MLP and LSTM models as independent variables. The model processes are as follows:

(1) The trip generation module starts with the calculation of trip production and attraction by trip purpose;
(2) The trip distribution module distributes these trips to each parcel using the gravity approach. Furthermore, mobile phone signal data are used to calculate and calibrate trip length frequency;
(3) A mode choice module, which is based on an absolute nested logit structure, distributes trips to different modes based on the utility associated with each mode;
(4) Trip assignment module: The trip assignment process reproduces the patterns of vehicular movements on the transportation system, which can be seen when the travel demand is satisfied. To obtain the volume of traffic on the network links and estimate aggregate network measures, the travel pattern of each O-D pair (origin to destination) is estimated. The assigned model generates congested skims which are fed back to the distribution model. The model uses the congested skim to perform the distribution and mode choice. This enables the production of utility-based accessibility based on congested time, which is input to MLP and LSTM models, as shown in Equation (5).

$$A_i = \text{Ln}(1 + \sum_{j=1}^{n} = \sum_{k=1}^{m} e^{U_{ij}^{k}} \times O_J) \quad (5)$$

where

- — A_i is the accessibility of parcel i;
- — i and j are both parcel numbers;
- — k is one of the modes of transportation;
- — n is the total number of parcels;
- — m is the total number of modes of transportation;
- — U_{ij}^{k} is the utility generated by the transportation mode k from parcel i to parcel j; and
- — O_j is the service or opportunity of parcel j;
- — $+1$ in case of no activity.

3.3.2. Multilayer Perceptron (MLP) Algorithms

Artificial intelligence-based algorithms (e.g., heuristics, metaheuristics) are promising and rapidly expanding application areas of urban planning and transportation, including online learning [61], vehicle routing [62], delayed start parallel evolutionary algorithm [63], non-dominated sorting genetic algorithm, multi-objective particle swarm optimization [64], and multi-objective optimization [65,66]. The multi-objective spatial optimization of land-use depends on two factors: land-use population capacity and land-use carbon emission [67]. In addition, DNNs are improved versions of traditional ANNs, with multiple layers. Due to their superior ability to learn nonlinear input–output mapping, DNN models have recently been gaining more popularity. However, recent research has demonstrated significant potential for ANN-based approaches in land-use changes [49,50]. The ANN approach was used to investigate the impact of transportation supply on mixed land-use changes at the parcel level. The ANN approach has four steps: (1) build the network, inputs, and outputs; (2) select a subset of the inputs and train neural networks; (3) validate ANN with the dataset of inputs; and (4) utilize ANN for a future year. One of the most common ANN architectures is the multi-layer perceptron (MLP) network, which is also employed in this study. MLP is a framework for feed-forward networks that provides non-linear functional mapping between a set of input and output variables. It has four layers: one input, two hidden, and one output. Neurons are represented by circles, while lines represent unidirectional interconnections between neurons in the corresponding layer [68]. The structure of MLP is shown in Figure 7.

To evaluate the effect of transportation supply on mixed land-use change, the input layer contains neurons corresponding to the input value of each neuron (features) x_i. The input layer considers 13 input values: space quantity 2012, average space price, maximum available space quantity, HH index, entropy index, different accessibility measures (residential, commercial, mixed residential–commercial), etc. The neurons in the output layer predict space quantity for 2015 for all parcels and the ratio of quantities of different types of land-uses by the HH index or entropy index. The weighted linear combination of the input variables is the output of the hidden neuron. In an MLP with one hidden layer, the sigmoid activation function is utilized to activate the *m*th hidden neuron.

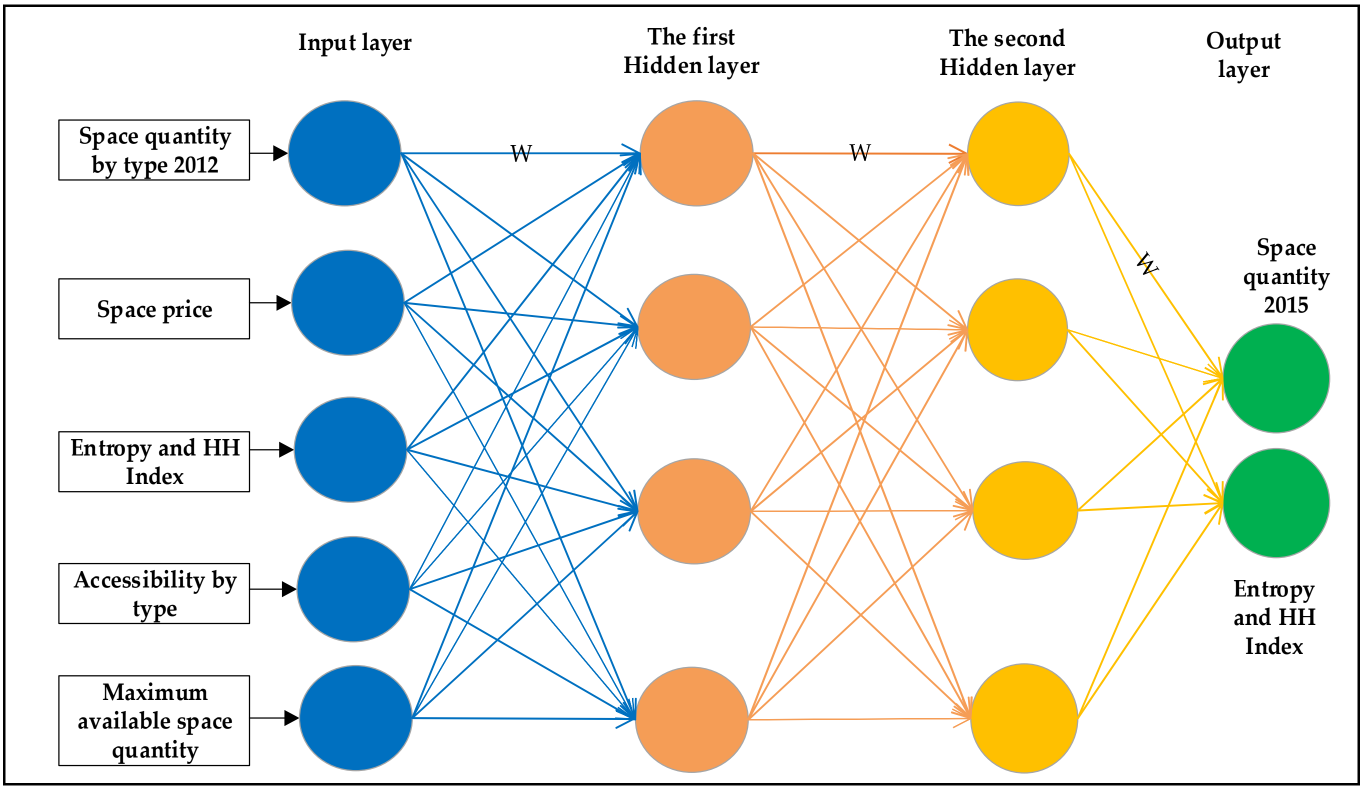


Figure 7. MLP neural network structure.

Equations (6) and (7) show the mathematical formulation of the MLP. Each neuron has its regression model, which consists of input data, weights, thresholds, activation functions, and outputs.

$$Z_i = \sum_{i=1}^{m} w_{ij} \times x_i + b_j \quad (6)$$

$$Output\ Y_i = \mathrm{F}(Z_i) = \begin{cases} 1\ if\ \sum_{i=1}^{m} w_{ij} \times x_i + b_j \geq 0 \\ 0\ if\ \sum_{i=1}^{m} w_{ij} \times x_i + b_j < 0 \end{cases} \quad (7)$$

where

— Z_i is the output value of the neuron *j*;

— x_i is the input value of the neuron *i* (space quantity 2012, accessibility, price, etc.);

— w_{ij} is the weight between the neuron i and neuron *j*;

— b_j is the threshold (bias) of the neuron *j*;

— Y_i is the output value after activation of the neuron *j* (the predict of space quantity 2015); and

— F is the activation function.

The weights are assigned to the input layers in the MLP once the input layers have been determined. These weights aid in determining the importance of any given variable, with larger weights contributing more to the final result than lower weights. Following that, all of the inputs are multiplied by their respective weights, then summed, and a threshold is established before they are fed through an activation function that has been defined. Thus, the output of that neuron becomes the input of the next neuron. Forward propagation is the term used to describe transmitting data from one layer to the next. All inputs are adjusted so that they fall within the range of (0, 1) [49].

The ultimate purpose of forwarding propagation of the MLP is to minimize the loss function. Thus, the network feeds the output data into the input and adjusts its weights and thresholds according to a loss function to attain a convergent point or local minimum, a process known as backpropagation. Gradient descent is used to optimize the model's orientation in order to reduce loss or error. Throughout each training process, the network's parameters gradually converge to a minimal value [69].

The selection of hyperparameters, such as activation functions, optimizers, etc., are critical in MLP. They show the ability, speed, and accuracy of the MLP training. The MLP hyperparameters include the learning rate, the batch size for training, the number of hidden layers, the number of hidden layer neurons, and the number of iterations.

3.3.3. Long Short-Term Memory (LSTM) Algorithms

Recurrent neural networks (RNNs) are a subtype of neural networks designed to deal with sequential data types such as text and time series. However, due to the vanishing gradient problem, conventional RNNs cannot capture long-term dependencies in data [70]. To address this issue, the long short-term memory (LSTM) network, a subtype of RNN, was developed. Due to its larger memory capacity, LSTM is more frequently used than traditional RNN. The cell state, sigmoid activation, forget gate, input gate, output gate, and *tan h* activation are all critical elements of LSTMs because they control the flow of relevant information through the network. The gates control the addition and removal of information from the cell state at each processing step [71]. Gates have sigmoid activation, which multiplies values between 0 and 1 to determine the percentage of data that will be retained or deleted. If the input equals 0, then the information is lost; if the input equals 1, the data are fully retained. *Tan h* activation produces values in the range of -1 to 1. The process of RNNs is shown in Equations (8)–(13), and Figure 8 shows the LSTM cell neural network structure.

$$i_t = \sigma\ (w_i[h_{t-1},\ x_t] + b_i) \quad (8)$$

$$f_t = \sigma\ (w_f[h_{t-1},\ x_t] + b_f \quad (9)$$

$$o_t = \ \sigma\ (w_o[h_{t-1},\ x_t] +\ b_o) \quad (10)$$

$$g_t = tan\ h\left(w_g[h_{t-1},\ x_t] +\ b_g\right) \quad (11)$$

$$c\ _t = f_t \times c_{t-1} + i_t \times g_t \quad (12)$$

$$h\ _t = o_t \times tan\ h(c_t) \quad (13)$$

where

— c_t denotes cell state, and h_t denotes the output for training 70% of space quantity 2015 and predicting 30% of space quantity 2015, at time step t;
— f_t denotes forget state, o_t represents the output gate, and σ represents the sigmoid function;
— w represents the weight, b represents bias, and g_t denotes a vector of the new candidate value called cell activation;
— f_t represents a value between 0 and 1, which means the ratio of old information that will be passed to the new cell state; and
— i_t decides the ratio of each value in a sequence from g_t that will be preserved.

From the training and prediction of floor-space quantity 2015, the LSTM model was used in a case study of the Jiang'an District in Wuhan, China, with model inputs encoded as transportation supply, average space price, and floor-space quantity. A total of 70% of the datasets were used for training purposes and the remaining 30% were used for testing the models.

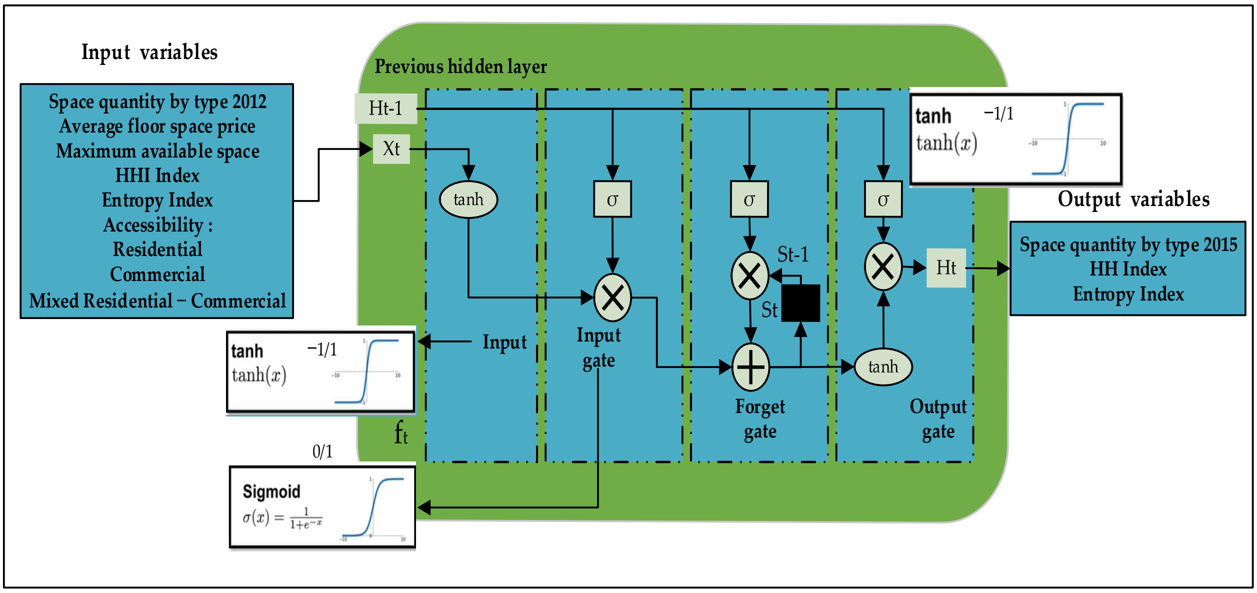


Figure 8. LSTM cell neural network structure.

4. Results and Discussion

Deep neural network models, namely MLP and LSTM techniques, were used to analyze the effects of transportation supply on MLU at the parcel level by taking a case study of the Jiang'an District, Wuhan, China. The dataset from the Jiang'an District contains 871 parcels for 2012 and 2015.

4.1. Accessibility and MLU Change at the Parcel Level (2012 and 2015)

Since accessibility to employment activities is positively correlated with the level of service (LOS) of the transportation system and the employment location, this paper applied three categories of employment accessibility measures, including those to residential, commercial, and mixed residential–commercial areas in the Jiang'an District, Wuhan for the years 2012 to 2015, as shown in Figures 9 and 10.

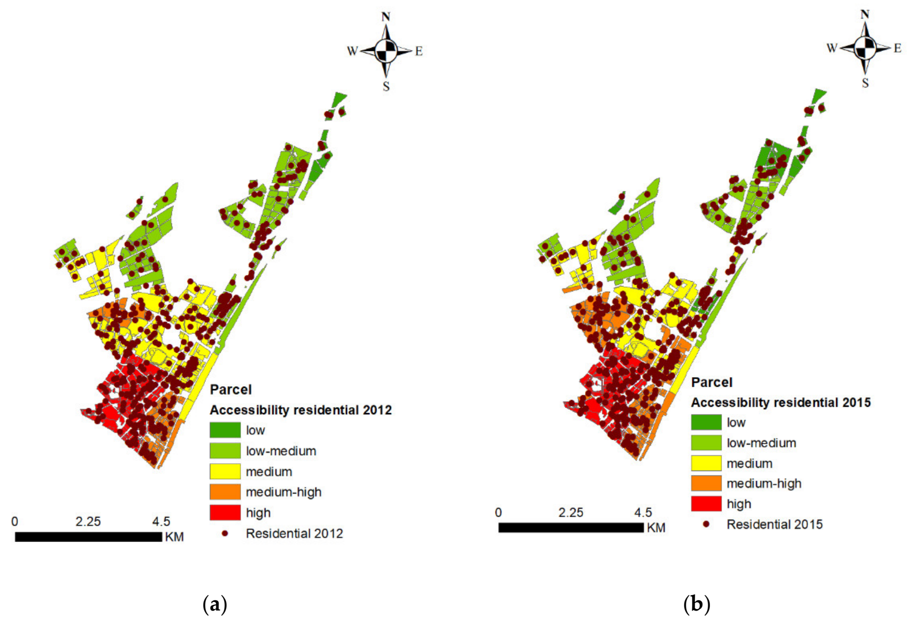


Figure 9. (**a**,**b**) Accessibility to residential activities and residential space developed at parcel level: (**a**) accessibility to residential activities (2012); and (**b**) accessibility to residential activities (2015).

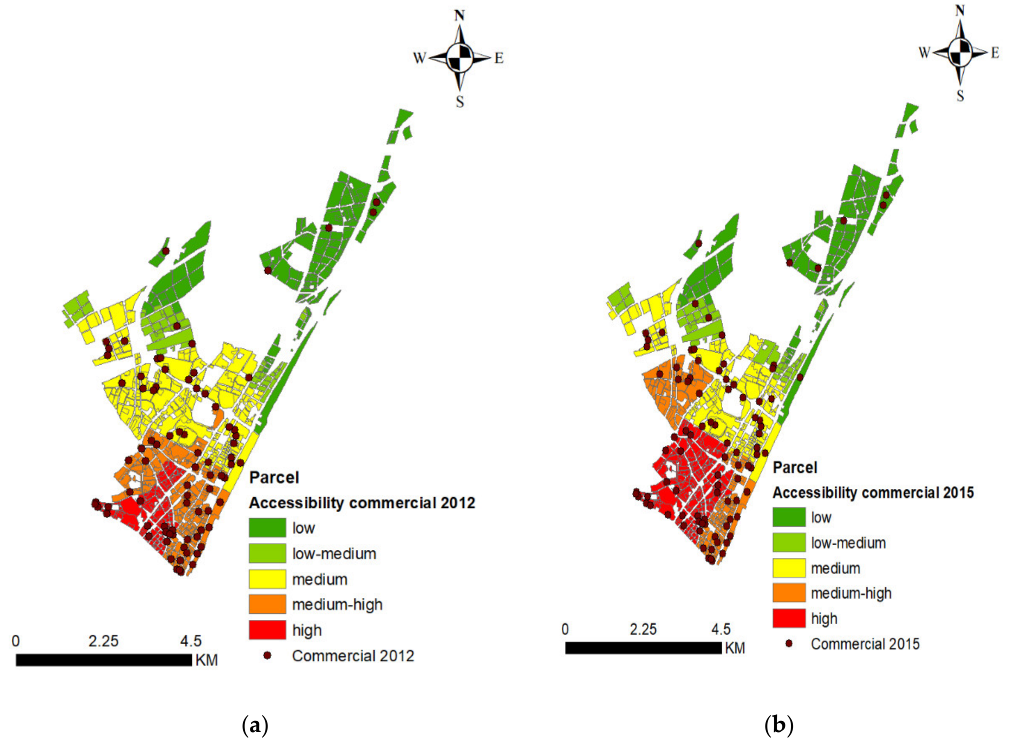


Figure 10. (**a**,**b**) Accessibility to commercial activities and commercial space developed at parcels level: (**a**) Accessibility to commercial activities (2012); and (**b**) Accessibility to commercial activities (2015).

In this study, correlation analyses were carried out to check the correlation between land-use and transportation indicators. Table 3 shows the degrees of correlation among variables. Using the dependent variable of space quantity for the following land-use types (R = residential, C = commercial, RC = residential–commercial, CR = commercial–residential) in the Year 2015 as an example, it is found that most of the variables are highly correlated with the quantity (see those numbers highlighted with * or **). The results showed that residential accessibility is highly correlated with residential space, and commercial accessibility has a high correlation with commercial space. Moreover, the mixed accessibility encouraged mixed land-use development in that places with high mixed accessibility have a high level of mixed land-use patterns, as shown in Table 3. In addition, the results depict that high accessibility encourages a high level of mixed space for residential/commercial uses, as shown in Table 3. Likewise, areas with high accessibility are found to have high space prices, which indicates that accessibility influences space prices significantly.

Figure 9a,b illustrate the accessibility to residential activities and residential spaces developed between 2012 and 2015. The results indicate that parcels with high accessibility to residential activities have high-density residential space developed. In 2015, it was found that the residential space was significantly developed in parcels with high accessibility. These results indicate that there is a strong relationship between accessibility and developed space. In addition, Figure 9a,b indicate the range of index values of accessibility for residentials in 2012 and 2015: low accessibility (10.96~11.84), low–medium accessibility (11.85~13.54), medium accessibility (13.55~14.38), medium–high accessibility (14.39~14.66), and high accessibility (14.67~15.07).

Table 3. Correlation matrix.

	Pearson Correlation	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
[1]	Mixed Accessibility (RCA)	1	0.789 **	0.798 **	−0.144 **	−0.043	−0.172 **	−0.140 **	0.050	0.097 **	−0.178 **	−0.143 **	0.047	0.096 **
[2]	Commercial Accessibility (CA)	0.789 **	1	0.988 **	0.373 **	0.453 **	0.060	0.078 *	−0.124 **	−0.019	0.055	0.083 *	−0.133 **	−0.022
[3]	Residential Accessibility (RA)	0.798 **	0.988 **	1	0.366 **	0.445 **	0.062	0.079 *	−0.103 **	−0.008	0.057	0.084 *	−0.114 **	−0.014
[4]	Mixed-Space Price 2012 (RCP)	−0.144 **	0.373 **	0.366 **	1	0.924 **	0.356 **	0.377 **	−0.216 **	−0.154 **	0.310 **	0.361 **	−0.202 **	−0.160 **
[5]	Mixed-Space Price 2015 (RCP)	−0.043	0.453 **	0.445 **	0.924 **	1	0.341 **	0.333 **	−0.195 **	−0.143 **	0.333 **	0.348 **	−0.201 **	−0.147 **
[6]	Commercial Space (CS) 2012	−0.172 **	0.060	0.062	0.356 **	0.341 **	1	−0.050	−0.063	−0.074 *	0.835 **	−0.042	−0.063	−0.075 *
[7]	Commercial–Residential Space (CRS) 2012	−0.140 **	0.078 *	0.079 *	0.377 **	0.333 **	−0.050	1	−0.082 *	−0.096 **	−0.042	0.924 **	−0.082 *	−0.090 **
[8]	Residential Space (RS) 2012	0.050	−0.124 **	−0.103 **	−0.216 **	−0.195 **	−0.063	−0.082 *	1	−0.122 **	−0.063	−0.084 *	0.914 **	−0.103 **
[9]	Residential–Commercial Space (RCS) 2012	0.097 **	−0.019	−0.008	−0.154 **	−0.143 **	−0.074 *	−0.096 **	−0.122 **	1	−0.074 *	−0.092 **	−0.107 **	0.965 **
[10]	Commercial Space (C S) 2015	−0.178 **	0.055	0.057	0.310 **	0.333 **	0.835 **	−0.042	−0.063	−0.074 *	1	−0.051	−0.063	−0.075 *
[11]	Commercial–Residential Space (CRS) 2015	−0.143 **	0.083 *	0.084 *	0.361 **	0.348 **	−0.042	0.924 **	−0.084 *	−0.092 **	−0.051	1	−0.084 *	−0.100 **
[12]	Residential Space (RS) 2015	0.047	−0.133 **	−0.114 **	−0.202 **	−0.201 **	−0.063	−0.082 *	0.914 **	−0.107 **	−0.063	−0.084 *	1	−0.124 **
[13]	Residential–Commercial Space (RCS) 2015	0.096 **	−0.022	−0.014	−0.160 **	−0.147 **	−0.075 *	−0.090 **	−0.103 **	0.965 **	−0.075 *	−0.100 **	−0.124 **	1

Note: * = correlation is significant at the 0.05 level (2-tailed), ** = Correlation is significant at the 0.01 level (2-tailed); R = residential, C = commercial, RC = residential–commercial, CR = commercial–residential.

Figure 10a,b depict the accessibility to commercial activities from 2012 to 2015 and the developed space quantity. The results indicate that most of the areas with high accessibility to commercial activities showed a high density of developed commercial space quantity. With the increase in accessibility to commercial activities in 2015, especially in the middle of the Jiang'an District, an area along subway line 1, a significant increase in commercial space quantity was found. These key results indicate that there is a strong relationship between accessibility and space quantity. Figure 10a,b indicate the range of index values of accessibility for commercial space in 2012 and 2015: low accessibility (8.774~11.55), low–medium accessibility (11.56~12.97), medium accessibility (12.98~13.80), medium–high accessibility (13.81~14.47), and high accessibility (14.48~15.01).

Figure 11a,b depict the accessibility to mixed (RC and CR) activities from 2012 to 2015 and the developed mixed-space quantity. The results indicate that most of the areas with high accessibility to mixed activities showed a high density of developed mixed (RC and CR)-space quantity. With the increase in accessibility to mixed activities in 2015, such as in the south and center of the Jiang'an District, close to the city center and subway line 1, a significant increase in mixed-space quantity was found. These key results indicate that there is a strong relationship between mixed accessibility and mixed-space quantity. Figure 11a,b indicate the range of index values of accessibility for mixed residential–commercial in 2012 and 2015: low accessibility (7.863~10.54), low–medium accessibility (10.55~11.70), medium accessibility (11.71~12.84), medium–high accessibility (12.85~13.36), and high accessibility (13.37~13.64).

Table 4 illustrates the number of buildings that changed from 2012 to 2015. As indicated in Table 4, the mixed RC shows the highest incidence of change to mixed CR from 2012 to 2015. Meanwhile, the incidence of mixed CR change to RC was found to be relatively low compared to other mixed changes. In addition, it was observed that 75 buildings changed from RC to residential. However, it was observed that 54 buildings changed from residential to RC and 392 buildings were demolished. Moreover, it was observed that only 4 buildings changed from commercial to RC, and 2 buildings changed to CR. The total number of buildings changed was recorded at around 2827.

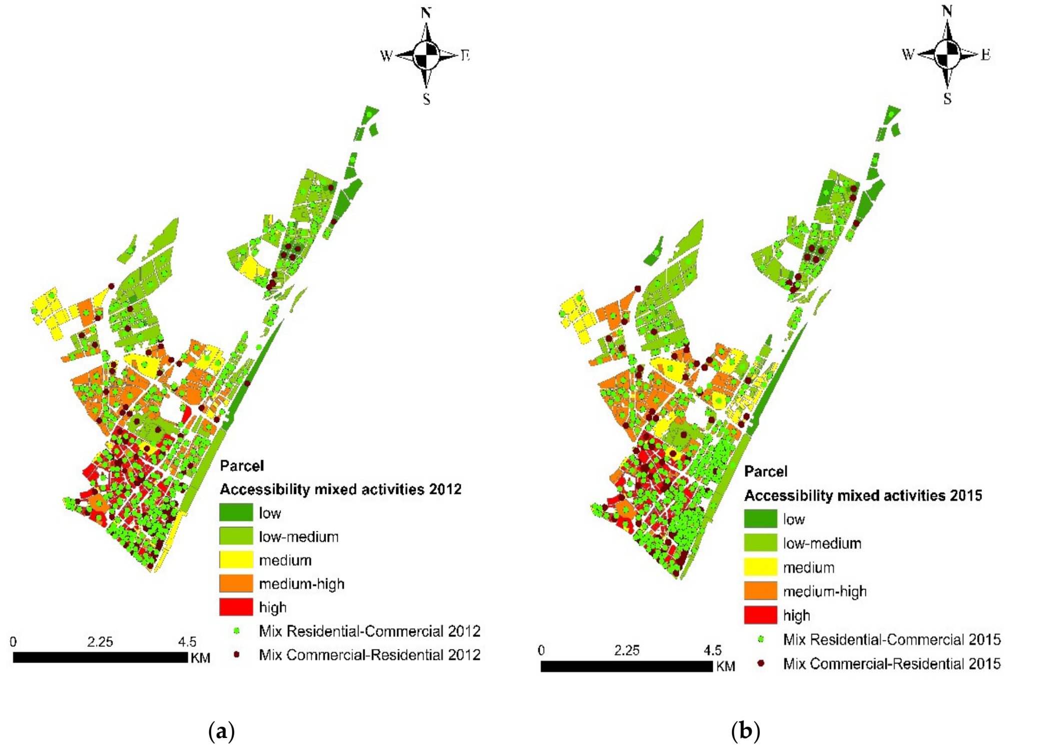


Figure 11. (**a**,**b**) Accessibility to mixed activities and mixed space developed at parcel level: (**a**) accessibility to mixed activities (2012); and (**b**) accessibility to mixed activities (2015).

Table 4. The total number of the buildings changed from 2012 to 2015 by parcel type in the Jiang'an district.

The Total Number of the Building Changed by Parcel Type						
2012/2015	**C**	**CR**	**D**	**R**	**RC**	**Total Change**
C	14	2	0	0	4	20
CR	4	54	10	0	11	79
N	13	4	0	97	6	120
R	3	6	392	680	54	1132
RC	0	317	379	75	705	1476
Total Change	31	383	781	852	780	2827

Note: R = residential, C = commercial, RC = mix (residential–commercial), CR = mix (commercial–residential), D = demolished, N = new development.

Table 5 illustrates how space quantities changed at the parcel level from 2012 to 2015. For instance, in mixed residential–commercial spaces in 2012, no space quantity changed to commercial in 2015, and a 63,122 square-meter space changed to mixed commercial–residential. Similarly, a 91,569 square-meter space was demolished during the period from 2012 to 2015, a 40,496 square-meter space changed to residential, and a 903,525 square-meter space remained unchanged. Moreover, for mixed commercial–residential in 2012, no space quantity changes to residential 2015 were recorded, and a 25,604 square-meter space changed to mixed residential–commercial. Similarly, a space of 14,231 square meters was demolished during the period of 2012 to 2015, a space of 1223 square meters changed to commercial, and a space of 62,629 square meters remained unchanged. The total change in space quantity was recorded as 3,679,405 square meters.

Table 5. Total space quantity change from 2012 to 2015 in Jiang'an district by Parcel type.

	Total Space Quantity Change (m^2)					
2012/2015	**C**	**CR**	**D**	**R**	**RC**	**Total Change**
C	73,890	2006	0	0	2856	78,751
CR	1223	62,629	14,231	0	25,604	103,686
N	249,380	47,042	0	769,870	2431	1,068,723
R	45,352	53,058	135,051	848,800	247,270	1,329,531
RC	0	63,122	91,569	40,496	903,525	1,098,713
Total Change	369,844	227,857	240,851	1,659,167	1,181,686	3,679,405

Note: R = residential, C = commercial, RC= mix (residential–commercial), CR = mix (commercial–residential), D = demolished, N = new development.

Figure 12 illustrates that most mixed residential–commercial and mixed commercial–residential spaces increased by 451,688 square meters and 125,054 square meters from 2012 to 2015, respectively. From 2012 to 2015, these areas had high accessibility, especially in the middle of the Jiang'an District, an area along subway line 1. However, mixed residential and commercial have increased relatively by 1,244,687 square meters and 374,746 square meters in the study area, respectively. Moreover, accessibility to commercial land increased in 2015. This means that increased accessibility due to public transportation (e.g., subway or regular bus) promotes mixed residential–commercial and residential development, but has little effect on mixed commercial–residential and commercial space development. A preferred commercial location may be close to major roads, allowing for easier access to the goods used in commercial and mixed commercial–residential parcels to meet the demand of customers.

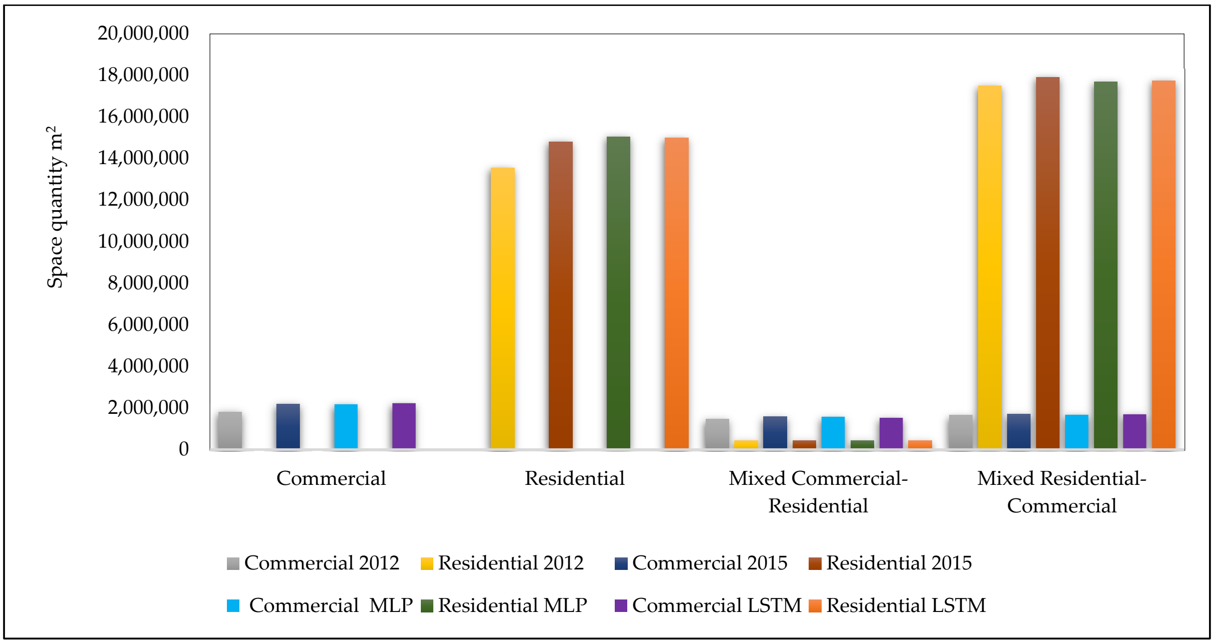


Figure 12. Comparison of the total space quantity change from 2012 to 2015 in Jiang'an district by Parcel type.

4.2. Parameter Settings and Model Training

There is a strong association between mixed land-use, accessibility, and space price. As mentioned earlier in Section 2.2, several factors, such as space prices and accessibility, influence mixed land-use density, the results show that high-accessibility areas tend to have high mixed-land and space prices, whereas low-accessibility areas have low mixed-land-use density and space prices [6,14,44,45]. Due to building, accessibility, and average space quantity data, DNNs can capture complex nonlinear relationships [48]. This paper uses deep neural networks (MLP, LSTM) to analyze the relationship between the mixed land-use pattern, which is the dependent variable, and accessibility and floor-space price as independent variables, with 871 parcels in the case study, utilizing Keras with Tensor Flow as the framework for building the network in Python. The input variables were used for training and testing the LSTM and MLP models. The input nodes and outputs of the parcel-level mixed land-use prediction model based on deep neural network nodes are shown in Table 6.

Table 6. Input and output data to the deep neural network model.

Input Variables for Training (70% of Data Samples)	Output Variables for Training	Input Variables for Testing (30% of Data Samples)	Output Variables for Testing
Average floor-space price from 2012 to 2015	Space quantity at parcel level 2015:	Average floor-space price from 2012 to 2015	Space quantity at parcel level 2015:
Maximum available space quantity Space quantity at parcel level 2012	Residential Commercial	Maximum available space quantity Space quantity at parcel level 2012	Residential Commercial
Accessibility from 2012 to 2015 by: residential, commercial, mixed residential–commercial	Residential–commercial Commercial–residential	Accessibility from 2012 to 2015 by: residential, commercial, mixed residential–commercial	Residential–commercial Commercial–residential

The MLP model comprises one input layer, two hidden layers for balancing simulation accuracy and speed, and a final output layer. The MLP and LSTM models were trained for 3000 epochs. The LSTM model consists of one input layer, two layers with a size of 100 each, two completely connected layers, and a final output layer. The remaining parameters are as follows: batch size: 16, learning rate: 0.001, input variables: 13, and hidden layer neurons: 128. ADAM optimization was used to enhance the prediction accuracy for the MLP and LSTM models comprised assessing missing data, imputing missing values, and investigating outliers and duplicated records.

4.3. Comparison of Forecasting Accuracy of MLP and LSTM Models

Table 7 shows the performance of the LSTM and MLP models during the training process. The models consider an effect between transportation supply and MLU at the parcel level during the training and forecasting process. The MLP model results in an average error of 1.80–1.82% for mixed use, and most of the 90th percentile errors are found to be lower than 5.68%; meanwhile, the LSTM model shows an average error of 1.20–1.22% for mixed use, and most of the 90th percentile errors were found to be lower than 2.68%. The MLP model results in an average error of 1.99–2.41% for single use, and most of the 90th percentile errors are found to be lower than 10.36%. Meanwhile, the LSTM model shows an average error of 1.40–1.62% for mixed use, and most of the 90th percentile errors are found to be lower than 3.78%.

Table 7. Comparison of the forecasting errors of MLP and LSTM (training).

Models	MLP Training Errors								LSTM Training Errors							
Error\Land Type	Single-Use Errors (%)		Mixed CR Errors (%)			Mixed RC Error (%)			Single-Use Errors (%)		Mixed CR Errors (%)			Mixed RC Error (%)		
	C	R	C	R	CR	C	R	RC	C	R	C	R	CR	C	R	RC
90th Percentile	10.36	7.02	3.31	2.37	5.68	2.13	3.32	5.45	3.78	3.68	1.38	1.15	2.53	1.08	1.60	2.68
80th Percentile	2.22	1.66	1.06	0.76	1.82	0.79	1.24	2.03	2.35	1.40	1.05	0.87	1.92	0.78	1.16	1.94
70th Percentile	0.75	0.99	0.74	0.53	1.27	0.52	0.81	1.33	0.70	0.96	0.71	0.51	1.22	0.57	0.74	1.31
50th Percentile	0.19	0.53	0.29	0.21	0.50	0.18	0.28	0.46	0.11	0.27	0.36	0.18	0.54	0.13	0.29	0.42
Average error	2.41	1.99	1.05	0.75	1.80	0.71	1.11	1.82	1.40	1.62	0.67	0.56	1.22	0.48	0.72	1.20

Note: R = residential, C = commercial, RC= mix (residential–commercial), CR = mix (commercial–residential).

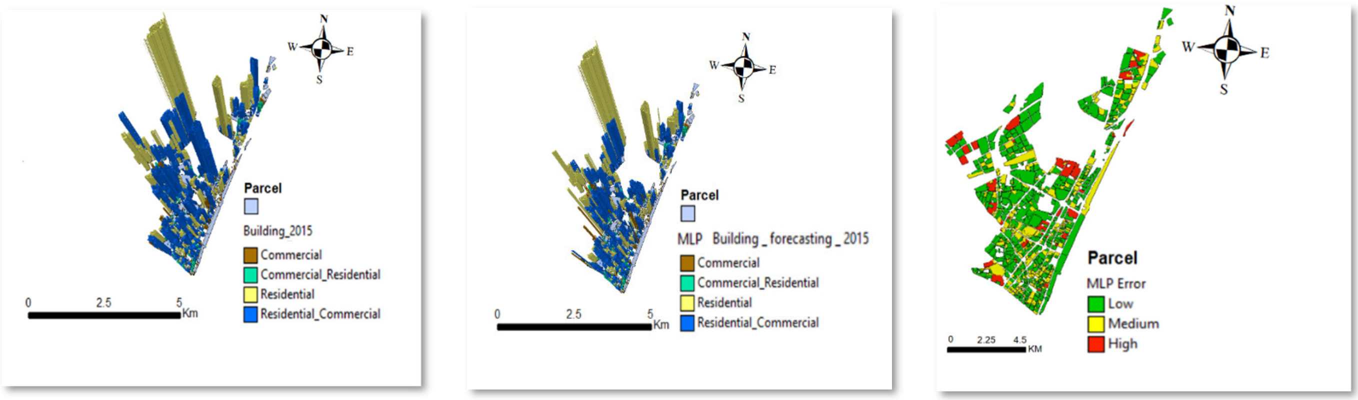
Table 8 presents the comparison results between the MLP and LSTM models. The MLP mixed CR model results in an average error of 7.36%, and the 90th percentile errors are found to be lower than 13.73%. Meanwhile, C in the MLP mixed CR model results in an average error of 4.53%, and the 90th percentile errors are found to be lower than 8.45%, while R in the MLP mixed CR model results in an average error of 2.83%, and the 90th percentile errors are found to be lower than 5.28%. The MLP mixed RC model results in an average error of 5.55% and the 90th percentile errors are found to be lower than 11.31%. Meanwhile, C in the MLP mixed RC model results in an average error of 3.21%, and the 90th percentile errors are found to be lower than 6.54%, while R in the MLP mixed RC model results in an average error of 2.34%, and the 90th percentile errors are found to be lower than 4.77%. The LSTM mixed CR model results in an average error of 4.28% and the 90th percentile errors are found to be lower than 10.46%. Meanwhile, C in the MLP mixed CR model results in an average error of 2.52%, and the 90th percentile errors are found to be lower than 6.16%, while R in the LSTM mixed CR model results in an average error of 1.76%, and the 90th percentile errors are found to be lower than 4.30%. The LSTM mixed RC model results in an average error of 3.62% and the 90th percentile errors are found to be lower than 9.17%. Meanwhile, C in the LSTM mixed RC model results in an average error of 1.59%, and 90th percentile errors are found to be lower than 4.03%, while R in the LSTM mixed RC model results in an average error of 2.03%, and the 90th percentile errors are found to be lower than 5.14%. These results indicate that the relationship between transportation supply and MLU is significant and, considering the accessibility factor, can also help to promote the accuracy of model predictions. The LSTM model has a lower error, indicating that it has a better capability for forecasting the dependency relationship between transportation supply and mixed land-use pattern than the MLP model.

Table 8. Comparison of forecasting errors of MLP and LSTM (testing).

Models	**MLP Testing Errors**								**LSTM Testing Errors**							
Error\Land Type	**Single Use Errors (%)**		**Mixed CR Errors (%)**			**Mixed RC Error (%)**			**Single Use Errors (%)**		**Mixed CR Errors (%)**			**Mixed RC Error (%)**		
	C	**R**	**C**	**R**	**CR**	**C**	**R**	**RC**	**C**	**R**	**C**	**R**	**CR**	**C**	**R**	**RC**
90th Percentile	20.17	10.00	8.45	5.28	13.73	6.54	4.77	11.31	16.58	9.43	6.16	4.30	10.46	4.03	5.14	9.17
80th Percentile	18.32	8.46	7.42	4.63	12.05	5.11	3.73	8.84	14.41	7.06	5.15	3.60	8.75	2.98	3.81	6.79
70th Percentile	16.44	6.79	5.85	3.65	9.51	4.33	3.16	7.49	12.25	5.31	3.85	2.69	6.54	2.30	2.94	5.24
50th Percentile	13.77	4.37	4.51	2.81	7.32	3.30	2.40	5.70	4.99	3.45	1.91	1.34	3.25	1.29	1.64	2.93
Average error	11.03	6.59	4.53	2.83	7.36	3.21	2.34	5.55	7.07	4.15	2.52	1.76	4.28	1.59	2.03	3.62

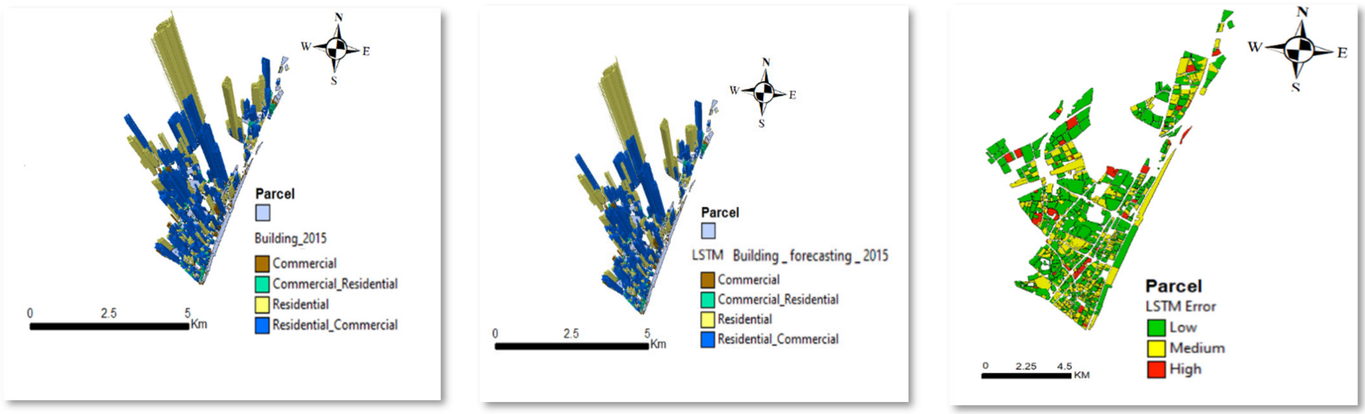
Note: R = residential, C = commercial, RC= mix (residential–commercial), CR = mix (commercial–residential).

Figure 13a shows the observed floor space and Figure 13b depicts the MLP-estimated floor space, while Figure 13c shows the MLP prediction errors. The value for the range of prediction errors indicates: low prediction errors (0.000~5.448), medium prediction errors (5.449~23.48), and high prediction errors (23.49~46.80). The findings reveal that the majority of parcels have low prediction errors across all space types (residential, commercial, and mixed-space types), whereas those showing a high error are usually large parcels with a low space quantity. Figure 14a depicts the observed floor space and Figure 14b shows the LSTM-estimated floor space, while Figure 14c shows the LSTM prediction errors. The value for the range of prediction errors indicates: low prediction errors (0.000~2.513), medium prediction errors (2.514~7.211), and high prediction errors (7.212~17.34). The results indicate that most of the parcels show low prediction errors for all space types (residential, commercial, and mixed-space types). The difference between the actual building type in 2015 with the MLP model prediction and the LSTM model prediction indicate that the LSTM model is more accurate at forecasting than MLP.



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

Figure 13. (**a**–**c**) The predicted results from the MLP model and the difference between the observed and predicted building quantities at the parcels level: (**a**) building type at parcel level 2015 (observed); (**b**) MLP model prediction; and (**c**) difference error between actual building types 2015 and MLP model prediction.



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

Figure 14. (**a**–**c**). The predicted results from the MLP and LSTM models and the difference error between the observed and predicted building quantities at the parcel level: (**a**) building type at parcel level 2015 (observed); (**b**) LSTM model prediction; and (**c**) difference error between actual building type 2015 and LSTM model prediction.

5. Conclusions

The objective of this study was to investigate the effects of transportation supply on mixed land-use. The study used deep neural network approaches such as LSTM and MLP models to evaluate the effect of transportation supply on mixed land-use at the parcel level. The study used 871 parcels of four MLU types in 2012 and 2015 in the Jiang'an District, Wuhan, China, as a case study.

According to the findings of this study, parcels with a high mixed accessibility usually have a high level of mixed land-use patterns, where the MLP and LSTM models result in an average error of 5.55–7.36% and 3.62–4.28%, respectively. Meanwhile, most of their 90^{th} percentile errors were less than 13.73% and 10.46% for the all-mixed land-use, respectively. These results indicated that the LSTM model performed better than the MLP model for all single and mixed land-use.

The study results showed that most parcels with mixed residential–commercial and residential land-use patterns changed significantly from the year 2012 to 2015 in areas that have high accessibility, such as in the south and center of the Jiang'an District, close to the city center and subway line 1. However, the mixed commercial–residential and commercial spaces remained relatively unchanged. Moreover, accessibility to commercial activities increased significantly in 2015 compared to 2012. This means that increased accessibility to public transit promotes mixed residential–commercial and residential land development, but has little effect on mixed commercial–residential and commercial land development. The MLP and LSTM models revealed that MLU is very sensitive to the supply of public transportation.

The proposed methods will allow accurate forecasting of a land-use pattern at the parcel level, even for parcels with few observations of a certain type, enabling policy analysis and simulations of development patterns across the city. Forecasting and corresponding simulations can assist decision-makers in better understanding various trade-offs that urban agents make when determining whether or not to take certain actions (e.g., whether to develop or not, what type of space, and how much to develop) within an urban real estate market. This study provides guidance and directions for a better understanding of the implications of transportation supply (especially that from public transportation) on MLU patterns. This paper studied the utility of the MLP and LSTM models in forecasting land-use patterns and using accessibility and average space-pricing as inputs. The models are found to produce accurate forecasts compared to those presented in the literature, and it is believed that they would be useful for simulating urban land-use patterns and for relevant policy analyses. The study has a few limitations that must be acknowledged:

1. The mixed land-use data for a series of years are not available for comparison, so a study of land-use changes versus those of transportation supply cannot be carried out. More data are required to develop a pricing model of mixed-space patterns and also to investigate how density, mixed land-use, and accessibility affect prices, since this study only focused on accessibility.
2. Future studies should consider additional data over a longer period in order to carry out the studies related to a "horizontal", neighborhood-wide mixed-space pattern versus a "vertical", within-building mixed-space use pattern.
3. Due to the differences in state planning policies between underdeveloped and developed countries. A cross-national study is needed to obtain meaningful results.
4. Based on the findings of this study, more advanced machine learning, ensembled approaches, and agent-based models, may be employed to improve the accuracy of forecasting different factors related to mixed land-use.

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Article

Planning Compact City in Rapidly Growing Cities—An Estimation of the Effects of New-Type Urbanization Planning in Hangzhou City

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Abstract: The Chinese New-type Urbanization (NTU) Plan indicated a major shift in planning towards compact development. This study developed an integrated framework to estimate the effectiveness of planning in promoting compact development in rapidly growing cities. We analyzed the coherence and conformance of planning, as well as the development outcome from a multi-dimensional perspective of compactness. Spatial data of both private and public development projects and big data of POI were employed for analysis in the case of Hangzhou. The findings indicate that land development efficiency and intensive urban functions at the local scale were significantly promoted after NTU planning's initiation. However, the planning was inefficient in leading a more centralized development at the city scale. This could be attributed to the inability of the planning to resolve conflicts between growth pressure and compact goals, which is reflected in the incoherent control between the master and local plans. The inefficiency is further underlined by the insufficient connection between city-wide and subject plans, as well as the permanent planning of the Urban Development Boundary without specific tools. Particularly, planning performed weaker in controlling public projects due to dual-track planning institution. These conclusions suggest the urgency of enacting a planning system that dynamically links plans of different scales and functions as a crucial element for implementing compact development in rapidly growing areas.

Keywords: new-type urbanization; planning effects; compact development; rapidly growing; Hangzhou

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1. Introduction

There is a growing interest in compact city planning as a promising vision to combat urban sprawl [1–4]. It has been suggested that a sustainable city is also a compact city [5]. The vision has been mainly formed by the idea of a densely developed core of European cities [6]. Even though there is no clear or generally accepted definitions of compact city, some aspects, such as concentrated, dense development with mix uses that intensify land efficiency and proximity of services, are commonly used dimensions to describe the "compact city" or "compact development" [7]. Compact development has been adopted as a guiding concept in the planning documents of various cities across the world. However, the practices of compact city planning were mostly implemented and discussed in the context of developed areas experiencing post-growth urban dispersion or even urban shrinking [8–11]. Nevertheless, the excessive supply of cheap suburban land and urban sprawl often increases fiscal stress in less-developed regions, which implies the need for efficient planning control in promoting compact development [12].

Chinese cities have undergone a high-speed urbanization since the economic reform in 1978. The evidence suggests that the national urbanization rate has risen from 17.9% in 1978 to 53.7% in 2013. This trend has brought conflicts in low-efficiency and consumptive land use, unreasonable urban structure and size, "urban diseases" such as transport congestion, environmental damages, and so forth in large cities. For instance, during 2000–2012, the urban built-up area has increased 76.4%, while at the same time the increase rate in urban population was 50.5%. Thus, in 2014, the Central Committee of the Communist Party of China (CPC) and the State Council of China jointly released the National New-type Urbanization Plan (NUP, 2014–2020). The plan indicated that China has entered the period of economic transition, which meant that the upgrade and facilitated modernization of the socialist country needs to transform from traditional extensive urbanization toward a new-type urbanization (NTU) focused on high quality development. As one prospect of the sustainable development, the compact city model is especially appealing. Therefore, one of the main targets of NTU is the promotion of compact and efficient urban growth characterized by intensive and mixed land use, as well as transit-oriented development.

The NTU has been frequently cited in official reports of local governments, and efforts have been made to apply the compact development strategy into plans. For example, in 2014, the Ministry of Housing and Construction and the Ministry of Land Resources jointly selected 14 cities to conduct the experimental planning of urban development boundary (UDB) to control excessive urban expansion. The implementation of NTU has drawn broad interest as an indication of the transformation of urban policies and planning in China [13]. However, the effects and outcomes of NTU planning are controversial. Although improvements were made in balancing urbanization at the national scale, the land-centered urbanization is still ongoing. Even some new development modes vigorously carried out by local governments under the title of NTU are actually land urbanization [14]. These new modes of NTU may unintentionally provide excuses for land expropriation, evidenced by uncurbed increment of land sale revenue. It is becoming clear that urban expansion is likely to continue regardless of NTU, which calls for profound planning reforms [15]. Deng revealed that NTU had a positive impact on the sustainability of land use, but the current level of land use efficiency in most cities is far behind NTU targets—evidenced by the frequent urban sprawl [16]. Moreover, the compactness of urban development and intensity of land use show an increasing trend from the aspects of investment density and economic output per land, but the coordination of development is basically unchanged [17]. Moreover, in general, land eco-efficiency has increased during the NTU period; however, the effects are distinctively different due to varied development strategies of NTU adopted by local cities [18]. This points to the necessity of rational investigation of the effects of NTU planning implemented at an intra-urban scale to reveal specific planning issues.

Even though a consensus has been reached that verifying planning outcomes can contribute to the accountability of public institutions and should guide improvements in plans and practices [19], little is known about whether NTU planning has achieved the spatial goals set in the NUP, such as compact development, and the evaluation of performance remains rather undetermined. Moreover, studies that attempted to preliminarily assess NUP outcomes were either qualitative descriptions of the progress and achievements of the plan from a general view of urbanization at the national/regional scale [14,15], or developed indicators to quantify NTU and its implementation [20,21]. For instance, Deng (2021) developed a system of proxy indices to incorporate NTU policies into a regression model, such as the proportion of urban population, construction land per capita, etc. [16] Even though conceiving the compact city in terms of a process rather than form holds more promise for sustainable development [1], the associations between the planning practice of compact development and spatial form is barely explored, and a theoretical framework to comprehensively estimate the effective of urban planning is almost absent.

This study aims to bridge this gap and provide evidence on the performance of NTU planning from the spatial dimension. The research questions are:

(1) How effective is the NTU planning in guiding and regulating development in rapidly growing areas?
(2) Does NTU achieve the objective of compact development? Or is the urban development under the NTU planning regulation more intensive and compact?

(3) What are the main obstacles in achieving compact development with NTU planning? How to improve the performance?

To address these questions, our study develops a framework for evaluating the effectiveness of NTU planning from the perspective of compact development. The focus is on the interaction of plans during the planning process that affects urban development forms. The results reveal critical issues in the implementation and performance of NTU planning and shed light on possible improvements to achieve the goal of compact development. Evaluating the effects of urban planning in promoting compact development in rapidly growing cities of emerging regions can provide hints for building an effective planning system that supports the sustainable urban development of such areas.

2. Theoretical Framework

It is widely accepted that spatial planning influences land use pattern and urban form. However, conceptualizing the role of planning in guiding urban development is quite challenging [22] and the evaluation of the effects of plans is rather ignored or overlooked [21]. Quantitative research that estimates the impacts of urban policies or planning on development is often performed with regression models that use urban planning or governance as a single indicator [23–26]. Another group of studies estimates potential effects of planning or land use policies by simulating urban development under different planning scenarios [27,28]. Nevertheless, this simplification of the planning factor can hardly explain the complex relationships during the implementation of planning nor can reveal critical issues that are insightful for political decisions. On the other side, much of the qualitative assessment of the effects of urban planning are usually historical narratives of developments and the role of urban planning in this process [29,30], which are relatively subjective in the evaluation criteria and sketchy in the assessment of planning outcomes.

There are two general directions of evaluation in planning: (1) plan evaluation that focuses on the plan's quality and its outcomes and (2) the evaluation of planning practices and processes. Accordingly, performance- and conformance-based approaches are the two main models of post-plan evaluation [31]. In general, there are two criteria for estimating the conformance of planning: (1) the degree to which outcomes on the ground conform to planning goals and (2) the extent to which implementation instruments support planning goals [32,33]. The conformance studies are often GIS-based comparisons of planned and actual urban development, where the goal is to identify discrepancy between the real and the planned land use [34–37]. Others focus on the effectiveness of a specific planning tool, such as green belts or growth boundary, by checking if the real development corresponds to the aims of planning policy [38,39]. Usually, a matching rate would be used to indicate this conformance [40]. Still, quantitative estimations are rare, especially for strategic and large-scaled plans. The focus is often on the process performance and plan utilization, i.e., if the planning concepts are influential in local programs and policy decisions [41], or by evaluating the partnership and coherence during the planning [42].

Although research on the planning practice and its impacts on urban development are equally necessary [39], only a small number of studies attempt to address both. The exceptions are Laurian et al. (2010), who used a triangulated approach to integrate the evaluation of plan coherence in the plan implementation and observe data-driven outcomes (known as plan-outcome-evaluation or POE methodology) [14], and Oliveira and Pinho (2009, 2010) that developed a Plan-Process-Results (PPR) approach to evaluate the implementation and outcomes of plans by using a checklist procedure [43,44]. Attributing outcomes to plans is difficult when external factors are considered. However, a "soft" comparison of outcomes and planning goals and logical reasoning to identify linkages could be conducted in such a case [45,46]. Associations between plans and outcomes or between intended goals and actual implementation also can be ascertained through methods using discriminating indicators [47], or tracking performance over time to establish the covariation of programs and outcomes [48]. In addition, Hersperger et al. (2018) stress that planning evaluation should make use of spatially explicit tools to assess whether land changes have occurred, as well as to determine their spatial distribution [22]. Therefore, combining a qualitative analysis of planning practice with a temporal comparison of explicit indicators of development outcomes could contribute to a detailed clarification of planning effects capable of revealing critical issues for political decision-making.

The planning system in China is theoretically hierarchical, but there have been cases where multiple plans interact with each other at different levels of the system [49]. Local plans that directly regulate development projects are drawn by three different departments—the Urban Planning Bureau, the Bureau of Land and Resources, and the Development and Reform Commission. The city's spatial plans—Master Plan (MP) and Detailed Control Plan (DCP)—are mainly prepared by the Urban Planning Bureau. Development permits are granted by the Urban Planning Bureau for both private and public developments. The Land and Resource Bureau is responsible for drafting Master Land Use Plans, the primary focus of which is to designate farmland conservation zones and to control the supply of land for construction. At the same time, five-year economic and social plans are made by the Development and Reform Commission to guide the entire development of the city.

At the end of 2013, a report of the Sixth Plenary Session of the 16th CPC municipal committee pointed out the need for a revision of Hangzhou city's plans to promote an urban system of a "compact city". Since then, "establishing the ideology of a compact city and smart growth" and "facilitating urban intensification based on urban renewal" have been frequently mentioned in the municipal government work reports and various action plans of Hangzhou. Under guidance of the municipal NTU strategies, a multi-level and diverse planning system of NTU was established (Figure 1). For the general plans, in the spatial MP, land use master plans, district plans, and DCP, a permitted/conditional building area is designated to control urban expansion. In the Hangzhou's MP of 2001–2020, which was revised in 2014, and in the district plans afterwards, urban renewal and designated urban redevelopment areas were highlighted to serve as a main focus for densifying.

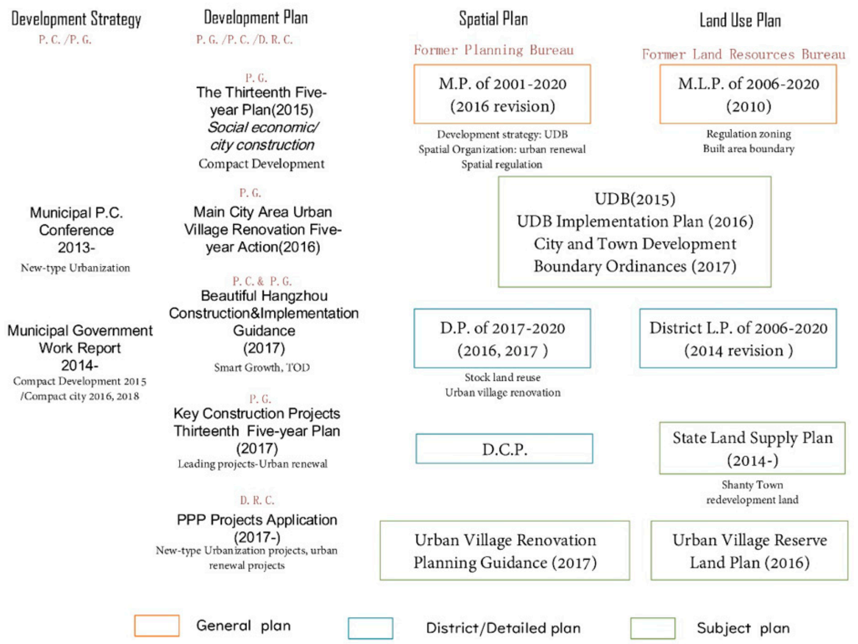


Figure 1. The NTU planning system in Hangzhou. (P.C.: Municipal CPC Party Committee; P.G.: Municipal people's government; D.R.C.: Development Reform Committee; M.P.: Master Plan; D.P.: District Plan; M.L.P.: Master Land use Plan; UDB: Urban Development Boundary; D.C.P.: Detailed Control Plan).

For the subject plans, Hangzhou announced an Urban Development Boundary (UDB) plan in 2015. The development boundary was drawn to protect existing green land and farmland conservation areas outlined in MPs and Land Use Plans. All development outside the boundary was strictly prohibited to contain extensive urban expansion, while urban intensification inside the boundary was intended to be promoted. On the other hand, Urban Village Renovation Guidance Plan and Urban Village Reserve Land Plan were compiled to promote planning of diverse service facilities for the functional intensification in renovation areas. Moreover, since 2014, the annual Land Plan largely increased the supply for shanty house area renewal and low-efficient stock land redevelopment, which provided resource support for urban redevelopment and land use densification. In sum, the control of urban expansion was mainly pursued through general plans and planning of UDB, while the intensification was promoted by subject plans for urban renewal.

This study developed a coherence–conformance-effects framework to comprehensively evaluate the effectiveness of NTU planning practice in Hangzhou city. The evaluation focused on the perspective of compact development. We first checked the vertical consistency between different levels of urban planning in the plan-implementation process, including relationships between the MP and district plans, the MP and subject plans, and the MP and DCPs, as well as the consistency between the Master Land Use Plan and District Land Use Plans. Further, we analyzed the horizontal coordination between plans of different functions, specifically, the coherence of planning goals and development regulations, the coordination of economic and social plans, and the rationality of Master Plans and Master Land Use Plans. Secondly, the conformance of planning was evaluated by comparing plans with actual development. At last, the effects of planning on compact urban development were estimated by quantitatively comparing the compactness of urban development before and after the implementation of NTU planning.

3. Materials and Methods

3.1. Study Area

Hangzhou is a regional central city on the Yangzi River Delta—the most economically strong area of China. As the capital of Zhejiang Province and a center for digital economy, Hangzhou underwent striking population growth and urban area expansion during the past decade. The city's population has reached 11.93 million in 2020, with a national top-level population increment index of 55.57% compared to 2010, while the increase rate of construction was 61.46% in the last decade. Thus, among Chinese cities undergoing dramatic growth in recent years, Hangzhou is the most outstanding one. Moreover, as discussed above, in 2014 Hangzhou was selected as an experimental city to conduct the UDB planning and the municipal government has consecutively set "compact city" as the main development target in social-economic plans, under the guidance of which a relatively mature NTU planning system has been constructed in the city.

The registered urban population of the city in 2020 was 5.68 million, while the city's urban built-up area was 666.18 km^2. In this study, we focused only on the main urban area of approximately 3334 km^2, where most of the population and urban development is clustered.

3.2. Plan Evaluation–Coherence and Conformance

Based on the theoretical framework, at first, a variety of plans implemented under the NTU were reviewed. The coherence of planning goals between different functional plans was analyzed by document scrutinizing. Development boundaries of the planning maps were digitalized in GIS so that the consistency of development regulations between plans could be verified.

In the land market of China, urban land is state-owned, while rural land is collectively owned by villagers. Only local governments have the right to transfer rural to urban land and lease that land to developers in case of profit-use projects or public projects designated on administratively allocated land (public facilities or public/resettlement houses). Thus, the second step was to obtain records of leased and administratively allocated land from www.Landchina.com (accessed on: 25 September 2022) for the analysis of the distribution of actual urban development. The dataset includes information on the project name, period of development, location, FAR, and function of the developed land. A total of 2620 development projects were recorded in the main urban area of Hangzhou between 2010 and 2020. Projects with industrial use are not included in this number because those projects are mostly clustered in the industrial zone and leased by negotiation. One thousand six hundred and seventy-seven of the total projects located in the main urban area were developed on leased land for profit (residential or commercial use), and another nine hundred and forty-three were developed on administratively allocated land by public institutions.

Subsequently, the comparison between distribution of development projects and planned areas was conducted via spatial overlay functions in GIS to estimate the conformance of developments to urban planning.

3.3. Measurement of Compact Development

As one prospect of sustainable development, the compact city is especially appealing for urban planning under NTU. Based on previous research, generally accepted characteristics of the compact urban form could be found in the contained urban expansion, higher density or intensive development, mix land use, and so forth [7]. While previous studies often used statistical parameters such as population density, built-up density, etc., for assessing compactness [50], this study primarily focused on indicators that reflect development patterns and practical urban function. Thus, by combining the general understanding of compact development and the explanation of compact development in the NUP—intensive development and efficient land use—in this study, we developed multi-scale indicators to estimate the compactness of developments.

1. Centralization

The original vision of compact city was a contained city with clear boundary between urban and rural areas [6]. Thus, the concentration of developments inside the urban area, especially the agglomeration in the central urban area, is widely accepted as the main feature of a compact city. Thus, the centralization in this study was estimated based on whether the development project was carried out in the central urban area designated by the MP, including sub centers. If that was true, the value for that development would be 1; otherwise, it would be 0.

2. Land efficiency

Density is the most common interpretation of a compact city [51]. Median-high density of built form could be achieved by efficient land use, where land parcels are densely occupied by buildings rather than partially built or left idle. Thus, efficient land use is one of the important indicators to measure compact development pattern. The land efficiency in this study was estimated according to the renewal aspect of the project in three levels: if the project was a redevelopment carried out on low-efficient urban stock land (urban vacant land, previously urban construction land, urban villages, etc.), the indicator value obtained would be 2; if the project was carried out in a rural village, the value would be 1; and if the project was carried out on natural or farmland, the value would be 0. To this end, the land use condition before the development was checked through historical satellite images with Google Earth Pro.

3. Functional intensity

The compact city is also envisioned as a vibrant city that provides a diversity of facilities [7,52]. In the compact city, transit needs would be largely reduced by allocation of plentiful services nearby housing. This means that the compact city is not only physically intensified by density of built, but also functionally intensified by varied and sufficient service facilities of good accessibility. Thus, functional intensity could be more representative of a compact city. In this study, the intensity of urban function was investigated through the density and diversity of service facilities in the local area.

Facility Density (FDE) was measured as the number of total facilities per area in Equation (1), while the Facility Diversity (*FDI*) was measured by the Shannon–Weiner index in Equation (2):

$$\text{FDE} = \frac{f_m}{A} \tag{1}$$

$$FDI_j = -\sum_{i=1}^{m} \left(\frac{f_i}{f_m} \times \ln \frac{f_i}{f_m}\right) \tag{2}$$

where f_i stands for the number of facilities of type i (car service, financial service, restaurants, shops and markets, medical service, daily service, culture and educations, sports and entertainments, toilets and newsstand) and f_m is the total number of facilities of total m types. A stands for the area of the study zone. Big data of Points of interest (POI) from Amap navigation were used for counting service facilities.

Finally, a one-way analysis of variation (ANOVA) was employed to investigate the variations of compactness of urban development in different planning periods to identify if the NTU planning promoted more compact development. The time span of the data is from 2010 to 2020. According to the planning transformation of Hangzhou and considering the time-lag of planning effects, we divided the observations into three periods for comparison: prior NTU period (2010–2013), transit period (2014–2016) during which most of the NTU plans were initiated, and NTU period (2017–2020). The research design is shown in Figure 2.

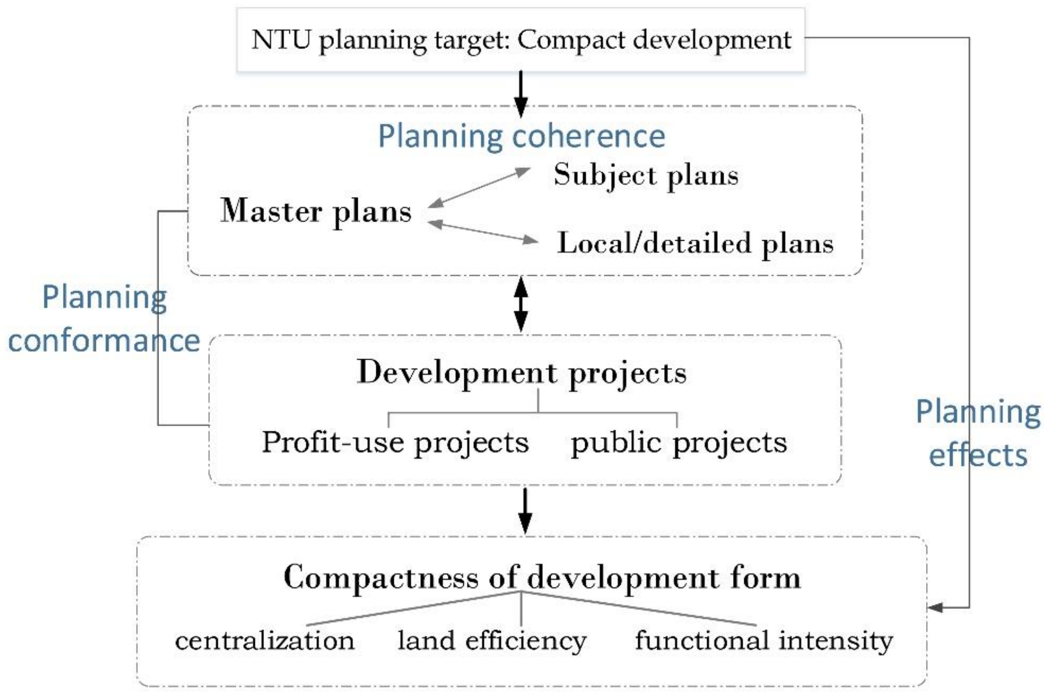
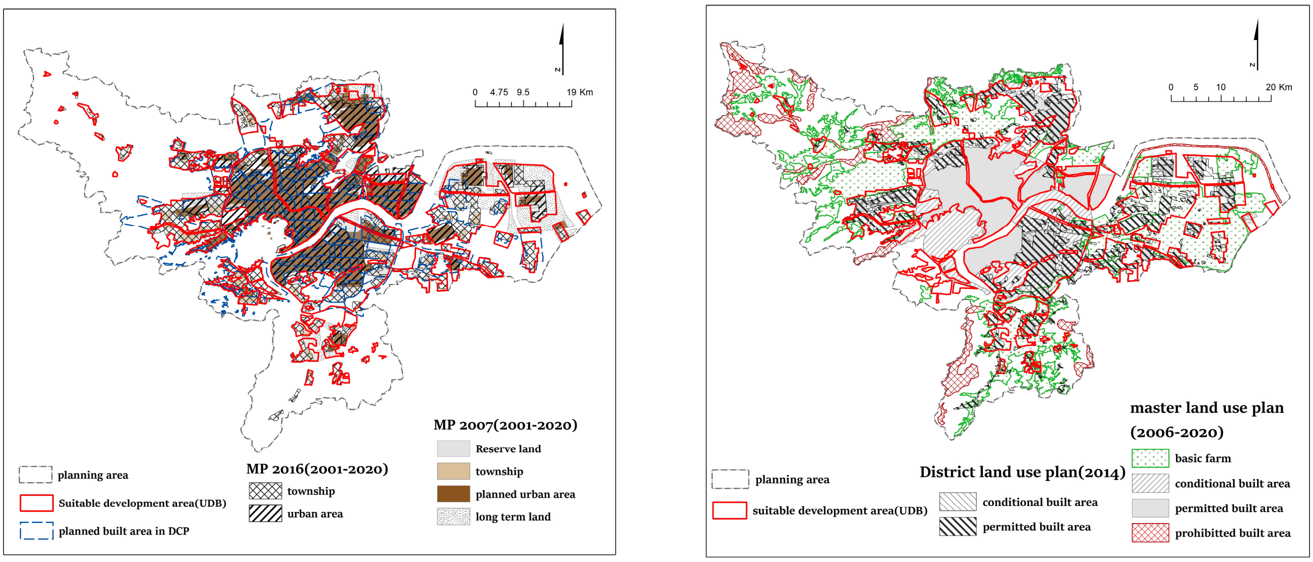


Figure 2. Research design.

4. Results

4.1. Coherence of Planning

Figure 3 reveals planned areas in the 2007 and 2016 MPs, the UDB (2015) and planned development area in the DCP. The planned urban area was just slightly expanded in the 2016 MP compared to 2007. However, the planned township area was significantly enlarged to accommodate outward development. Most of the planned area of the DCP was contained in the UDB, yet the planned area of several new DCP was beyond the city-level planning boundaries. Meanwhile, parts of the township in the MP were not covered by the DCP (Figure 3a). Considering land use plans, we found that permitted and conditional development areas of the original Master Land Use Plan were significantly enlarged in the revised District Land Use Plans (2014) of the two peripheral districts, even encroaching onthe planned basic farmland (Figure 3b). Therefore, the vertical coherence of NTU's planning control was insufficient since control lines were constantly expanded and the target of compact development was overlooked.



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

Figure 3. (**a**) The spatial plans of Hangzhou; (**b**) the land use plans of Hangzhou.

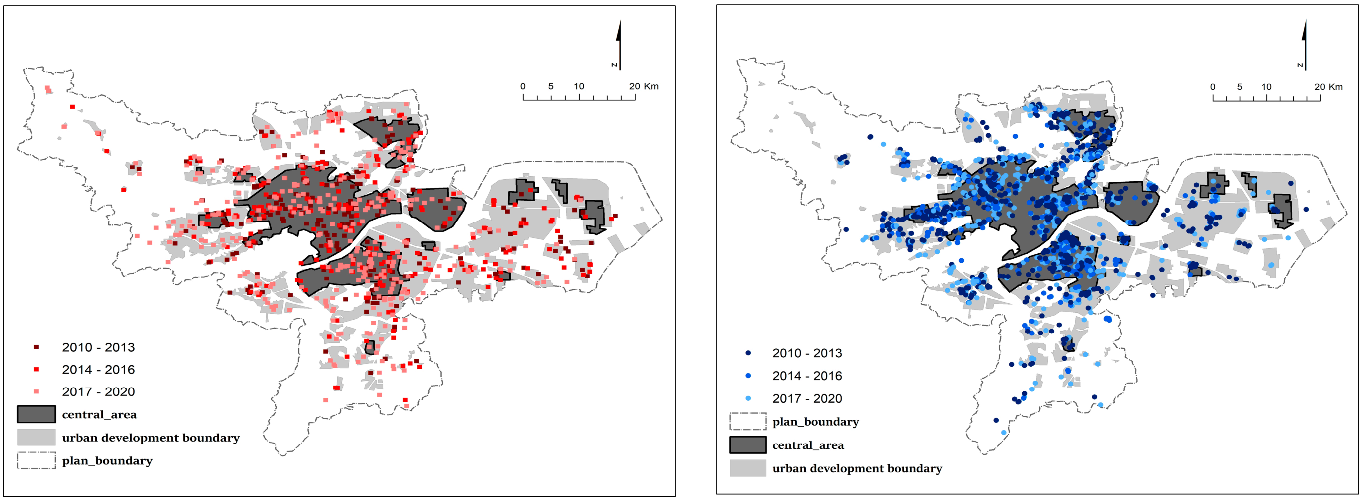
4.2. Planning Conformance

The distribution of development projects for profit are shown in Figure 4a and public projects in Figure 4b. Only half of the projects (53.50%) developed before the implementation of the revised MP of 2001–2020 occupied leased land contained in the planned urban area (Table 1). This inconformity was largely alleviated during the implementation period of the revised MP (2016–2020). It can be observed that projects carried out in the planned township area increased significantly. Furthermore, the predominant part of the profit-use projects was confined by the UDB (92.61%), while the matching rate was lower for the control of DCP. This might be due to the piecemeal and slower progress of enforcing the DCP. In terms of conformance with land use plans, it was revealed that a total of 30.47% of the profit use projects were outside the area of the Master Land Use Plan of 2010. However, in the revised District Land Use Plans of 2014 the conformance rate increased to 94.95%. It seems that the NTU planning was effective in development control. However, it is because these new or revised plans generally expanded planning boundaries that deviated from compact development goals. For example, 150 profit-use projects were carried out on land planned as basic farmland in the MLUP. One hundred and seven of these projects were later included in the revised DLUPs. Notably, public-use projects initiated by local governments are more likely to deviate from the urban planning than profit-use projects (Table 2).

4.3. Compactness of Urban Development

4.3.1. Centralization

The variation of centralization of developments in different planning periods is illustrated in Table 3. The test results of ANOVA demonstrated that the centralization of profit-use projects was not improved during the transition and NTU periods. Moreover, for the public projects, even a trend of decentralization was observed in the significantly higher mean value of centralization in prior-NTU period compared to the transition and NTU periods. The variation of centralization between transition and NTU periods was not significant.



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

Figure 4. The distribution of development projects of Hangzhou (2010–2020) (**a**) Profit-use projects; (**b**) public projects.

Table 1. Conformance between the urban planning and projects on leased land.

		Planned		**Unplanned**
	urban area	township area	Reserved and long-term area	Outside the planned area
MP 2007 (2010–2015)	534 53.50%	69 6.91%	140 14.03%	255 25.51%
MP 2016 (2016–2020)	403 59.35%	231 34.02%		45 6.63%
UDB		Suitable development area 1553 92.61%		Outside the boundary 124 7.39%
DCP		planned area 1409 84.02%		Outside the planned area 268 15.98%
Master Land-use plan (2010–2020)	Permitted building area 754 44.96%	Conditional building area 412 24.57%	Basic farm 150 8.94%	Outside the planned area 361 21.53%
District Land-use plans (2014–2020)	Permitted building area 409 79.42%	Conditional building area 80 15.53%		unplanned 26 5.05%

4.3.2. Land Efficiency

Table 4 reports the variation of land efficiency of the development projects in different planning periods. The land efficiency of profit-use projects was significantly strengthened in the NTU period compared to the prior-NTU and transition periods, while the variation of land efficiency was not significant between prior-NTU and transition period. Thus, more projects were allocated to former low-efficient land than to the green sites under the NTU planning. A similar trend could also be observed for the public projects, which indicates the densifying of the land development is developing.

Table 2. Conformance between the urban planning and projects on administratively allocated land.

	Planned			Unplanned	
	urban area	township area	Reserved and long-term area	Outside the planned area	
MP 2007 (2010–2015)	232 50.43%	32 6.96%	59 12.83%	137 29.78%	
MP 2016 (2016–2020)	192 39.75%	148 30.64%		143 29.61%	
UDB	Suitable development area 790 83.78%			Outside the boundary 153 16.22%	
DCP	Planned area 720 76.35%			outside 223 23.65%	
Master Land-use plan (2010–2020)	Permitted building area 392 41.57%	Conditional building area 206 21.85%	Basic farm 164 17.39%	Prohibited building area 2 0.21%	Outside the planned area 179 18.98%
District Land-use plans (2014–2020)	Permitted building area 277 61.56%		Conditional building area 49 19.89%	unplanned 124 27.56%	

Table 3. Multiple comparisons of centralization of development projects between different periods.

	Profit-Use Projects			Public Projects		
	Prior-NTU Period	**Transit Period**	**NTU Period**	**Prior NTU Period**	**Transit Period**	**NTU Period**
	2010–2013	2014–2016	2017–2020	2010–2013	2014–2016	2017–2020
Obs.	743	368	566	298	263	381
mean	0.561	0.576	0.553	0.5302	0.422	0.407
2010–2013 [1]		−0.0149	0.0082		0.108 *	0.123 *
2014–2016			0.0231			0.0152
ANOVA [2]		0.242			5.715 **	
homogeneity test of variance [3]		0.955			3.820 *	

[1]: ** Robust multiple comparisons (Tamhane's T2) significance level at at 0.05 or less and * for significance level at 0.1 or less; [2]: Robust test of equality of means if it is a heterogeneity of variance (Welch); [3]: Levene Statistic.

4.3.3. Functional Intensity

In this section, we analyzed the variations of functional intensity between 2015 and 2020—the POI data before 2014 was insufficient due to technology deficiencies. We focused on the 500- and 800-m buffer area of redevelopment projects that were completed or under implementation during 2015–2020 and were designated the major area in the Urban Village Renovation Planning Guidance. The objective was to estimate if the urban renewal contributed to the improvement of functional intensity of neighborhoods during the NTU period.

Table 4. Multiple comparisons of land efficiency between different periods.

	Profit-Use Projects			Public Projects		
	Prior NTU Period	Transit Period	After NTU Period	Prior NTU Period	Transit Period	After NTU Period
	2010–2013	2014–2016	2017–2020	2010–2013	2014–2016	2017–2020
Obs.	743	368	566	298	263	381
mean	0.607	0.715	0.910	0.789	0.734	0.961
2010–2013 [1]		−0.108	−0.303 *		0.055	−0.172 *
2014–2016			−0.195 *			−0.227 *
ANOVA [2]		18.711 ***			11.103 ***	
homogeneity test of variance [3]		24.742 ***			16.359 ***	

[1]: *** Robust Multiple comparisons (Tamhane's T2) significance level at 0.01 or less, and * for significance level at 0.1 or less; [2]: Robust test of equality of means if it is a heterogeneity of variance (Welch); [3]: Levene Statistic.

The results of the FDE variation test between 2015 and 2020 showed that the density of facility in 500 buffer area of renovation projects decreased, but FDE increased in the 800 m buffer. However, in general, the increment or decrement were not significant, which indicates that the promotion effects of renovation projects in functional density were weak.

Nevertheless, the diversity of service facilities (FDI) was increased significantly in both buffer areas during the same period (Table 5). The result indicates that the functional diversity and mixed use in and around renovation projects were promoted by the subject plans of urban renewal. This is probably due to the focus of renovation planning guidance on the supply of sufficient facilities for the residents living in these local areas.

Table 5. Variation of functional intensity of surrounding areas of main urban village renovations between 2015 and 2020.

		500 m Buffer Area		800 m Buffer Area	
		2015	2020	2015	2020
FDE	Obs.	58	58	58	58
	Mean (N/km^2)	575.950	563.519	518.039	542.431
	anova [1]	0.016		0.093	
	homogeneity test of variance [2]	0.498		1.866	
FDI	Obs.	58	58	58	58
	mean	1.554	1.669	1.643	1.752
	anova [1]	5.840 **		10.919 **	
	homogeneity test of variance [2]	0.007		3.049 *	

[1]: Robust test of equality of means if it is a heterogeneity of variance (Welch), ** for significance level at 0.05 or less and * for significance level at 0.1 or less; [2]: Levene Statistic.

The results demonstrate that the urban renewal did not trigger more dense investment into surrounding areas, but the living convenience was improved due to more balanced distribution of services and strengthened mix-use urban functions. There are two probable reasons for this fact: (1) from the results of centralization analysis, we now know that more concentrated and denser developments were not promoted at the city scale as a consequence of under-performance of general plans; and (2) the absence of interaction between the subject plans and city-wide plans also did not promote densification. For example, a major area designated in the Urban Village Renovation Planning Guidance was not incorporated as a target area in any master plan or district plan. The DCPs also did not prioritize planning conditions for these areas.

5. Discussion

The NTU planning targets in Hangzhou were generally coordinated and centered on municipal strategies of compact development. The main undertakings were intensive developments based on reuse of low-efficient stock land, urban renewal, as well as strict control of urban expansions. However, it was found that regulations of different plans are not consistent since planning boundaries were still subject to constant enlargements. The culture of frequent plan revisions to cope with rising development demands, noticed broadly in the literature of Chinese urban planning, seems to persist in the NTU planning period. For a rapidly growing city such as Hangzhou, the competition for inward migration and mega-projects is overwhelming. The planning seems caught in the dilemma to accommodate a great amount of new development while keeping planning control goals set by the NTU.

A considerable amount of development is still outside the original plans; however, plans after the NTU performed better in planning conformance. The interesting finding is that public projects initiated by local governments were more likely to breach planning boundaries. This points to the deficiency of planning institutions, where the dual-track planning permission system requires projects on administratively allocated land to be first reviewed by a development committee in charge of social-economic development and afterwards a planning permit is issued. In this sense, spatial plans only serve economic plans—a legacy of the former planned economy. Thus, the need to strengthen the coordination between economic and spatial planning is implied. However, the current focus is more on coordination between the spatial plan and the land use plan. Therefore, the low conformance of NTU planning is mainly the consequence of incoherent planning.

From the aspects of development outcomes, we found no clear evidence to indicate that development was transitioning to be more concentrated during the NTU period. Public developments even presented a decentralized pattern. The lack of planning conformance has led to a less centralized form. Many of the public projects were schools, resettlement houses, and community centers for rural villagers whose land was expropriated. This indicates that cheaper rural outskirts are rapidly trending towards urban development since public projects are triggers for private investments. NTU plans should not only focus on the control of development boundaries but find appropriate policies to drag inward development and promote more concentrated urban form inside the planning area. We draw a parallel with the compact city policies of Melbourne 2030, where the lack of specific mechanism to direct development into the targeted activity center was criticized as a key reason for its failure [53].

On the other side, land efficiency was improved in the NTU period for both profit and public projects. This shows that the implementation of subject plans for land consolidation and urban redevelopments was efficient. The improvement of functional diversity is likely a direct outcome of urban village renovation plans with detailed designs. The fact that denser function was not gained further signifies the failure of plans in promoting centralized development at a broader scale. This is probably since renewal plans are not linked with general plans. For instance, the floor area ratio or development intensity for these renewal areas are not designated with higher priority in MPs or DCP, nor incentives are provided.

Finally, the effects of NTU planning in promoting compact development in Hangzhou are fragmented. The NTU planning is generally effective in improving land efficiency and intensifying urban functions at the local area. Yet, NTU planning is still weak in promoting concentrated urban development at the city scale. From the streamlined analysis of relationships between the coherence, conformance, and effects of planning, we claim that the reason behind this ineffectiveness could be found initially in the inconsistent planning controls under pressure for rapid development. Secondly, there is a general lack of coordination between the economic and planning departments. Thirdly, subject plans are usually developed apart from city-wide plans and are not incorporated into general plans later. Thus, the effect of compacting is limited to local areas.

In addition, Urban Growth Boundary (UGB) or Green Belt is a common planning tool for growth management. However, as revealed by Siedentop et al. (2016) [39], UGB may be efficient in preserving open space, but its effects are limited in urban structure due to low degree of compactness. This conclusion is confirmed in Hangzhou. The concept of China's UDB was always viewed as a static control line, which does not differ much from the traditional planning lines with a single physical function. The permanent drawing of a large-scale UDB in Hangzhou seems to have resulted in a fragmented or leapfrog development inside the boundary, similarly as the UGB resulted in a patchwork development of Tokyo´s suburbs [54]. Instead, a timely and sequential revision of the UDB seems necessary to achieve more compact development. As argued by Boyle and Mohamed (2007) [55], growth management of strong power is constituted by mandatory comprehensive planning and an auxiliary policy. More innovative planning tools, such as fiscal incentives and FAR bonuses, public-private cooperation for projects carried out in target areas, as well as development fees on projects in peripheral dispersed areas, could be options to assist the UDB.

6. Conclusions

New-type Urbanization has been the central development strategy in China since 2014. Compact development was stated as one of the principal goals of NTU. The research question tackled in this study is whether the NTU planning of China was effective in promoting compact development in rapidly growing cities and what might be critical problems in this planning system. An analysis framework was developed by integrating an estimation of coherence of planning, conformance of planning with development outcomes, and actual development forms. Multi-dimensional indicators of compact development—centralization, land development efficiency and functional intensity were employed for evaluating the 'compactness' in the case of Hangzhou.

We concluded that urban functional diversity and land development efficiency at the local scale were indeed promoted during the NTU planning period. This could be attributed to the well-implemented subject plans for urban renewal. However, the urban planning is still weak in directing more concentrated and dense urban development form at the city scale. The reasons for this underperformance could be found in insufficient coherence between plans from different levels—seen in the enlargements of the master plan's urban area in district plans and DCPs—the inadequate coordination between economic and spatial plans reflected in the low conformance of public projects to the planed area, the patchwork of plans, and the absence of planning tools to support the UDB.

The compact development still faces great challenges, especially in rapidly growing cities. The competition for investments creates a dilemma between accommodating a great amount of new development while keeping the compact development goals. Central planning mainly targets expansion control and balanced development, while local governments pay more attention to economic growth based on urban land exploitation. Consensus between central and local states should be reached before seeking an efficient development mode. On the other hand, the function of planning in development guidance and regulation should be strengthened. This stresses the importance of a coordinated planning system that dynamically links different plans and different departments to achieve the desired goal of compact development. For example, the Ministry of Natural Resources of China was established in 2018 to uniformly exercise all responsibilities of land use and spatial planning, and to promote the multiple-plan integration. This program's effects in planning coordination could be measured in further studies. Moreover, public participation in the planning and bottom-up plan-making based on coordinating demands from different stakeholders may improve the coherence of planning.

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Land-Use Change Dynamics of Agricultural Land within Belgrade–Novi Sad Highway Corridor: A Spatial Planning Perspective

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Abstract: At the global level, there is an awareness of the need to protect agricultural land from permanent physical loss through land-use change. Preservation of high-quality agricultural land is currently at the center of the international debates, including those of food safety. The main aim of this paper is to provide quantitative analysis of agricultural land-use change dynamics within the area of the Belgrade–Novi Sad highway corridor, as a distinct route that connects two largest cities in Serbia. The results in land-use change and the accompanying contextual aspects are observed between 1990 and 2018, i.e., within the four research periods: 1990–2000, 2000–2006, 2006–2012 and 2012–2018, using GIS-based analysis. The research methodology used Corine Land Cover and Urban Atlas data and revealed dynamics relating to the most influential land take directions during the ca. 30 years by the means of the land take indicator. The results were complemented with the qualitative content analysis of spatial and regulatory urban plans for the study area, as one of the land-use management instruments in Serbia. The findings indicate that the most intense agricultural land-use change to non-agricultural land occurred in the period 1990-2000 due to various drivers (vicinity of large cities, illegal construction, developed transport infrastructure), but also distinguish the role of spatial and urban planning documentation in promoting the new land take.

Keywords: land-use change; land take; agricultural land; GIS; spatial and urban planning

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1. Introduction

Agricultural land is subjected to high pressure regarding the change to competing land uses due to urbanization. The link between agricultural land loss and urban sprawl is discussed in studies [1,2] highlighting the issues related to agricultural land fragmentation effects on landscape [3,4], and especially harm to agricultural productivity [5]. Current global turbulences influencing the degradation of socioeconomic conditions highlight the importance of food security and increasing food prices [6,7]. In those circumstances, land-use change in urbanization processes is considered a consequence of various drivers: government policies, economic conditions, demography, cultural setting, technology or availability of infrastructure, (in)effectiveness of the local land-use management instruments, as well as natural factors [8,9]. In that sense, the transportation network is considered one of the basic frameworks for directing urban development, while its spatial structure affects the formation and development of the urban areas [10].

Urban sprawl represents one of the most prevailing forms of land-use change in Europe [11]. The territorial dimension of urban sprawl can be manifested in a form of dispersed development of settlements in the peri-urban areas [12], as well as the physical pattern of low-density unplanned expansion of large urban areas mainly into the surrounding agricultural areas [13]. The impacts of urban sprawl across Europe are often quantified by systematic monitoring [14] of land take or soil sealing indicators [15]. Land take (hereafter LT) is the process of transforming agricultural, forest and other semi-natural and natural land to construction land and other artificial land use [13]. This process often implies an increase of settlement area over time at the expense of rural areas [16], and it is manifested as an increase in artificial surfaces [17]. Nevertheless, LT does not always coincide with urban sprawl, since it can occur outside of urban or peri-urban areas [9]. Soil sealing is essentially an irreversible process and the most intense form of LT, with permanent increase in Europe since 2006 [16]. Besides the aforementioned urban sprawl and LT approaches, recent studies focus on diverse modes of urbanization and their impacts on sustainability in a broader way [18]. Across Europe, the "no net land take" concept gained attention in spatial planning and land-use management to stop the process of land take by 2050 [19]. It aims to prevent construction and soil sealing on agricultural land, forestry and other natural areas, whereas any new LT will need to be recompensed by the reclamation of artificial land [20]. It should be noted that LT has progressed faster than the EU population growth [16], whilst the overall annual loss of undeveloped land in the period 2012–2018 is more than tenfold larger than the scope of the recultivated area [20]. Globally, there is a more determined approach to reduce LT by 2030 by accomplishing Sustainable Development Goals (SDG) [21]. SDG target 11.3 presents dynamics in LT per person, aiming to accomplish a rate of increase in built-up land, i.e., LT/land consumption that does not exceed the rate of population growth [21]. The LT indicator shows disproportionately high rates of land-use change in relation to urban development and population dynamics at the global level [22]. So far, SDG indicator 11.3.1 and the EU indicator of LT are nominally seen as most suitable for ex post assessments of land-use change and for post hoc evaluations of planning policies and policy interventions [23].

There is a widely accepted notion that land-use planning represents a key tool to protect agricultural land and to limit urban sprawl and LT [24]. At the same time, land-use planning is "sufficiently comprehensive, binding and restrictive" to contribute to a reduction of LT [9], p. 349. Still, there are studies that recognize land-use policies and spatial planning as a fundamental driving factor for a variety of land-use change processes [8], p. 32.

The Context and Factors of Agricultural Land-Use Change in Serbia

In the local planning context of Serbia, the instrument of land-use change in plans and programs of their implementation can enable LT, as further elaborated. Previous studies verified a significant role of spatial and urban planning in affirmation of land-use change processes [25,26]. According to a recent comprehensive quantitative study [25], a predominantly negative index of agricultural land-use change in the analyzed planning documents of municipalities in Serbia is a consequence of the planned expansion of the construction area for the needs of infrastructure corridors and industrial and commercial units, but also the intensive enlargement of certain urban settlements in peri-urban areas. Moreover, the newest Spatial Plan of the Republic of Serbia (hereafter SPRS), a strategic document for spatial development at the national level, recognizes that urban plans may contribute to the excessive expansion of urban settlements by unrealistic consideration of future needs for construction land. Some of the identified plans give preference to "greenfield" instead of the development/reactivation of "brownfield" sites [27].

The Law on Agricultural Land, as a sui generis, defines agricultural land as a resource of public interest for the Republic of Serbia, which is used for agricultural production [28]. The protection of agricultural land as a basic natural resource for food production, along with controlling land-use change, is a priority outlined in all national strategic documents (cf. [29]). The Strategy for Agriculture and Rural Development of the Republic of Serbia 2014–2024 advocates for a higher degree of agricultural land-use, more efficient use of poor quality or non-arable agricultural land and controlled agricultural land-use change [29]. As a main planning document at the national level that determines a long-term basis for organization, development, use and protection of space, and that gives guidelines for plans at the lower hierarchic level (spatial and urban plans), the Spatial Plan of the Republic of Serbia (SPRS) proclaims the sustainable use and protection of natural resources as one of the main goals for the planning and development of settlements. Starting from the first SPRS (1996) and the following one (2010), one of the priority goals regarding land was the mandatory protection of agricultural land and the preservation of its quality and natural fertility for food production. Some of the main threats in this regard relate to the expansion of settlements and greenfield investments, etc. Hence, the draft of the newest SPRS [27] encourages the use of existing construction funds for new developments instead of greenfield and brownfield investments.

The current Law on Planning and Construction prescribes special procedures in cases where the planning document changes the land use from agricultural land to construction land. In that case, agricultural land can be used for agricultural production until the new land use is formally designated [30]. In cases of planned change from agricultural to other land uses—i.e., for urban and industrial purposes determined by spatial and urban plans—current legislation in the Republic of Serbia prescribes the conditionality of the planning procedure and an approval from the side of the competent ministry in the field of environmental protection. At the same time, the change of agricultural land use and its conversion into other land uses causes significant pressures on land and other elements of the environment.

The area coverage of agricultural land in Serbia has annually decreased in the last three decades. In the period 1990–2012, 11,367 ha of agricultural land in Serbia changed its designated land use into the artificial areas, while the most extreme changes occurred in the period of 2006–2012 with reduction of 4391 ha [31]. Dabović et al. [32] stress that political, institutional and economic drivers were some of the key factors for urban sprawl in Serbia between 1990 and 2000 and emphasize the role of urban and regional land-use planning in enabling urban development. Relying on previous long-term and stable tendencies in the growth of area coverage of artificial land, artificial land cover is expected to continue at the expense of agricultural land ([33], p.49). Massive illegal construction on agricultural land is considered a dominant form of urban sprawl since the late 1980s and a cause for the dramatic decrease in area coverage of agricultural land [34]. The initial stages of illegal construction followed the social and political context of the 1990s, which included the wave of immigration of escaped and exiled population from the former Yugoslav republics of Croatia and Bosnia to Serbia after the dismantling of the former common country. Agricultural land was occupied mainly for the construction of new settlements to satisfy the housing need of the force-displaced inhabitants, while the municipalities were not prepared to adapt urban plans to the sudden influx of population.

The metropolitan area of Belgrade and Novi Sad (hereafter the Belgrade–Novi Sad metropolitan area) has traditionally been a significant potential for development based on its high functional and demographic capacity, excellent transport connection and solid infrastructure boundaries [35], with the capacity to become the hub of the metropolitan region in this part of Europe [35]. The main features of the local urban economy in this area are the polarization of territorial development in the zones of construction land and corridors, concentration of economic activities with about 66% of GDP, employment and business assets, etc. [36]. Previous research has already recognized the Belgrade–Novi Sad metropolitan area and its surroundings as an area that may require large-scale land-use change of agricultural land [37] due to significant residential pressure on the suburbs and agricultural land in peri-urban area, especially in the belt of the highways [38], i.e., peripheral urban and suburban settlements along the transit corridors. Consequently, the agricultural land in the settlements along the main transport corridors in Serbia is highly attractive for investors/developers and, therefore, is often subjected to land-use change, thus enabling LT in order to increase their economic value.

This research focuses on the spatial aspects of agricultural land-use change within the highway corridor belonging to the Belgrade–Novi Sad metropolitan area using GIS-based spatial analysis for quantification of changes. The main objective of the research is to identify the ongoing land-use change dynamics within the study area using the satellite remote sensing data (Corine Land Cover) and assess changes from the spatial planning perspective within the time frame of 1990 to 2018. The following section describes the study area in more detail, as well as the materials and methods used to achieve the main research objective. It goes on to discuss the research results, as well as to indicate some of the most prominent conclusions and open fields for further research.

2. Materials and Methods

2.1. Study Area

Belgrade is the capital, administrative center and largest city in Serbia, while Novi Sad is the second largest city and an important macroregional urban center. Currently, the Belgrade–Novi Sad metropolitan area is undergoing fast urbanization in relation to the rest of the country. It contains quality agricultural land and spatially attractive zones between the two cities, encompassing a strong infrastructure network with international importance. In this research, the study area comprises 19 settlements within municipalities affiliated to the metropolitan area and the highway impact area, covering around 910 km^2 (Figure 1). It should be noted that the Belgrade–Novi Sad metropolitan area in total covers a much wider area than the study area. Along the study area pass two branches of pan-European transport corridor X, with the branch linking Belgrade and Novi Sad with Budapest (national A1 highway) and branch Belgrade–Zagreb–Ljubljana (national A3 highway), as well as corridor VII (Danube River), international railway with an important railway node. Spreading over around 70 km within the study area is State Road IB category No.100, a road with two tracks that represented a main connection between the two cities since 1950s. It remained an important transport communication with Belgrade for numerous settlements along the route. Part of A1 between Belgrade and Novi Sad is in use since 1975.

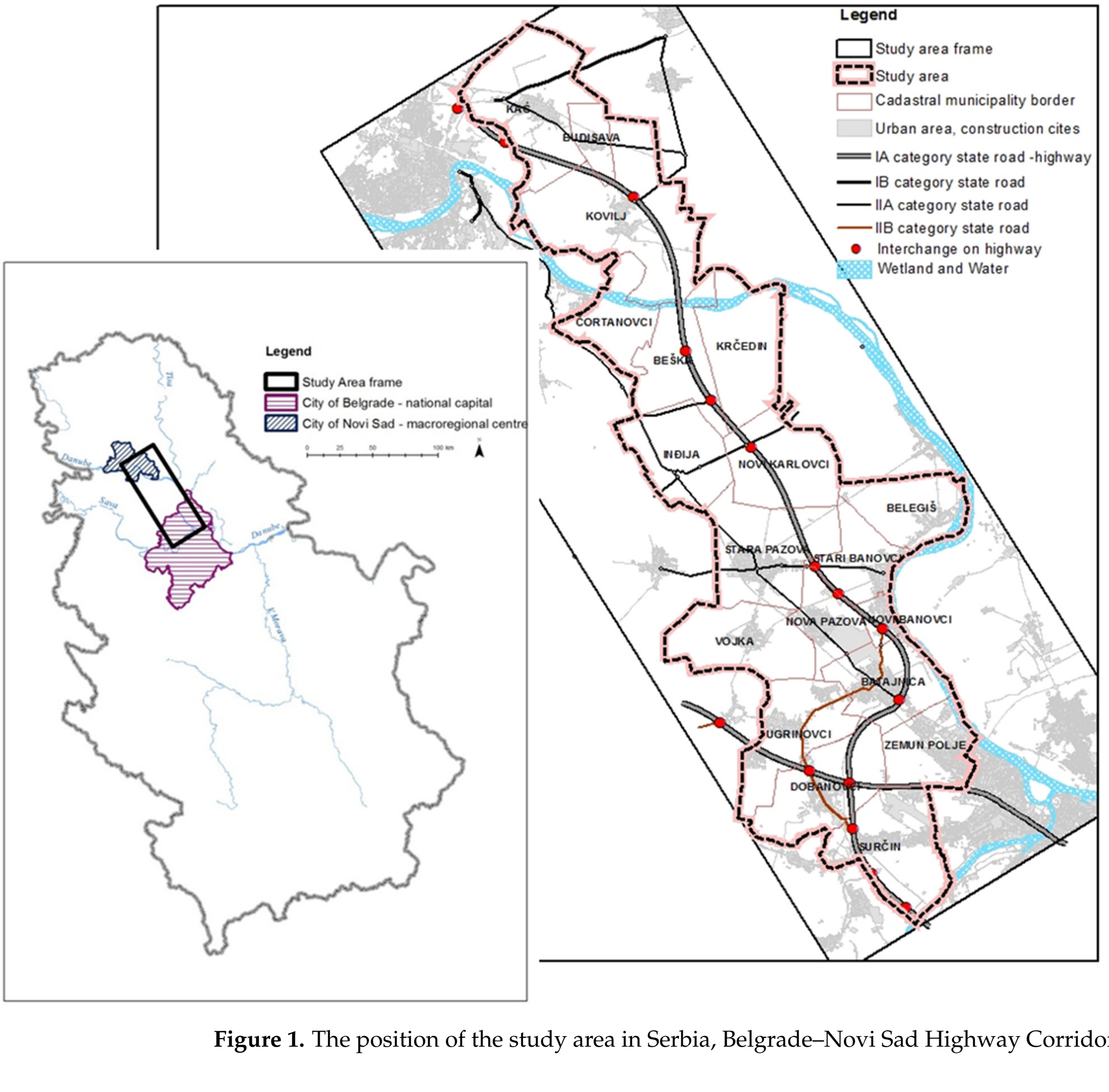


Figure 1. The position of the study area in Serbia, Belgrade–Novi Sad Highway Corridor.

Borders of the study area are defined on the basis of spatial and urban planning documents considering the impact area of the A1 highway corridor between Belgrade and Novi Sad, with regards to both the normative elements of the plans, as well as the authors' own elaboration of the available data.

2.2. Data Sources, Data Processing and Methodology

The undertaken research comprises quantitative analysis of complementary sources of data within the GIS platform, thus allowing comparability of data, as well as replenishment of the attribute feature table in line with the requirements of the selected spatial analysis. Corine Land Cover is based on 10 years and 6 years of remote sensing data collection, structuring, cataloging and validation processes. The analysis included the Corine Land Cover (CLC) datasets and related CLC-Change data (the time series 1990, 2000, 2006, 2012 and 2018). To obtain a more detailed land cover and land-use information, the analysis also used the data from Urban Atlas (available for urban areas of Belgrade and Novi Sad) that is, together with CLC, considered a component of the Copernicus Land Monitoring Service [39]. Preliminary results were complemented with the data obtained from content analysis of spatial and urban (regulatory) plans for the study area using the GIS. The synthesis of data from different sources, analysis and interpretation of data for the study area was performed in ArcGIS (ESRI).

Land-use change data is presented in form of land take indicator (LTI) according to the SDG indicator 11.3.1. [40] and EEA land take indicator [20]. Here is adopted the calculation [23,40] of the land take indicator (LTI) as follows:

$$LTI = \frac{\ln\left(\frac{Urb_t+n)}{Urb_t}\right)}{(y)}$$

where:

- ln = Natural logarithm;
- $Urb_t + n$ = Surface occupied by urban areas in km^2 in the final year;
- Urb_t = Surface occupied by urban areas in km^2 at the initial year;
- and y = the number of years between the two measurement periods.

Besides comprehensive studies [23,41], there is no available record of extensive application of this indicator yet. It should be noted that the structure of CLC-Change data cannot detect small-scale land-use changes (cf. [23]) for the areas that are not covered by Urban Atlas data (area between the City of Belgrade and City of Novi Sad, Figure 1, left image). Taking this factor into account, the GIS-based results are contextualized through qualitative content analysis of the available planning documentation in the study area.

3. Results

Observing the basic land cover structure (2018), from the total area (908.9 km^2), agricultural land dominates and is represented by 77.9%, artificial surfaces 13.0%, wetlands and water 2.8%, and forests and seminatural areas 6.4%. (Figure 2).

From 1990 to 2018, land take consumed 3.1% of agricultural lands that was converted to industrial and commercial land use and further changed due to the expansion of residential housing areas. Observing all Corine Land Cover in study period, areas containing agricultural land have reduced by 100 ha per year. "Artificial surfaces" have increased at the same pace (Figure 3).

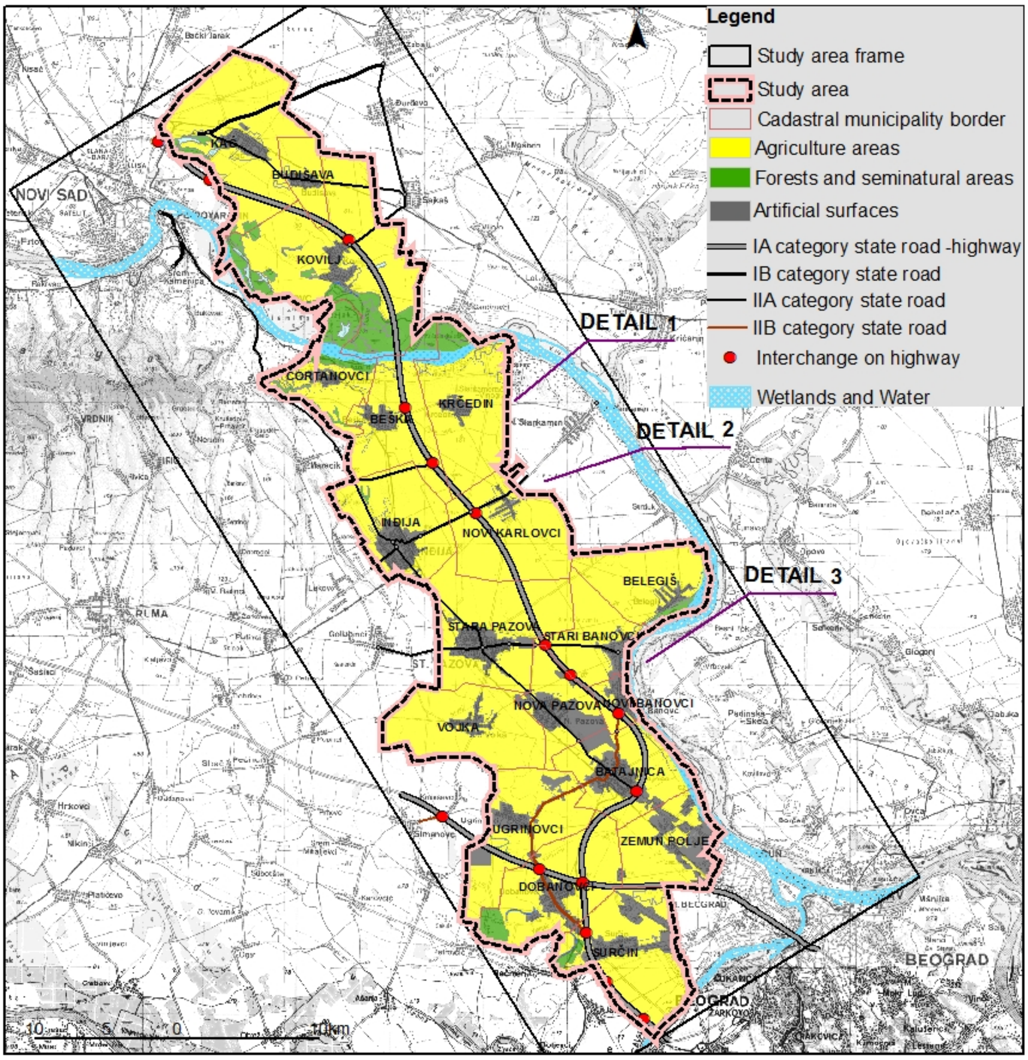


Figure 2. Land use in the study area 2018 (authors' elaboration on the basis of CLC 2018 database, UA 2018 database [39] and National Spatial Data Infrastructure GeoSrbija [42]).

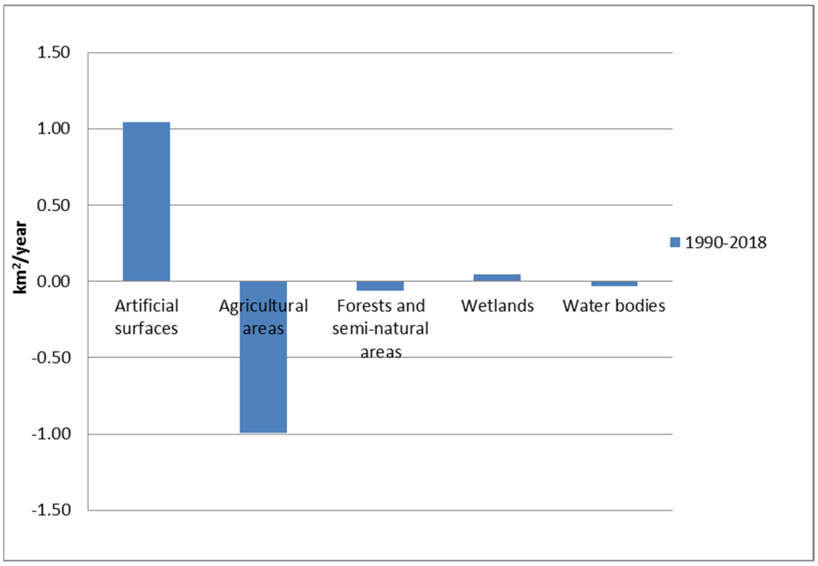


Figure 3. Yearly land take per major land cover category in study area for period 1990–2018.

Using the formula for calculating the land take indicator, the value obtained for the period 1990–2018 is:

$$LTI = \frac{\ln\left(\frac{Urb_{2018}}{Urb_{1990}}\right)}{(y)} = \frac{\ln\left(\frac{117.96}{88.80}\right)}{(28)} = 0.01$$

Compared to land take at European level (cf. [20]), this is not considered an important change.

A more detailed insight into the land-use change through the Land Cover Changes (LCC) database suggests that in the observed period of ca. 30 years, out of the total number of all recorded cases (polygons) recoding land-use change, around 45% of polygons show the change from the category of *agricultural land use* to the category of *artificial land use* (Figure 4a). The results point out the parts of the study area in which these changes were more distinct, as well as the dynamic of land-use change in the time series from 1990 to 2018 (Figure 4b).

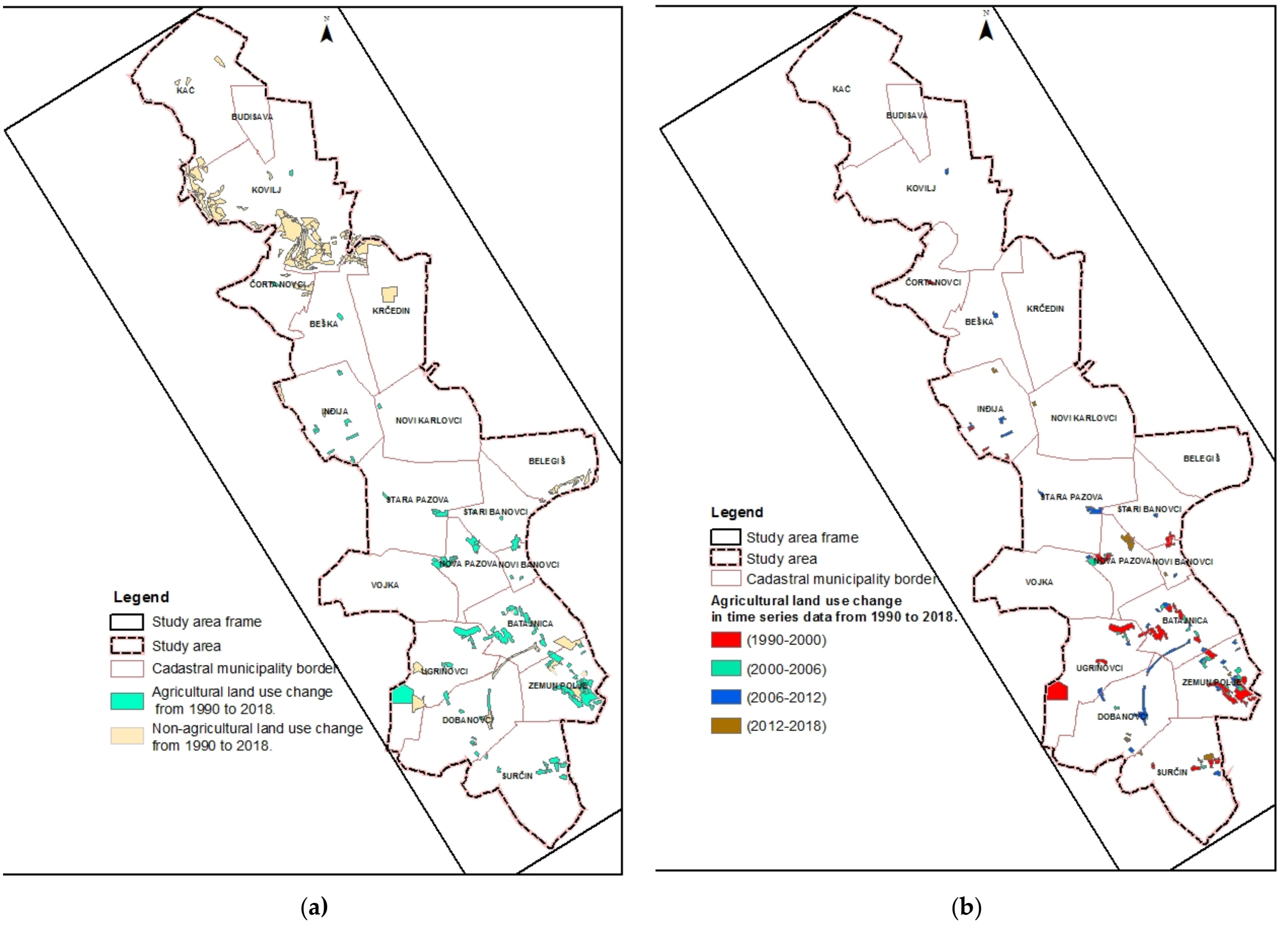


Figure 4. (**a**) Agricultural land-use change to other land uses in the period between 1990 and 2018; (**b**) dynamics of agricultural land-use change in the time series data of 1990–2000–2006–2012–2018.

Data from Figure 4b is presented in the table showcasing the dynamics of agricultural land-use change through different time series (Table 1).

Table 1. Agricultural land-use change in artificial land-use in times series from 1990 to 2018 (in ha).

Times Series	1990–2000	2000–2006	2006–2012	2012–2018	Total
Changes from agricultural land use to artificial land use (ha) *	1133.45	262.92	517.90	188.87	2103.13
%	53.9	12.5	24.6	9.0	100

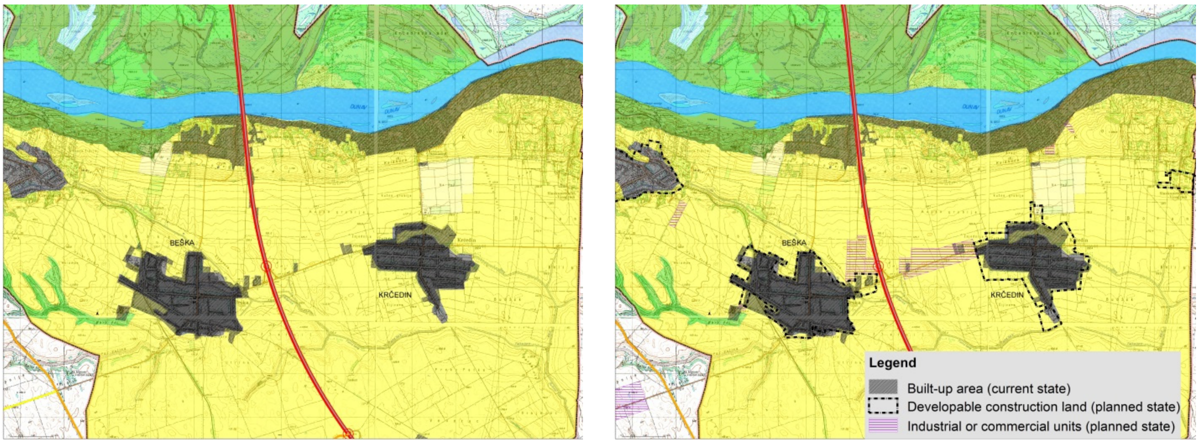
* Calculated on the basis of Land Cover Changes (LCC) datasets. The data are approximative, although the Change layers have higher resolution than CLC, i.e., minimum mapping unit (MMU) is 5 hectares for Land Cover Changes (LCC).

As previously discussed, some of the land-use changes that imply agricultural LT in the period between the 1990s and 2000s are related to the intensive illegal construction (particularly in the peri-urban areas of Belgrade) due to the forced resettlement of population from other ex-Yugoslav countries and the pressing housing demand in Serbian cities. The period after 2006 is characterized by the accelerated transition to a market economy, the arrival of large-scale retail in Serbia and their need for the most suitable accommodation close to main economic activities. These local conditions caused changes from agricultural land to construction land in the near proximity of smaller cities that have a good connection to the highway and are close to larger economic activities in Belgrade and Novi Sad. In these areas, land is more affordable than the land close to big cities, while the infrastructure is being arranged for economic activities. In the period after 2012, the process of agricultural land loss was slowed down, if compared to previous periods. This notion can be linked to adoption of urban policy that required a strict definition of work zones within the construction areas of settlements through spatial and urban plans. Some of the identified land-use changes are further contextualized through analysis of planning documentation within the borders of the study area.

Surveys in 1990, 2000, 2012 and 2016 CORINE Land Cover (CLC) and Land Cover Changes (LCC) datasets revealed some of the most prominent agricultural land-use change dynamics in the study area. Still, there are limitations in the spatial resolution of CLC and LCC, which include: minimum mapping unit (MMU) 25 ha (status layer), 5 ha (change layer), NUTS-3 level, equivalent scale 1:250,000 (status layer), 1:100,000 (change layer) had to be considered in the analysis, as well. These are more significant land-use change than the results presented in Figure 4 and Table 1, which should be considered an important factor in spatial and urban planning.

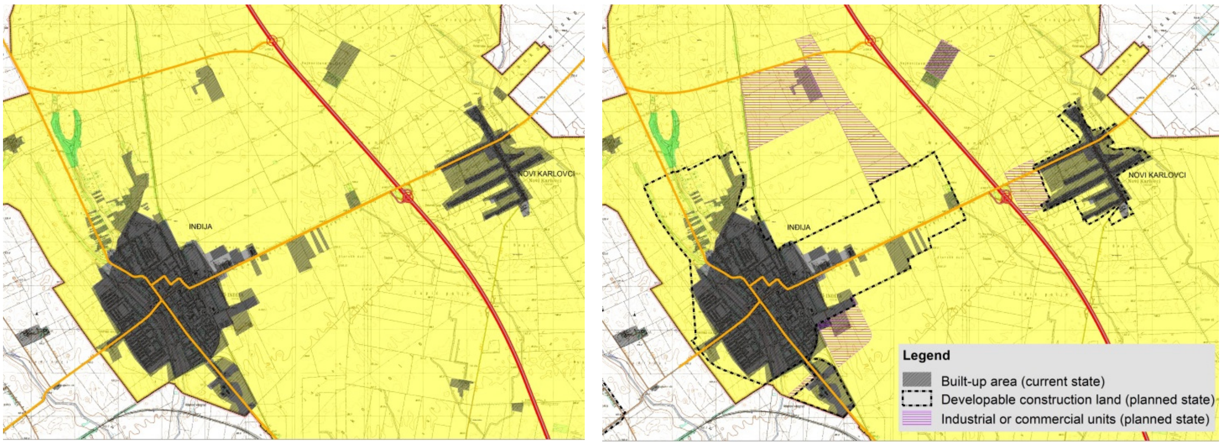
As an illustration of the agricultural land-use change that falls within the aforementioned category, three characteristic locations within the study Area are distinguished. For those locations, the data referring to built-up areas are supplemented by topographic and ortho-photo maps of higher resolution. The positions of selected locations are marked by labels Detail 1, Detail 2 and Detail 3 on the general map of Figure 2. Figure 5 shows a detailed elaboration of agricultural land-use change along the following interchanges: Beška–Krčedin settlements (Detail 1a), Inđija–Novi Karlovci settlements (Detail 2a), Stara Pazova–Nova Pazova–Banovci settlements (Detail 3a). The extensive agricultural land-use change along the access roads from the settlements to the highway is clearly identified.

Further research of the current planning documents indicated future tendencies in agricultural land take within the study area. Figure 5 shows planned land-use change within the observed locations on the basis of formal spatial and urban plans (Detail 1b, Detail 2b, Detail 3b, respectively). In some of the designated planning documents within the study area, the reduction of agricultural land occurs mainly for the purpose of developing industrial and commercial units outside the construction area of the settlements. According to the planning documentation for Inđija and Stara Pazova municipalities, there is a clear tendency for encouraging greenfield investments and new housing in peripheral urban and suburban areas, especially in the settlements along the main highway corridors. Taking into account the high quality of land in these areas, the planned construction may even cover about 70% of meadow–black soil and about 30% of chernozem [43].



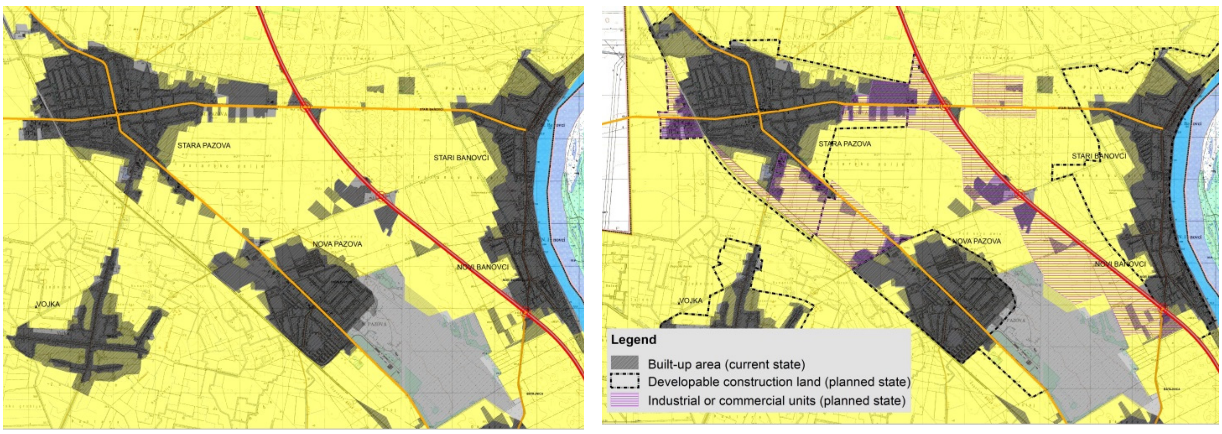
(1a) Current state of built-up area (1b) Land use change in spatial plan

Detail 1: Beška–Krčedin settlements (Inđija municipality)



(2a) Current state of built-up area (2b) Land use change in urban plan

Detail 2: Inđija–Novi Karlovci settlements (Inđija municipality)



(3a) Current state of built-up area (3b) Land use change in spatial plan

Detail 3: Stara Pazova–Nova Pazova–Banovci settlements (Stara Pazova municipality)

Figure 5. Detailed elaboration of agricultural land-use change [44,45].

In addition to the above details, Figure 4 and Table 1 illustrate the most intense agricultural land-use change to non-agricultural land in the municipalities in the immediate vicinity of Belgrade. These findings are supported in formally adopted planning documents that allocate planned land use for the wider area of the city of Belgrade. Urban and rural development is defined in the spatial plans of local self-government units (municipalities) and urban plans, as one of the land-use management instruments defined by law [30]. Generations of General Urban Plans (i.e., master plans) for Belgrade (1972, am. 1985, am. 2002) aimed to restrict new development on existing agricultural land in the peri-urban area of the city, covering the cadastral municipalities of Surčin, Zemun Polje, Batajnica and Dobanovci (Figure 6). However, the planned land-use for this area in the General Urban Plan from 2003 [46] and in the General Urban Plan from 2016 [47] directed intensive development of the industrial and commercial units in the proximity of the infrastructural corridors (i.e., in the area of Belgrade Airport Nikola Tesla and Belgrade–Novi Sad Highway Corridor, marked in purple color in Figure 6) and allocated extensive agricultural zones for the housing land use (marked in yellow color in Figure 6).

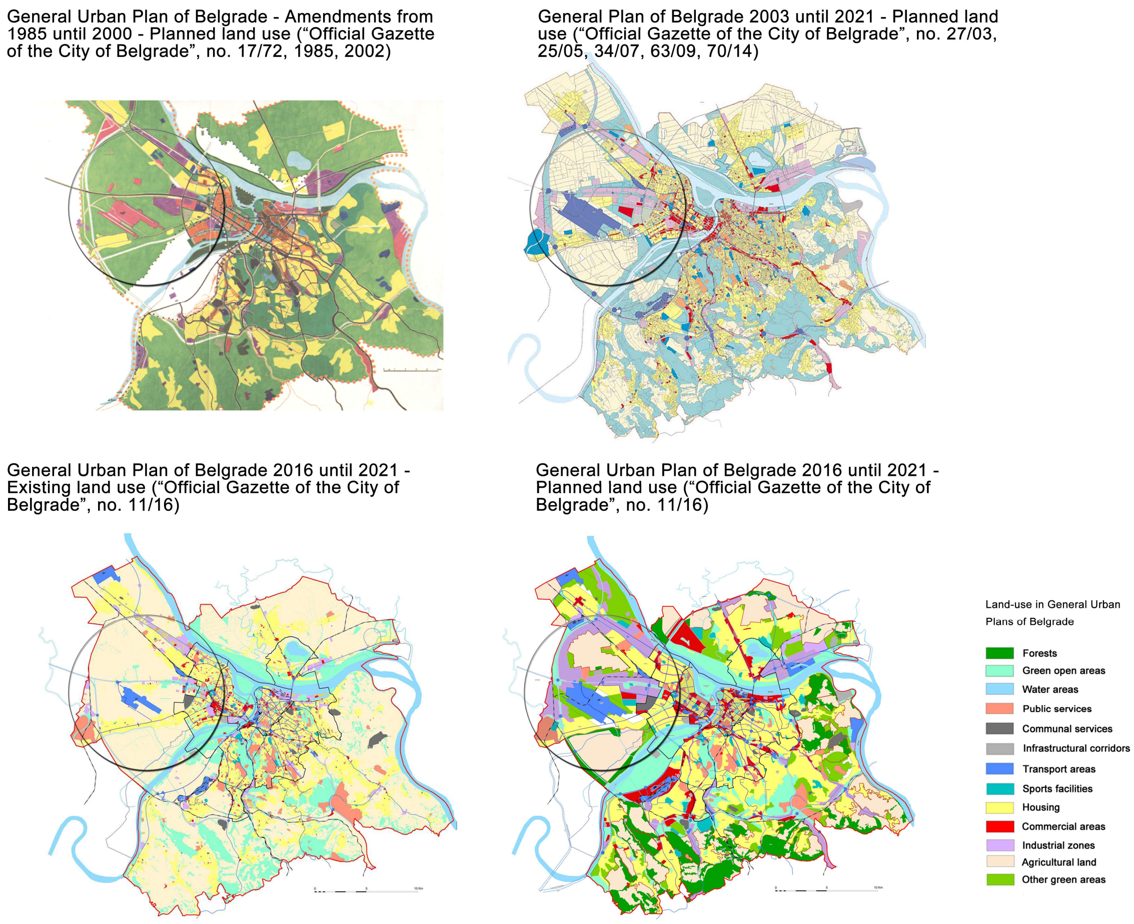


Figure 6. Generations of General Urban Plans for Belgrade (1985–2016). Source: [48].

Agricultural land that was occupied for the purpose construction of new settlements or for development of industrial and commercial units on the outskirts of Belgrade became recognized as developable construction land in lower-level planning documents as well (i.e., General Regulation Plan of Belgrade [49]).

4. Discussion

Agricultural land is nominally considered to be one of the principal natural resources in Serbia. However, recent quantitative analysis of spatial and urban land-use plans and policies at the local level has shown tendencies of a long-term reduction of the scope of agricultural land [25]. The intentions for reduction of agricultural land were underpinned by requirements for new developments in public ownership (i.e., construction of public infrastructure, energy, water facilities, etc.) as well as for other developments that are not publicly owned (i.e., housing, industrial and commercial units) [25]. Within the planning determinants that have significantly affected the spatial development of municipalities and cities, the use and protection of agricultural land is most often marginalized. The dominant planning decision to stop the illegal construction and degradation of land can be inconsistently applied as a measure in urban plans, or occurs "on ground" without the adoption of comprehensive planning policy. The concept of sustainable development in urban agriculture and use of land in accordance with its ecological properties has been promoted only recently. The new SPRS proclaims the use of existing construction supply (brownfield instead greenfield investments) for new activities and uses where possible [27]. Planning of "greenfield" land-use is considered in the line with the neo-liberalist global policy agenda in which urban planning is "more about promoting economic development and less about regulating land and guiding future development" (Fainstein, 1991; Gerber, 2016 as cited in [8]). However, in order to continuously and prospectively ensure "no net land take", innovative and more targeted instruments are needed in spatial planning and governance [23]. At the same time, there is an established relationship between traditional planning instruments at the local level, such as zoning regulations, and protection and preservation of agricultural areas and urban agriculture [50–52]. Many countries and cities are already enforcing stricter laws to protect highly fertile agricultural land in their rural hinterlands [53], while some other examples emphasize the weakness of municipal land-use planning practices in limiting urban sprawl and protecting agricultural and natural heritage [54].

The results of this research relate to: (1) the identified dynamic in agricultural land-use change into construction land; (2) tendencies of continuality of such processes; and (3) systemic support to agricultural land-use change in planning policy. The possibility of changing agricultural into construction land use was first introduced in the Law on Planning, Spatial and Settlement Development [55] for the use of the rural community. This decision was further reinforced in the Law on Planning and Construction (2003) [56] after public land became a commodity. The incentives for agricultural land-use change to developable construction land were supported through the Law on Legalization of Buildings [57], which regulates the conditions, procedure and method of legalization of buildings, and parts of the building built without a construction permit (i.e., illegally built buildings), to allow the approval for development and/or registration in the cadaster. These actions provided an incentive for continuity with regards to illegal construction on agricultural land. The decades of restricting construction on agricultural land in the planning legislation until the 1980s has intensified the aforementioned conflicts in land use [55]. From 1991–2011, urban sprawl in the Belgrade metropolitan area affected the increase in land consumption by 2.9 times (i.e., to 670 m^2 per person), which was significantly higher than in other European cities [34]. The wider area of Europe (EEA) reports the rate of 7.7% LT intensity of the total urban area expanded to cover agricultural and semi-natural land for the period 2000–2018 [58]. It should be noted that grid resolution between the EEA reports and the study area analysis significantly diverges, as previously elaborated in the Results section.

The study area belongs to the radius of intense agriculture, which requires further planning activities to support the designated use of agricultural land, the establishment of effective mechanisms to control the implementation of appropriate urban and spatial planning measures, as well as prevention of excessive occupation of fertile land for non-agricultural purposes, especially in the peripheral zones or along traffic corridors [44,45]. Still, agricultural production is highly dependent on the volume and quality of land resources, which are limited and practically non-renewable.

The proximity of large urban centers (Belgrade, Novi Sad) conditioned that the attractivity of the agricultural land within the study area is to be highly attractive for investors/developers. There are studies that address the loss of cultivated land and other natural and semi-natural land types, and the change to construction land for the purpose of highway development, where "the road has become the axis of regional urban expansion" [10]. The improvement of regional accessibility, reduction of the economic production cost and improvement of the suitable functions of the land along the corridor line, result in the rapid expansion of the construction land area [10]. With time, this became the case along the Belgrade–Novi Sad highway and local roads. Agricultural land changed between the observed periods from being clustered to scattered along the road (Figure 4a,b). Spontaneous and uncontrolled urban growth and intense expansion of construction areas (planned as well as illegal ones), with extremely inefficient use of construction land and excessive and prevailing agricultural land-use change, were recognized as one of the most significant challenges in terms of the efficient use of construction land [36]. This can be considered an effect of unreliable law enforcement and construction inspection, as well as the issuance of inadequate construction permits, which contributed to the accelerated illegal development on publicly owned land at the periphery of cities [59,60], but also planned expansion of industrial and commercial units at the expense of agricultural land.

5. Conclusions

The issue of agricultural land-use change and LT is recognized worldwide, especially regarding the global crises in food security. Taking into account that in Serbia LT is predominantly enabled through urban sprawl, the role of spatial and urban planning comes to the forefront of the debate related to the competing land uses.

The results of the undertaken quantitative and qualitative research point out that agricultural LT has been taking place through agricultural land-use change in the study area, mostly in the form of urban sprawl. The main drivers of LT within the study area are recognized: the force of attraction of Belgrade and Novi Sad, commercial and industrial activities, previous illegal construction and transportation (highway). Even though land-use planning is considered a factor that reduces LT, the undertaken analysis of the formal planning documentation for the study area affirms new LT through land-use change and orientation from agricultural to other activities in the field of economic development (commercial, industrial, etc.). These findings are supported by the previous research of agricultural land-use change in Serbia [26], in which the planning decisions at the municipality level would be a highly relevant complementary source of data. We recognize the importance of future research and analysis of agricultural land-use change and LT spatial and temporal dynamics, which is currently scarce in the research of planning practice in Serbia. Hence, a scientific and expert-based debate in that field may be directed on the conflict between the profit-oriented land-use change on the one hand and the preservation of agricultural land on the other. Moreover, it is important to question the validity regarding the expansion of industrial units, commercial activities (e.g., shopping malls) and housing, etc., on high-quality agricultural land and open areas. Planning solutions should aspire to reduce agricultural land take (hence, sealing) to zero, while seeking for and balancing realistic needs with development and investment interests. Thus, the land-use change of now undeveloped open space into new developments and agricultural land fragmentation should be avoided. Along with empirical importance, the GIS-based analysis can be used for understanding and providing input for the land-use management, future planning and governance. In addition, the research results reinforce the need for comprehensive analyses of the consequences of unregulated, but also of designated, land take and agricultural land-use change into construction land in the observed highway corridor, as well as in Serbia.

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Article

Spatial Correlation between Urban Planning Patterns and Vulnerability to Flooding Risk: A Case Study in Murcia (Spain)

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Abstract: Cities in the Spanish Mediterranean regions have undergone an extensive process of urban growth in recent decades. This urban transformation has often failed to consider the variable of flooding in its planning. Such a situation, combined with the current meteorological changes derived from climate change phenomena that increasingly cause less frequent but more extreme rainfall events in this part of the planet, has caused a sharp increase in the vulnerability of many urban areas against flooding. This research aims to analyze, from a spatiotemporal approach, in the case study of Murcia, a Mediterranean city in southeastern Spain, the existing spatial statistical correlation between urban planning patterns of growth of the city and the increase in risk due to its current vulnerability to flooding. Using GIS-based multivariate indicators and geostatistical analysis, the behavior patterns of said correlation will be numerically evaluated, and possible future trends and scenarios for this problem will be raised.

Keywords: retrospective GIS analysis; urban planning; Murcia; flooding vulnerability; spatial statistics; territorial management

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1. Introduction

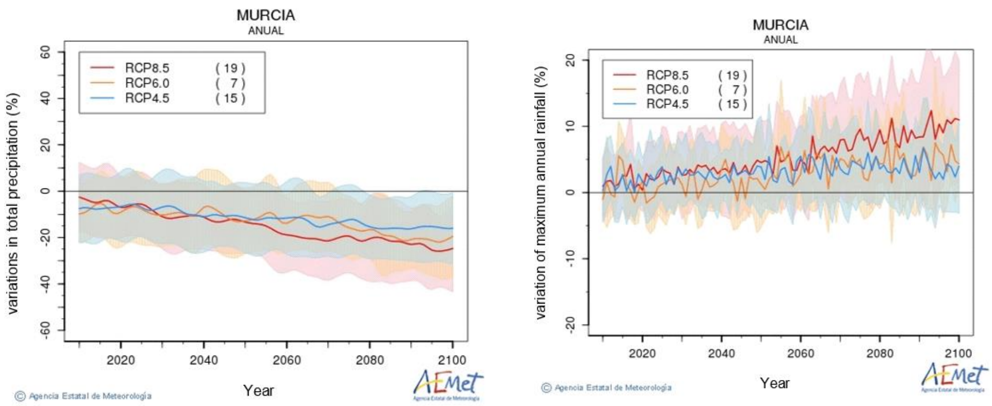
The need to plan the urban growth of cities, taking into account the natural risks associated with climate change, is a problem that is gaining increasing importance in the scientific field of urban planning [1]. In this context, flood risk analysis is a discipline that has traditionally been separated from research on urban planning since it is a problem that is univocally linked to the scientific field of hydrology and hydraulics [2,3]. However, the strong urban growth and population concentration that has occurred on the planet in the last 50 years (the United Nations Organization forecasts that almost 70% of the population will live in cities in the year 2050 [4]) requires rethinking that approach from a research point of view.

At the European level, the Spanish Mediterranean regions have been areas with the greatest urban growth in recent decades [5–7]. This growth has led to a major development of cities located in highly flood-prone environments, a variable that in the past has, on many occasions, not been considered, subsequently generating numerous problems in some cities today [8]. In this context, it should be noted that the problem of flooding is especially complex in urban environments, given the difficulty in reliably modeling the ground conditions [9]. In addition, these are environments in which the implementation of flood-rolling infrastructures is more complex, especially in large, low-density urbanized areas where the existing orography can limit the efficiency and profitability of these hydraulic infrastructures [10].

Currently, the increasing effect of climate change on the phenomena associated with torrential rains is forcing a rethink in those methodologies and approaches in this type of urban areas, where it is more rational to try to reduce vulnerability to flooding in urban planning sooner rather than having to undertake hydraulic lamination infrastructures later [10–12]. One of the locations where this change has been particularly virulent is in the Spanish Mediterranean basins. The appearance of the DANA (Spanish acronym for upper-level isolated atmospheric depression) phenomenon in those areas has replaced the traditional flash floods associated with cold fall phenomena [13]. In practice, a DANA is a weather phenomenon quite similar to a cold drop, although its intensity and effects are proving to be far more devastating. This has already prompted some researchers to begin to warn Europe about the growing phenomenon of "medicanes" [14–16]. These meteorological phenomena, named after the analogy in their effects with the usual hurricanes in the USA, are increasingly present every year in Mediterranean regions driven by climate change [17].

Mediterranean areas have traditionally been characterized by being subject to frequent floods, some of which are even historically quite relevant. However, during the last two decades, relevant flooding events and damage have increased exponentially (Figure 1). This phenomenon, which occurs in most of the Mediterranean basins, is likely influenced by the effects of climate change, as some recent studies have begun to alert [18,19]. Paradoxically, the existing predictions in the meteorological studies carried out in Mediterranean regions [20,21] show a global trend towards desertification in the area due to the annual loss of rainfall. This contrasts with a statistically rising value of maximum daily rainfall, detected and forecasted by Spanish authorities for recent years, which denotes a trend of increasing frequency and intensity for these extreme events (Figure 2).

Figure 1. Impact level of flooding events between 1950 and 2020 in the Region of Murcia. Source: Consorcio de Compensación de seguros de España [22].



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

Figure 2. Climate change scenarios for 2020–2100 regarding precipitation in the city of Murcia area using three different Representative Concentration Pathway (RCP) greenhouse scenarios: (**a**) annual rainfall and (**b**) maximum daily rainfall. Source: AEMET [23].

This meteorological context, combined with the urban situation that has occurred in the cities of Spanish Mediterranean regions during the last three decades, has produced a dangerous cocktail in which the risk of flooding in all these urban areas has increased notably in a way that is hard to assess [24]. In addition, a relevant variable that scientific studies in this field do not normally take into account is the forecast of urban development of cities in areas concerned with the risk of flooding [8]. This problem is the result of the fundamentally hydraulic and hydrological approach to this type of research [25]. This issue, which shares many common approaches with the problem of seismic risk [26], has also recently begun to be studied from a more integrated perspective with urban planning. However, the most recent approaches have been fundamentally oriented, for example, towards analyses that have focused more on indicators of a socioeconomic nature [3] or in the search for environmental issues [27]. We can also find some analyses aimed at developing mitigation strategies for the problem of flooding in the context of climate change [28–30]. Nonetheless, these are concrete urban plans or frameworks of a palliative nature rather than sustained corrective actions in the field of urban planning.

It must not be forgotten that this situation is also a consequence, from a practical point of view, of the fact that urban planning instruments have habitually classified land as developable since long before flood risk assessment tools were sufficiently technologically accurate to assess the risks of existing urban planning from a holistic spatial perspective [2,31]. Thus, it is a problem that will entail a greater social impact and economic consequences in the coming years.

In this study, a new methodological approach is proposed to correlate, through spatial statistical analysis, the (past and future) urban growth patterns of cities with the risk of flooding. In this way, it seeks to demonstrate how the urban planning carried out in recent decades in many Mediterranean cities has failed to take into account the problem of flooding, which is now posing an important challenge for the future in this area of Europe due to climate change. In this context, for the case study of the city of Murcia, the urban development of the last 100 years and future areas classified as developable will be assessed, as well as what possible future scenarios may be. This will be carried out by means of a spatial trend analysis of current behaviors.

For this, a retrospective space-time analysis of multivariable GIS indicators related to different territorial anthropization phenomena will be used, which will later be statistically correlated with the evolution of the risk of flooding at a spatial level in the city. The different levels of statistical correlation of the indicators with the problem of current flooding will help us to determine which phenomena have most affected the current increase in the risk of flooding in the area.

2. Materials and Methods

2.1. Area of Study

The city of Murcia is in the southeast of Spain, and its metropolitan area has a population of over 600,000 inhabitants (the area under analysis in the case study is provided as Supplementary Information in a GIS file). Located on a large agricultural plain of more than 35,000 hectares called "Huerta de Murcia" (Figure 3), it is crossed by the Segura River, which in the past frequently overflowed during the rainy season.

It is a territory in which traditional agriculture has been deeply rooted since the time of the Muslim invasion of the Iberian Peninsula (8th to 14th centuries), which built a complex network of ditches that supplies water to the entire area. This sophisticated hydraulic infrastructure has allowed the city to live from agriculture for centuries, having been known as "the orchard of Europe".

The city is subject to the traditional Mediterranean climate with little rainfall throughout the year (300 mm/year) but occasional torrential rains in autumn and winter that usually cause severe flooding in various zones of its urban area. To these boundary conditions, it must be added now that it is an environment with a fairly dispersed urban population whose built-up area has grown considerably in recent decades (Table 1).

Figure 3. Metropolitan area of the so-called "orchard of Murcia" (**up**) and the main urban area of the city (**bottom**). Source: Sentinel 2 satellite.

Table 1. Evolution of the urban metropolitan area of Murcia area in terms of urbanized land and population from 1950 to 2019.

	1950	1960	1970	1980	1990	2000	2010	2019	Planned
Urbanized land (Ha)									
Urban metropolitan area	526	1079	1886	2782	3931	6156	8532	8867	11,624 [1]
Population									
Metropolitan area district	260,023	297,806	304,522	371,237	432,851	491,290	551,119	626,451	680,409 [2]

[1] Planned as buildable land in the current masterplan of the municipality. [2] Population estimated for the year 2030.

2.2. GIS Indicators of Analysis of Urban Growth Patterns and Determination of Flood Zones

Based on the bibliographic review of certain publications on urban growth patterns in cities based on multivariate methods [32–37], the following GIS indicators for urban and territorial analysis have been selected, with some of them being adapted to the interest in the specific topic of spatial analysis of flooding to be studied. The indicators are:

2.2.1. Land "Artificialization" Rate (LAR)

The loss of natural land is the main example of urban sprawl transformation phenomena [38,39]. That transformation affects the intrinsic ability of a territory to mitigate the effects of a flood since it reduces its natural capacity to absorb water during a rainfall event. For the determination of this parameter, all the surfaces established as being artificial by the Information System on Land Occupation of Corine Land Cover 2018 (category 1 uses [40]) have been considered. Therefore, it is an indicator aimed at analyzing the phenomenon of soil sealing at a global level caused by urbanization processes.

Calculation Method: evaluation of land use changes according to European Corine Land Cover 2018 land uses and Inspire Directive criteria [41] for each reference sector. The higher the index value, the more "artificialized" the area is.

$$LAR = \frac{S_n}{S_{tr}} \quad (1)$$

S_n = Land use changed to Corine Land Cover 2018 category 1 uses (m^2)
S_{tr} = territorial surface in reference (m^2)

2.2.2. Indicator of Infrastructural Anthropization (IFA)

One of the characteristics of soft anthropization in a territory is the development of fragmented configurations through linear elements that "unstructure" the natural landscape of a territory and fracture the homogeneity of plots [42]. These linear communication infrastructures, such as urban paths, roads and highways, can generate "dam micro-effects" altering the course of the water if they lack appropriate cross-drainage elements. In addition, the number of crossings that occur between this type of infrastructure must be taken into account since these areas are usually points of conflict from the point of view of local drainage. In that context, the increase in the density of construction for these elements and its configuration (more or less generator of crosses in its layout) may be a clear indicator of flood vulnerability because of the generation of unbalanced urban sprawl in metropolitan areas.

Calculation method: evaluation of the fragmentation of the territory through the density of paths and urban roads per square meter; the higher the index value, the more important the fragmentation is.

$$IFA = \frac{\sum h_i {L_i}^2}{S_{tr}} \cdot \frac{c_j}{l_k} \quad (2)$$

L_i = length of existing linear infrastructures (m)
h_i = weighting coefficient (highway = 1, normal road = 0.75, urban path = 0.5)
S_{tr} = territorial surface in reference (m^2)
c_j = number of crossings generated by linear infrastructures in a reference sector
l_k = number of sections generated by the crossings in a reference sector

2.2.3. Indicator of Urban Fragmentation (UFI)

Fragmented urban structures are usually associated with mixed areas with dysfunctional plots where urban sprawl grows anarchically [43]. This type of growth is usually linked to a high degree of fragmentation of urban development, jeopardizing rural environments or agricultural spaces in the transition to urban areas. Therefore, certain links can be determined between the behavior of this parameter and the existence of unbalanced urban sprawl patterns in a territory. In addition, from the point of view of flood risk, it is possible that this type of fragmented urban fabric configurations, although they do not profoundly alter the traditional hydrographic network of a territory, may reduce its drainage effectiveness.

Calculation Method: fragmentation due to the increase in built-up areas. The evaluation of the fragmentation of the territory within urbanized areas creates a barrier; the higher the percentage of the index, the more important the fragmentation is.

$$UFI = \sum \frac{L_i}{L_{tr}} \times \sqrt{\sum \frac{Su_i}{S_{tr}}} \quad (3)$$

L_i = maximum dimension of urban boundary (m),
L_{tr} = dimension of reference boundary (m)
Su_i = Urbanized area (m^2)
S_{tr} = territorial surface in reference (m^2)

2.2.4. Index of City Compactness (ICC)

One reason that several authors attribute to the increased vulnerability of cities to flooding is the lack of compactness of the urbanized territory [44]. Urban and agricultural areas sometimes have a tendency for plot atomization as a result of the loss of traditional land uses in its periurban areas or the unbalanced urban sprawl phenomena, creating mixed areas quite vulnerable to flooding. As explained before, this problem usually leads to flood risk management problems due to the difficulty of implementing corrective measures through mitigation infrastructures that are economically profitable and efficient from the functional point of view in areas with such a dispersed population.

Calculation Method: the relationship between the perimeter of the different homogenous land uses and the surface of this area to the circle, which has the same surface area as the urban area in consideration. The higher the value is, the more compact and homogeneous the global urban structure of the city is understood to be.

$$ICC = \sum_n \frac{\sqrt{a^2 f_i}}{p_i} \quad (4)$$

a_f = area of a homogeneous urban subunit i of urban land use
p_i = perimeter in reference to the global urban sector of analysis i
n = total number of urban subunits analyzed in the area of study

2.2.5. Index of Agricultural Transformation (IAT)

The transformation of the use of periurban agricultural land into mixed or low-density residential uses often has important connections with the loss of the natural or traditional hydrographic characteristics of the land. In this sense, this global index seeks to highlight transformation processes in non-urban and periurban areas associated with human actions (partial urbanization, the transformation of natural areas and the transformation of historical crops into irrigated or greenhouse crops, etc.). This indicator, unlike the LAR indicator, is not limited solely to the problem of the sealing effect of the soil since it involves not only urban transformations but also land use changes within agriculture. The latter are not always significant large-scale alterations or do not always affect the landscape of a territory but do involve distortions in the hydrological functioning of a territory.

Another aspect that may have some impact concerns the changes within the agricultural land regime itself, both due to its conversion from rainfed to irrigated land as well as the transformation of large estates into partially urbanized agricultural areas as a consequence of the atomization of the parcel structure. All these transformations are relevant to analyze because one of the purposes of the research is also to assess to what extent the destructuring of the semi-naturalized historical hydrographic network generated since the time of the Muslim occupation in the Iberian Peninsula in Spanish orchard areas has contributed to the current increase in the vulnerability of peri-urban areas to flooding.

Calculation Method: Natural areas or permanent crops transformed into arable land and non-irrigated crops transformed into different agricultural periurban areas for year *i*:

$$IAT = \sum \frac{NAT_i + NIC_i}{S_i} \quad (5)$$

NAT_i = Natural areas transformed into arable land or permanent crops for a year *i* [Ha]. These changes are evaluated by comparison of two different years for sufficiently significant areas (agricultural crops of 1 Ha have been taken as the minimum units of evaluation), and crops are identified using criteria based on Van Vliet et al. [45].

NIC_i = agricultural land use relevant changes for a year *i* [Ha]. Those crops existing in the territory prior to 1950 have been considered traditional historical crops. To ensure that these are structural alterations of the periurban areas of a territory, the changes must be permanent and not situational, so annual milestones have been taken for at least 10 years.

S_i = surface of the sector of study for a year *i* in the reference area of study [Ha].

2.2.6. Flood Zones Index (FZI)

Numerous categories of flood-prone areas are included in the Spanish regulations, depending on the level of risk of occurrence and hazard for the population. The delimitation of the flood zones is conducted by defining the so-called Significant Potential Flood Hazard Areas (SPFHAs). These areas are obtained from the Preliminary Flood Risk Assessment (hereinafter, PFRA) in accordance with Directive 2007/60 of the European Commission [46]. In this research, for the analysis of the flooding spatial data and metadata, the return period of 100 years from the Spanish National Flood Mapping System geoportal website [47] has been used. This value was chosen because it is the one which currently has more urban planning implications in the regulations to obtain subsequent urbanization authorizations.

One of the usual main limitations of this official spatial data system published openly by the Spanish authorities is the limitation to realistically model the behavior of water flow in highly anthropized urban areas (the difficulties to adequately represent all the artificial elements that influence the characteristics of the flow in the hydraulic model, and the computational limitations derived from a large amount of processed data sometimes cause the flood results to differ from the model forecasts). The competent bodies need to update these flood maps every six years to adapt them to technological advances and to the statistical variations of the historical series.

These flood risk analysis maps, although they represent an important step forward in the management of this problem at the spatial level, are not easy to interpret since they lack a numerical or conceptual analysis to be transferred to the urban planning policies of the cities' masterplans. Therefore, although they represent an interesting source of information, it is spatial information that is currently scarcely exploited from the point of view of urban planning research. In this context, the approach proposed in the present research may be of great interest to better understand how to update these maps, as well as to improve city planning.

2.3. Geostatistical Analysis

To assess the level of spatial correlation between the different GIS parameters described in the previous sections, a geostatistical evaluation will be carried out using ArcGIS Pro 10.5.0 (ESRI Corporation, Redlands, CA, USA) and GvSIG Desktop 2.5.1 (GvSIG Association, Valencia, Spain) software. This analysis will enable us to understand numerically the relationship between the spatial distribution of the urban growth patterns in the city of Murcia and the mapping of the risk of flooding existing in the territory of its metropolitan area from a spatial perspective.

To carry out this task, both georeferenced local historical cartography, as well as the spatial database of the Cadastre, with temporary metadata available from the Ministry of

Finance of Spain, will be used. Historical cartography is available for the following years (1929, 1945, 1956, 1967, 1972, 1981, 1990, 1995, 1999 and 2001–2019) with differing levels of resolution; these are detailed in Table 2.

Table 2. Technical characteristics of georeferenced spatial data used.

Mapping Data Years	Pixel Size Projected on the GSD Ground (cm)		Planimetric Accuracy (X, Y) Mean Squared Error (m)	Altimetric Accuracy (Z) Mean Squared Error (m)	Mesh Step
	Flight	Orthophoto			
<1956	90	100	<2.00	<2.00	5 × 5
1981	45	50	<2.00	<2.00	5 × 5
1990–2004	45	50	<1.00	<2.00	5 × 5
2005–2020	22	25	<0.50	<1.00	5 × 5

To implement the analysis of the spatial statistical correlation between urban growth patterns and flooding parameters, it will be necessary to discretize the territory into a finite number of parts of the study area. For this, homogeneous orographic-urban spatial units (HOUU) will be generated, whose implementation methodology will be detailed in the results section. This analysis will allow us to assess the extent to which the urban transformation patterns of the city of Murcia have influenced the current vulnerability to flooding of its metropolitan area. The spatial relationships of these units will be parameterized and assessed using Global Moran's I [48] and Anselin Local Moran's I [49] bivariate statistics (both are geoprocessing tools from ArcGIS software).

These indicators enable us to evaluate the statistical correlation of a set of geolocated data obtained spatially and to know whether the sign of this autocorrelation is positive or negative. The bivariate Global Moran's I statistic formula is given as I (6):

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{6}$$

where z_i is the deviation of an attribute for feature i from its mean $\left(x_i - \overline{X}\right)$, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and S_0 is the aggregate of all the spatial weights of (6):

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} \tag{7}$$

The z_I-score for the statistic is computed as in (8):

$$z_I = \frac{I - E[I]}{\sqrt{V[I]}} \tag{8}$$

where $E[I]$ and $V[I]$ can be calculated as follows:

$$E[I] = -1/(n-1) \tag{9}$$

$$V[I] = E\left[I^2\right] - E[I]^2 \tag{10}$$

This autocorrelation statistic returns three types of values: the Moran's I Index, the z-score and the p-value. Given a series of spatial features and an associated attribute, the bivariate Global Moran's I statistic indicates whether the pattern of behavior for this feature is spatially clustered, dispersed, or random and its numerical degree of statistical correlation. When the z-score or p-value indicates statistical significance, a positive Moran's I index value indicates a trend toward clustering, whilst a negative Moran's I index value indicates a trend toward dispersion. The z-score and p-value are measures of statistical significance that provide us with information about whether to reject a null hypothesis of the statistical calculation. For this analysis, the null hypothesis states that the values associated with the spatial distribution of urban growth diagnosis indicators and flood risk mapping have no statistical correlation.

From this information, we can even implement, in a geolocated way, hot and cold spots in the mapping through the Local Indicators of Spatial Association (LISA) from Anselin [49] through Getis-Ord Gi* geoprocessing from ArcGIS. Each Anselin Local Moran's I statistic of spatial association I is given as:

$$I_i = \frac{x_i - \overline{X}}{S_i^2} \sum_{j=1, j=i}^{n} w_{i,j} \left(x_j - \overline{X}\right) \tag{11}$$

where x_i is an attribute for feature i, $\overline{X}$ is the mean of the corresponding attribute, $w_{i,j}$ is the spatial weight between features i and j, and:

$$S_i^2 = \frac{\sum_{j=1, j=i}^{n} \left(x_j - \overline{X}\right)^2}{n-1} \tag{12}$$

with n equating to the total number of features. The z_I-score for the statistic is computed as:

$$z_I = \frac{I - E[I]}{\sqrt{V[I_i]}} \tag{13}$$

where $E[I]$ and $V[I]$ can be calculated as follows:

$$E[I] = -\frac{\sum_{j=1, j=i}^{n} w_{i,j}}{n-1} \tag{14}$$

$$V[I] = E\left[I^2\right] - E[I_i]^2 \tag{15}$$

When these parameters are calculated, the null hypothesis means that the correlation values of two features are randomly distributed. Therefore, the strong intensity of the clustering of these values is represented by a high (or low) z-score. In this sense, we have three possible scenarios: a z-score near zero that implies no apparent clustering, a positive z-score denoting clustering of high values, or a negative z-score indicating clustering of low values. Thus, a bivariate statistical correlation assessment between the distribution of urban GIS indicators and flood mapping can help us to understand the relationship that exists between urban growth patterns and flooding. Consequently, the spatial distributions of the multivariate spatiotemporal indicators that analyze past urban growth patterns and future urban planning trends in the city and the evolution of the distribution of the risk of flooding determined by authorities in the territory of the metropolitan area of Murcia will be statistically correlated to reveal the most important phenomena in the problem studied.

3. Results

Based on the methodological framework described in the previous section, the relationship between urban growth patterns in the city of Murcia and the increase in flood risk in its territory will be analyzed. In the first place, how these growth patterns of the metropolitan area have evolved will be analyzed through the GIS indicators proposed using a retrospective spatiotemporal approach. Secondly, the urban structure will be analyzed from a spatial point of view in the context of the risk of flooding in the study area, generating discrete homogeneous orographic-urban units (HOUU) for subsequent analysis of spatial correlation. Thirdly, from a numerical point of view, the statistical correlation existing between the spatial distribution of the GIS indicators of analysis of the urban growth patterns of the city and the distribution of the current indicator of flood risk will be evaluated.

3.1. Analysis of Spatial Patterns of Urban Growth in the City of Murcia

To carry out the analysis of urban growth patterns in the city of Murcia during the last century with a spatial-temporal approach, the database of the General Directorate for Cadastre of the Ministry of Finance of the Government of Spain has been used. This database, although not fully representative of all the data since the dates that appear correspond to rehabilitations of buildings (not to their first construction) on some occasions, is very reliable from the statistical point of view since that proportion of cases is numerically very low with respect to the total volume of data. Therefore, a spatial database is available with the construction dates of all the buildings in the Murcia metropolitan area over the last 120 years (see Figure 4).

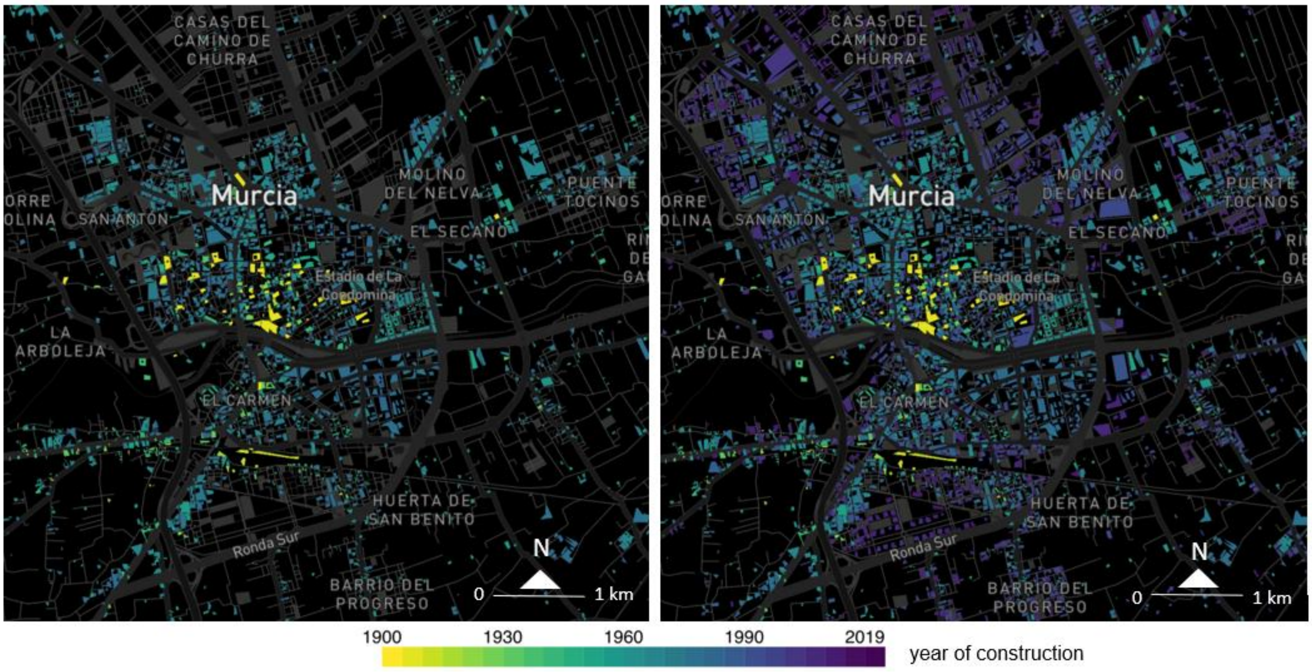


Figure 4. Spatial representation at a city scale of existing buildings by date of construction in the city of Murcia in 1980 (**left**) and 2019 (**right**). Source of data: General Directorate for Cadastre of Spain.

If we analyze these spatial patterns on a larger scale, covering the entire metropolitan area of Murcia, we can observe how the development of linear transport infrastructures has greatly conditioned the urban growth of the city (Figure 5). At a general level, urban development has largely followed the layout of several of the main communication infrastructures of the city, such as the road that connects with Madrid in the north, the road to Alicante in the northeast, the Alcantarilla road to the west, or the Cartagena highway to the south. These linear infrastructures can also have the opposite effect. As can be observed with the railway line that crosses the southern part of the city horizontally from east to west, it has generated a "barrier effect" favoring greater urban development in the northern area compared to the southern area in recent decades.

This phenomenon of urban structuration of the city through the fragmentation generated by the infrastructures can be observed graphically and numerically in the evolution of the IFA parameter in Table 3. Another phenomenon that can also be seen from this table is the recently increased transformation of urbanized land. This is clearly seen in the early 20th century, in which yellow and green values are proportionally much smaller than the late 20th century bluish and dark values. This trend is verified at a numerical level in the table through the evolution of the LAR parameter.

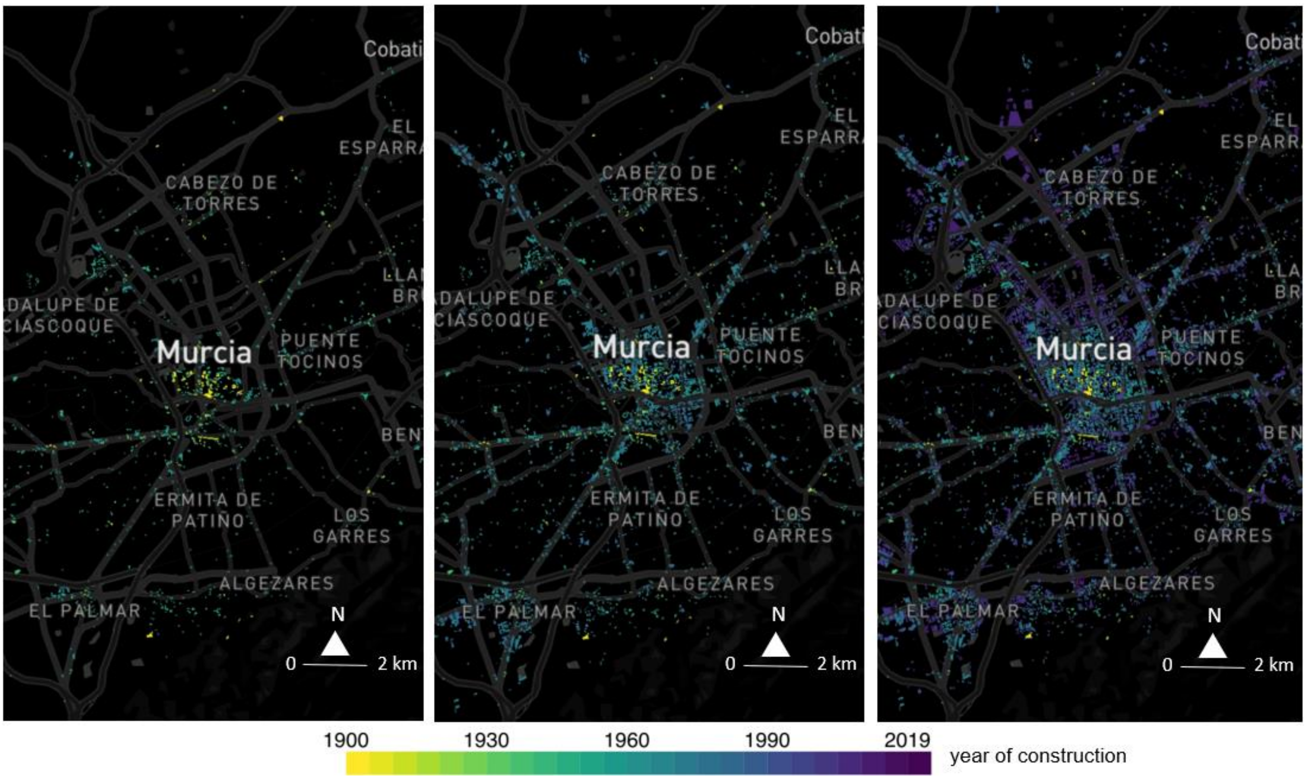


Figure 5. Spatial representation at a metropolitan scale of the evolution of urban growth in the metropolitan area of the city of Murcia in 1940 (**left**), 1980 (**center**) and 2019 (**right**). Data source: General Directorate of the Cadaster of Spain.

Table 3. Numerical evolution of GIS indicators of urban growth in Murcia from 1950 to 2019.

	1950	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2010**	**2019**
LAR	0.028	0.036	0.068	0.116	0.174	0.232	0.396	0.515	0.548
IFA	0.064	0.075	0.088	0.101	0.125	0.174	0.223	0.279	0.310
ICC	0.233	0.216	0.195	0.220	0.221	0.228	0.236	0.252	0.257
UFI	0.346	0.374	0.411	0.459	0.510	0.552	0.614	0.646	0.668
IAT	0.041	0.053	0.077	0.121	0.177	0.234	0.398	0.516	0.548

We can also observe how, at a general level, the metropolitan area presents increasingly greater dispersion patterns over time (yellow and green colors present a higher level of spatial grouping compared to the more bluish and darker colors that show further distance, with no specific structural pattern). This hypothesis is corroborated numerically when we observe the numerical evolution of the ICC compactness values and the UFI urban fragmentation value.

It is interesting to observe the contrast between the behavior of the city compactness index ICC and that of the urban fragmentation index UFI. The compactness index has increased progressively in recent decades after an initial decrease, which should theoretically indicate a higher level of compactness of the built-up structure. However, the fragmentation index clearly shows an increasing trend right from the start, which underscores a rather scattered pattern of growth. This possibly shows that the compactness index is too rudimentary to analyze the behavior patterns of urban growth since possibly its increasing value is not due to greater urban compactness but rather to a higher aggregated level of saturation as there is more and more urbanized surface. The higher level of analytical sophistication of the formulation of the urban fragmentation index, therefore, confirms that the urbanization process is increasingly dispersed, thereby giving this indicator a higher level of reliability.

Finally, we can indirectly infer, with the IAT parameter, how the transformation of agricultural land use has evolved in favor of urban land. This can be easily verified numerically by comparing its evolution with that of the LAR parameter, which only analyzes the transformation of the land due to urbanization processes. The initial decoupling of almost 50% between the two values has progressively diminished until they have become practically similar in recent years due to the growing weight of urbanization processes in the orchard as opposed to simple changes in agricultural land use.

3.2. Implementation of the Flood-Urban Growth Correlation Model

As described in the methodology section, Flood risk maps for a 100-year return period from the National Flood Zone Cartography System [47] have been used to incorporate the flooding variable into the analysis of urban growth patterns in the city of Murcia. In this section, metadata, including information on two issues, have been incorporated into the spatial analysis model. On the one hand, the floodplain with risk for the population of urban areas has been included for the said return period. On the other hand, information on the level of drafts and speed of the water has been incorporated, taking into account the orography and contour conditions of the terrain to prioritize the level of said danger (see Figure 6).

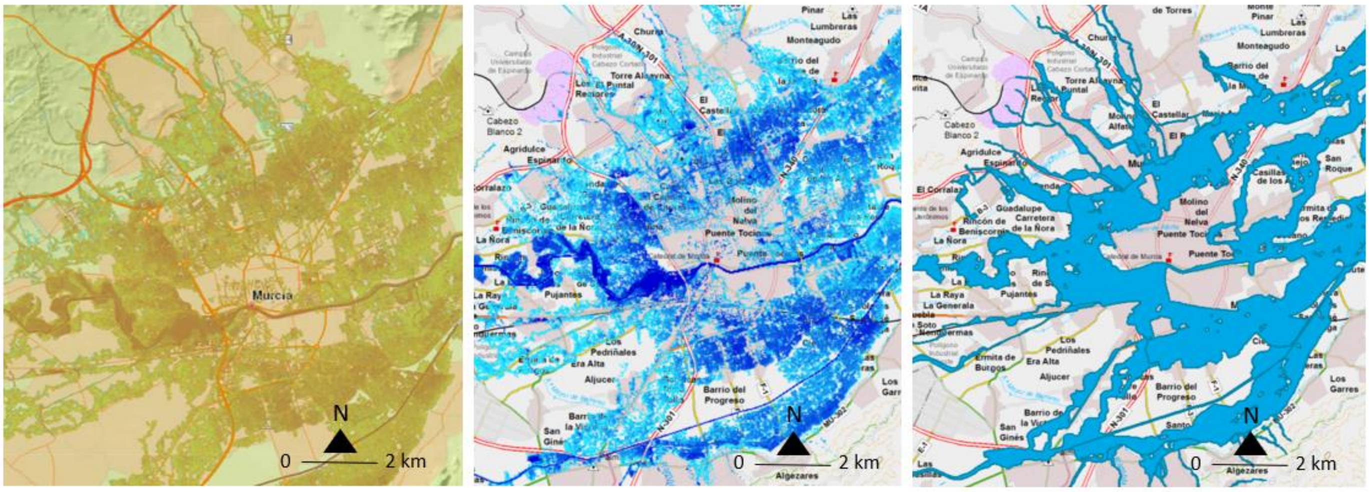


Figure 6. Implementation of spatial information on flood-prone areas: terrain elevation model incorporating orographic conditions in areas at risk of flooding (**upper left**), map of flood-prone areas with risk for the population in urban areas (**upper right**), map depths (**bottom left**) and preferential flow areas where the water flow only acquires greater speed (**bottom right**).

If we evaluate the buildings in the city of Murcia located in flood-prone areas according to the criteria established in the previous section, we can see that such construction has been mainly carried out in recent decades. In addition, there is currently a large amount of land classified as developable located in currently floodable areas that are earmarked for new construction in the coming years (Figure 7). Another relevant issue to observe is that, during the last decade, there has not been a large amount of building in these flood-prone areas, which may be connected to the greater number of restrictions due to the improvement of the diagnosis of this problem. However, it is quite possible that this question is more related to the economic crisis that notably hit the real estate sector in Spain during this period, as can be verified by the existing drop in the urbanized area globally in Murcia during that decade (see Table 1).

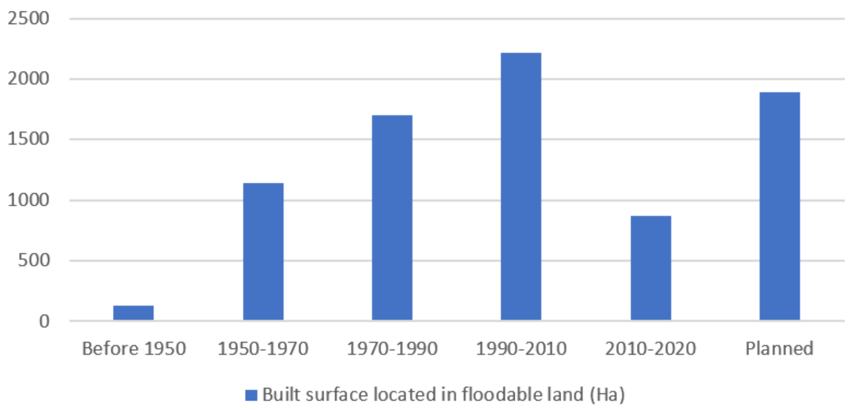


Figure 7. Breakdown of the surface areas built in the different decades in areas currently determined as flood-prone areas in the metropolitan area of the city of Murcia.

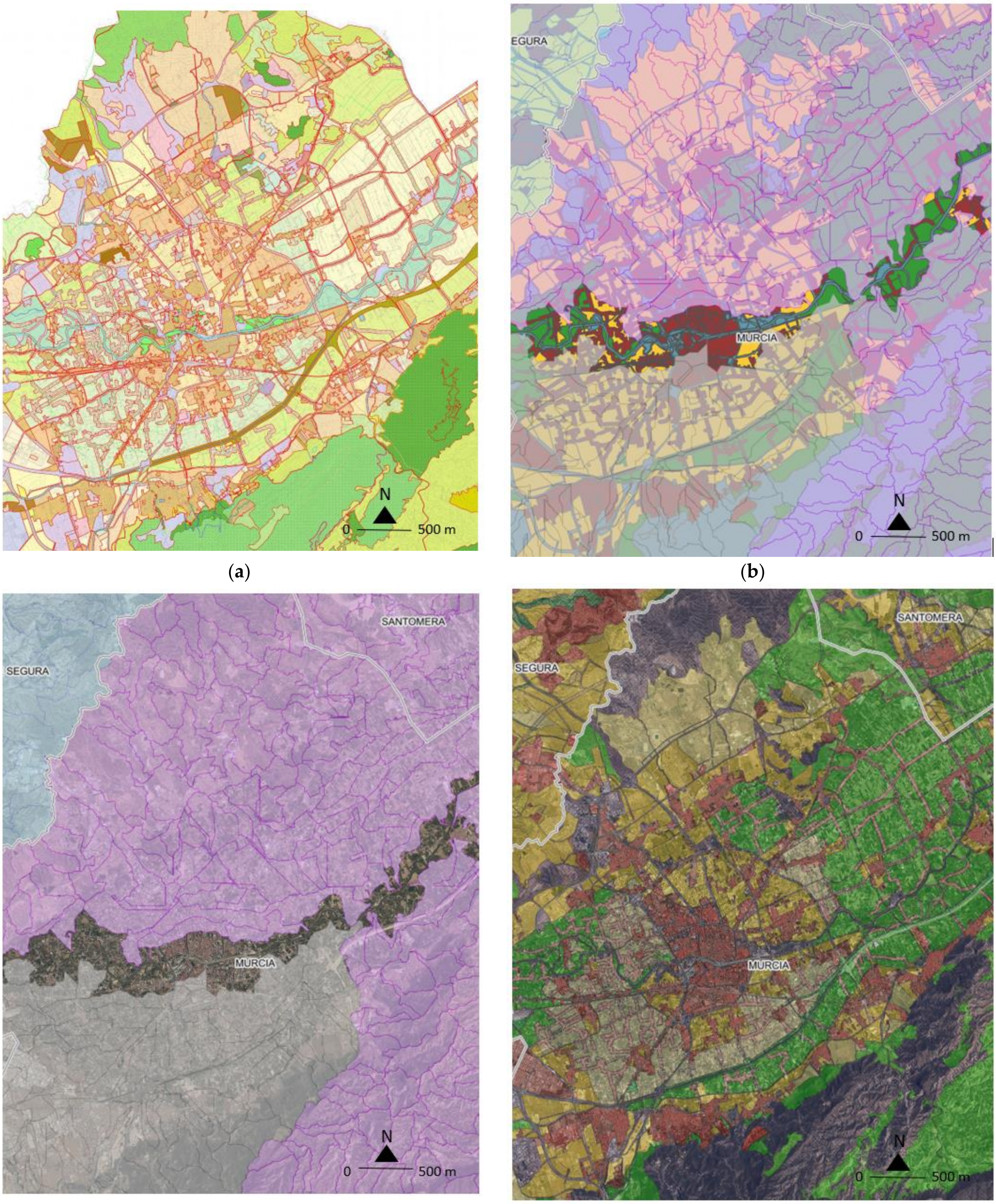
In any case, in light of these data, it is evident that it is important to incorporate the variable of flooding into the urban planning of the city to improve this planning. However, this approach is not easy to integrate since the effect of existing buildings in each case is not known, nor how current urban forecasts may affect this in the future. Consequently, the common procedure is usually to demand that specific flooding studies are carried out for the development of each individual urban planning sector likely to be affected by flooding in the master plan. However, this procedure is increasingly controversial in many cases since it involves private land developers undertaking heavy investments in flood mitigation infrastructure, which generates conflicts that we shall address later in the scientific discussion section. In this case study, to more accurately assess how the city's growth patterns have affected the current flood risk in recent decades, the spatial distributions between the analysis indicators of the city's urban growth and the current distribution of floodable areas will be statistically correlated.

To achieve this, the analysis areas need to be discretized into a finite number of sectors. These sectors, called homogeneous orographic-urban units (HOUU), will be spatially established from the weighted intersection of internal orographic sub-basins of the main basin corresponding to the Huerta de Murcia and sectors of homogeneous urban land use included in the masterplan of the metropolitan city area (Figure 8). The numerical diagnosis of how each of the variables analyzed with the indicators has affected these sectors will provide us with more precise knowledge regarding the level of interaction between these variables. This will help us to improve future urban planning by taking a priori planning actions to design greater resilience to the problem of flooding instead of referring said problem to subsequent actions related to the execution of the urbanization.

3.3. Geostatistical Analysis of the Spatial Correlation between Indicators

Based on the model described in the previous sections, the level of statistical correlation between the current spatial distributions of the growth patterns indicators for the city of Murcia corresponding to each of the homogeneous orographic-urban units (HOUU) of its urban metropolitan area and the indicator of flood risk in each one of these units has been calculated (Table 4). As indicated in the methodology section, the risk of flooding has been carried out following the distributions of the GIS maps of the National Mapping System for flood-prone areas of Spain [47].

These maps, made by the Spanish Ministry of Ecological Transition, are updated every six years to incorporate technological innovations that improve the model's accuracy and take into account the statistical variations of the historical series. Therefore, two spatial data series are available for the FZI flood risk indicator generated by official bodies since the approval in 2007 of the European flood risk management directives [46]: the first one was carried out during the period 2007–2013, whilst the second one was carried out during the period 2013–2020.



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

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

Figure 8. Generation of discrete homogeneous orographic-urban units (HOUU) for spatial analysis: (**a**) zoning map of urban planning uses of the Murcia masterplan; (**b**) current orthophoto of the city of Murcia with a layer superimposition of sub-basins of homogeneous orography; (**c**) superposition of layers of homogeneous sub-basins and classification by masterplan land planning classes and (**d**) homogeneous orographic-urban planning units generated.

Table 4. Results of the evaluation of the existing statistical correlation between the indicators for the analysis of urban growth patterns in the city of Murcia and the FZI flood zone indicator.

GIS Indicators	FZI Flood Hazard Index (1st Cycle 2007–2013)			
	B	Std. Error	t	Sign.
LAR	0.238	0.007	2.179	0.000 *
IFA	0.265	0.005	2.744	0.000 *
ICC	−0.138	0.008	−2.575	0.000 *
UFI	0.255	0.009	4.003	0.000 *
IAT	0.098	0.009	1.510	0.000 *
Akaike's information criterion (AIC): 21,364.7 Multiple R-squared: 0.19 Adjusted R-squared: 0.18 F-statistic: 136.72 Prob (>F) (3,3) degrees of freedom: 0				
GIS Indicators	**FZI Flood Hazard Index (2nd Cycle 2013–2020)**			
	B	**Std. Error**	t	**Sign.**
LAR	0.249	0.006	2.684	0.000 *
IFA	0.286	0.006	3.368	0.000 *
ICC	−0.192	0.011	−1.884	0.000 *
UFI	0.313	0.006	2.811	0.000 *
IAT	0.062	0.009	1.667	0.000 *
Akaike's information criterion (AIC): 23,191.3 Multiple R-squared: 0.22 Adjusted R-squared: 0.22 F-statistic: 154.88 Prob (>F) (3,3) degrees of freedom: 0				

* Significant at 0.01 level.

The results obtained numerically corroborate several of the issues that had been observed conceptually from a spatial point of view. There is a clear positive correlation between the LAR indicator related to land urbanization, but this correlation is even greater when said urbanization presents high levels of urban fragmentation shown for UFI. This can be verified since there is also a clear negative correlation with the level of compactness ICC (that is to say, the higher the compactness, the lower the risk of flooding), given that the urban structure of the metropolitan area of Murcia presents a very dispersed configuration. In the fragmentation caused by linear communication infrastructures, IFA also shows stronger values than LAR, which denotes that it is a determining parameter within the phenomenon as a whole.

Another interesting issue is the comparison between the values of the first period 2007–2013 of the flood risk indicator and those corresponding to the second period 2013–2020. As can be seen, all the values in the former case are higher than in the latter. This denotes an implicit increase in the risk of flooding since the values of the indicators associated with the urban growth patterns of the city have not increased (as verified in the first subsection of the results). The values of AIC and R2adj corroborate this hypothesis since they present comparatively higher values than those of the other GIS indicators, showing their higher ability to explain the phenomenon as a model variable.

Two factors may be responsible for this situation. On the one hand, it may be due to a higher level of precision of the flood analysis tools in this second period, when a greater risk was quantified in the area than had initially been diagnosed. On the other hand, the statistical series of precipitation are increasingly frequent and of greater intensity as a consequence of climate change. Both phenomena are probably partially to blame in this matter, so this issue will be addressed in greater detail in the scientific discussion section.

4. Discussion

The research carried out has highlighted a problem that, although in this case it has been analyzed specifically for the city of Murcia, could be clearly generalizable to many other cities in Spain and almost certainly to the European Mediterranean arc [50,51]. These are regions that have traditionally had a strong urban development in their cities, both as a consequence of phenomena associated with tourism and economic growth, as well as by the simple vegetative growth of the population. In the case of Spain, the urban planning of most of the cities of the Mediterranean zone underwent a major expansion during the decades of the 1980s, 1990s and 2000s as a result of real estate bubbles. This pushed the urban planning departments in many cities to classify a lot of land as developable at a time when flood risk diagnostic tools did not have the level of sophistication and accuracy available today.

In the last decade, thanks to the technological development of tools based on geographic information systems, it has been possible to catalog the risk of flooding with greater accuracy from the point of view of spatial evaluation. This technological improvement has also been accompanied by a legislative drive at the European level thanks to the approval of Directive 2007/60/EC on flood risk assessment and management, which has been transposed in subsequent years to all European Union countries [46]. In the case of Spain, this has allowed the development in recent years of numerous national regulations on land use limitations due to flood risks, with an approach linked to the spatial planning of the territory.

However, those in charge of executing urban planning and its subsequent urbanization processes are not state agencies but city councils. In this regard, we are currently in a situation in which a major part of the urban planning of cities has already been approved for many years, as the economic crisis of 2008 slowed down the real estate development of many cities in Spain and Europe [52]. With the economic recovery of recent years, we have found thus ourselves in a context in which greater knowledge of the risk of flooding in cities is combined from the spatial point of view with the existence of numerous constructions and buildings developed in the last decades located in flood-prone areas. This problem regarding flooding is, moreover, of a growing nature in these areas of the Mediterranean arc, where the phenomenon of climate change produces more and more frequent and intense torrential rainfall [53]. This phenomenon will therefore require national authorities to periodically reconsider the statistical return periods associated with the risk of flooding in cities.

To add further controversy to the situation, this complex situation is compounded by the existence of large pockets of developable land now located in areas determined to be at risk of flooding in the various urban plans of the cities that, with the current economic recovery, may be developed in the coming years. These are areas in which landowners have already legally consolidated their right to build, and so public administrations must manage that difficult situation. Nowadays, municipal authorities often have to choose between legally litigating with those owners to oblige them to make large private investments in flood mitigation infrastructures in order to authorize the execution of development. Otherwise, they face having to subsequently carry out important public investments in hydraulic infrastructures for the rolling of avenues to avoid unsafe situations. Given the low socioeconomic profitability in the case of low-density areas, these investments are also, in some cases, politically controversial.

This complex combination of events can currently be found in numerous cities throughout Spain, and the rest of the European Mediterranean arc [13,51] and will arise more and more often in the coming decades. In this context, it is advisable to try to avoid a priori the greatest number of future flooding problems in the general urban planning of cities instead of referring them to the evaluation of subsequent specific studies of each of the sectors to locally authorize their development. In this sense, the investigative approach adopted in this study using geostatistical analysis to parameterize the extent to which urban planning can pose an added risk to the current vulnerability to flooding of a city may be quite interesting in diagnosing future problems. This approach makes it possible not only to determine to what extent a city's growth patterns have contributed to increasing its vulnerability to flood risks but also enables future scenarios based on current urban planning forecasts to be estimated.

In the specific case of the city of Murcia, through the geostatistical analysis carried out, we have been able to observe how the patterns of urban transformation of the city have significantly contributed to increasing its vulnerability to flooding. The Huerta de Murcia area had a natural hydrographic network whose orography and territorial structure allowed the floods that occurred due to torrential rains from cold drop phenomena to be laminated quite efficiently. This natural structure has been disappearing as a consequence of the intense urbanization process that the city has experienced in the last five decades. Although this phenomenon can be found in other places in the world [10,11,54], it presents certain interesting local nuances here.

The process has developed fundamentally in two ways. On the one hand, the continuous transformation of the periurban territory of the municipality from orchards into low-density urbanized land has generated a global phenomenon of soil sealing, significantly reducing the absorption capacity of this territory against floods. In this sense, it can be said that the traditional territory of the Huerta de Murcia has gradually become a residential structure of the "garden city" type (Figure 9). On the other hand, this process of transforming the territory by replacing orchard paths and nature trails with roads has completely modified the natural and traditional hydrographic structure of the basin that had covered the metropolitan area of the city of Murcia for centuries (Figure 10). A new artificial configuration has been created with multiple sub-basins generating "micro-dam effects" because of these linear infrastructures. According to that observed in the statistical numerical analysis, this has resulted in contributing to a notable increase in the risk of flooding in the city.

If we spatially project the current urban growth patterns identified in the city into the future, this problem, far from being mitigated or stabilized, will grow in the coming years. This will be caused both by the current forecast of urban development of different "conflictive pockets of land" classified as developable in the master plan of the municipality (Figure 11), as well as by the aforementioned effects of climate change on rainfall in these Mediterranean areas. Consequently, it can be concluded that there is a dangerous general trend in the current urban growth patterns to accentuate flood risks that occur in this metropolitan area, therefore requiring a rethinking of urban planning that takes the issues of flooding more into account.

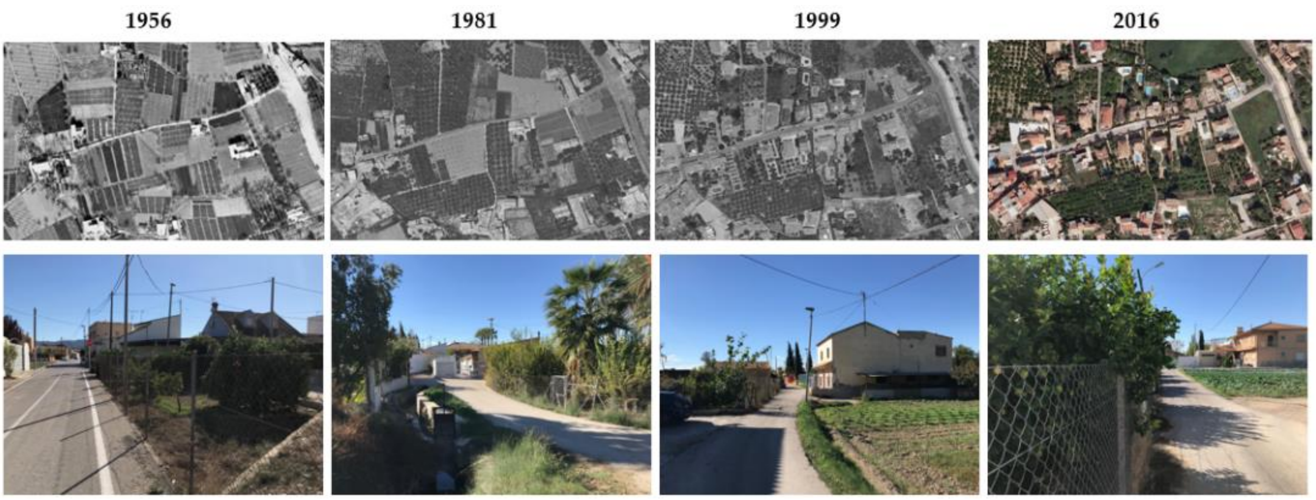


Figure 9. Example of evolution over time of a traditional orchard area in the metropolitan area of Murcia (**above**). Images of the current landscape configuration of the old peri-urban areas of Huerta: the construction of numerous paved roads as a consequence of an increasingly fragmented plot structure focused on residential urban development has ended up completely misconfiguring the natural hydrographic network (**below**).

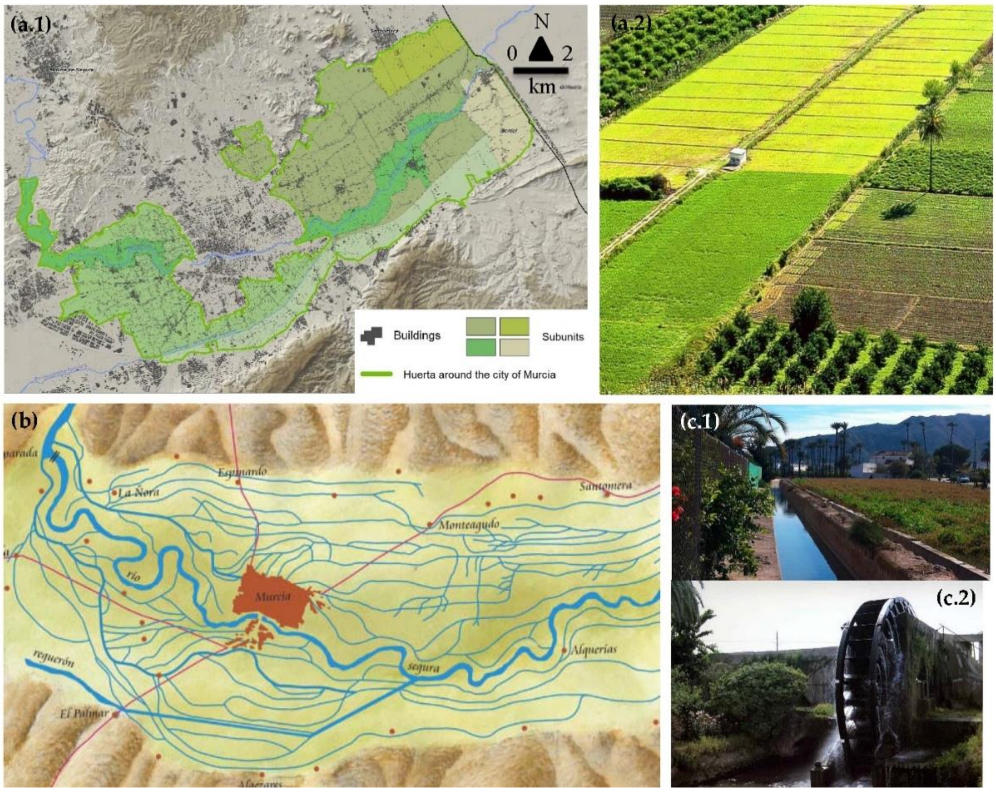
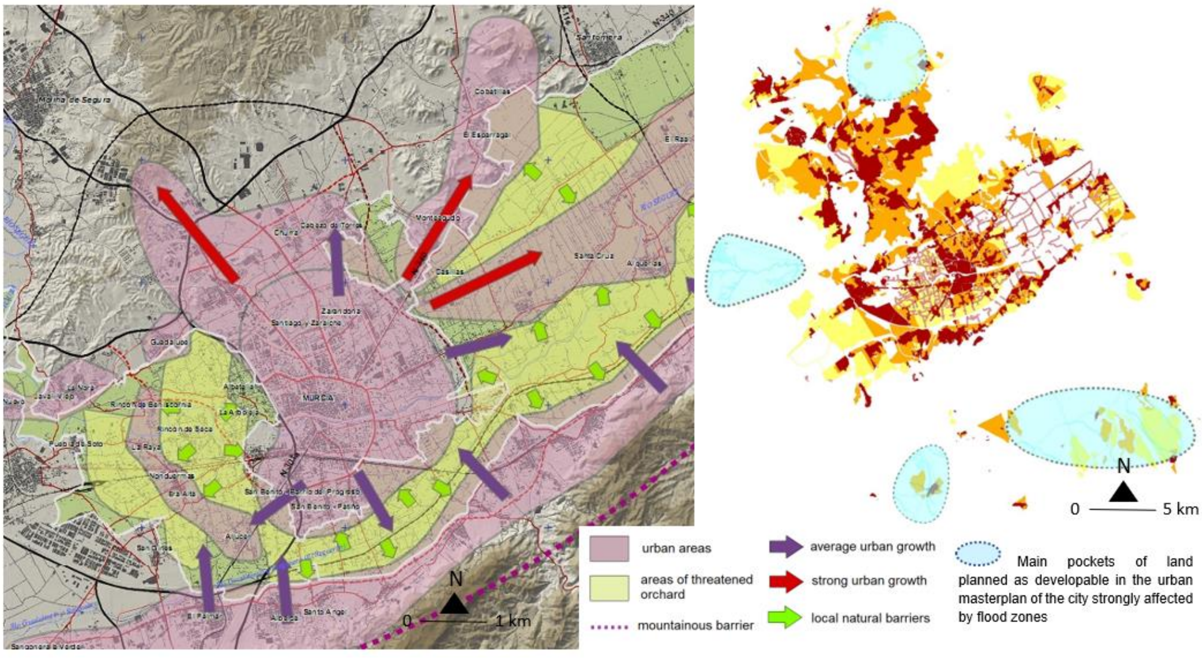


Figure 10. The Huerta de Murcia traditional landscape: (**a.1**) Extension of the area and subunits of the Huerta directly linked to the metropolitan area of the city of Murcia (**a.2**) example of its traditional landscape, (**b**) scheme of the traditional agricultural hydrographic network of the Huerta and (**c.1**,**c.2**) traditional hydraulic infrastructures existing since the Muslim period (8th–14th century).



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

Figure 11. Graphical scheme representation of trend analysis of growth patterns in the city of Murcia: (**a**) spatial distribution of the main vectors of growth and transformation of the peri-urban space vs. the resistance inertia of the orchard; (**b**) Levels of the demographic intensity of the urban areas of the city and main "pockets" of urban development foreseen in the planning in flood-prone areas.

The case study analyzed is quite paradigmatic but is not exclusive to the city of Murcia (Barriendos et al., 2019; Delgado-Artés et al., 2022). If we evaluate the data on land transformation and urbanization in recent decades for other cities in the Spanish Mediterranean arc, it can be confirmed that orchard areas are usually in regression. In metropolitan areas with size and periurban contour conditions similar to those of Murcia, such as Valencia, Zaragoza, or Barcelona, we can observe similar patterns of behavior from the point of view of the temporal evolution of the urbanization of the city over the last decades. This situation is combined with the growing consolidation of a significant risk of flooding in the areas surrounding the urban areas of these cities, and it can also be encountered on a smaller scale in many other middle-sized Spanish Mediterranean urban areas such as Figueres, Roses, Blanes, Castellon, Alzira, Jávea, Castellón, Cartagena, Lorca, Los Alcazares, etc.

In the case of Barcelona and Valencia, for example, the peri-urban growth in the north and south of the cities is currently strongly conditioned by the risk of flooding in the old orchard areas. In the case of Zaragoza, the dispersed urban growth of the city to the east and west, following the course of the river on the old agricultural areas that were cultivated on its banks, is also strongly conditioned by the current controversy of the risk of flooding. These issues are verified from the numerical point of view of the generation of urbanized or planned land as developable in their urban masterplans (Figure 12).

In addition, this problem is not exclusive to the European Mediterranean area. It is a phenomenon that, with different local nuances, is beginning to have an increasing impact in several cities all over the planet. We can find specific problems in urban areas that have grown very fast in developed countries in recent decades, such as Seoul [55], or derived from suburbanization phenomena in cities of developing countries, such as Rio de Janeiro [56]. The enormous casuistry existing in this matter is nothing more than a sample of the need for greater integration of flood risk analysis in master plans and large-scale urban planning instruments for cities.

In this sense, the methodological framework proposed can be very useful to diagnose and therefore introduce improvements in the urban planning of cities a priori at the time of its update instead of waiting for the generation of specific studies when a specific sector of the city masterplan is to be developed. Even so, it must be assumed that the method proposed still poses numerous limitations due to its fundamentally prospective nature. In this sense, the analysis carried out must be strengthened through its implementation in other case studies to verify its correct functioning. It should also be perfected in future lines of research. Given its initiatory nature, the approach may have left aside other variables whose inclusion could help the model to become more reliable and robust in other cases that present different boundary conditions. Finally, at the level of policy implications, once the model has been developed in a more sophisticated way, it would be interesting for it to be capable of helping at the spatial level in a segmented way rather than in an aggregated one as has been proposed in this research. It would be a real advance in the matter to develop a more robust graphic design tool with greater computing capacity that would be capable of integrating flooding analysis and urban planning, transferring results in a localized manner for each of the city's urban planned sectors. This would enable what is currently a simple scientific investigation to become a true graphic tool in order to help to design the urban planning of cities.

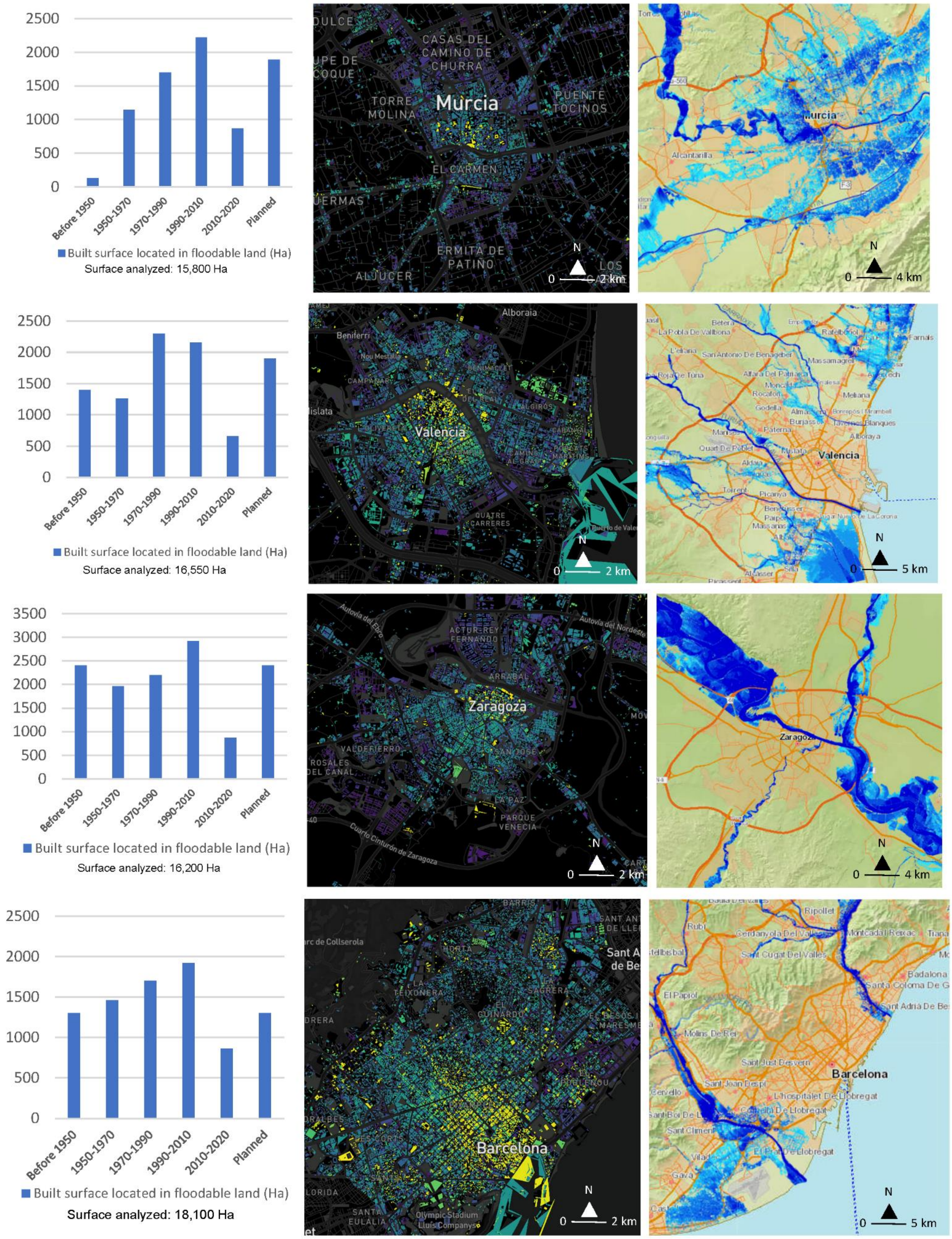


Figure 12. Temporal evolution of the urbanized vs. flooded areas in Murcia, Valencia, Zaragoza and Barcelona.

5. Conclusions

The incorporation of flood risk as a design variable in urban planning is a challenge for the future of cities in the 21st century. The great growth of urbanized areas in most regions around the world, together with the meteorological changes caused by climate change, make it increasingly necessary to consider the impact of urban growth patterns in the study of flood risk in a city. In this field, the proposed analysis framework raises a new and innovative methodological approach that integrates urban growth patterns with traditional elements of flood risk analysis to improve future city planning. This approach makes it possible to numerically quantify from a spatial point of view interaction phenomena that until now had been applied from a more conceptual perspective.

Using this innovative approach, the Spanish city of Murcia and its metropolitan area have been analyzed from a retrospective spatiotemporal point of view. The results obtained for this case study show that the increase in variables such as urban fragmentation or the transformation of the traditional agricultural hydrographic network caused by linear infrastructures can be even more negative from the point of view of vulnerability to flooding than the simple soil sealing effect caused by land use transformation. The diagnosis of future problems is also particularly interesting, given that the current urban inertia combined with a large amount of land planned as developable in the master plan and located in potentially floodable areas will generate a greater scenario of conflict and risk for safety in the coming decades.

Even so, this is an initial proposal that addresses in an aggregate way this increasingly important problem in the urban areas of the Mediterranean arc due to climate change. Therefore, it should be further developed in greater depth through future lines of research to address, in more varied cases and with greater precision, the two-dimensional relationships between each of the urban planning variables and the future risk of flooding.

Supplementary Materials: A GIS file of the area of study can be downloaded at: https://www.mdpi.com/article/10.3390/land12030543/s1.

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Multi-Scenario Land Use Simulation and Land Use Conflict Assessment Based on the CLUMondo Model: A Case Study of Liyang, China

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Abstract: By predicting and analyzing regional land use conflicts (LUCs), the contradictory relationship between urban development and land resources can be revealed, which can assist in achieving the rational use of land resources. Taking Liyang as a case study, this paper simulated land use in 2030 under three scenarios, namely, the natural growth scenario (NGS), economic development scenario (EDS), and ecological protection scenario (EPS), using the CLUMondo model. The ecological risk assessment model was used to measure the LUCs under each scenario. Through the comprehensive analysis of land use conversion, spatial distribution, and the change characteristics of LUCs, optimization strategies for future land use are proposed. The results indicate that (1) the intensity of land conversion under the three scenarios is ranked as EDS > NGS > EPS; (2) there is little change in the LUCs under the EPS, while significant deterioration is observed under the NGS and EDS; (3) the intensity of LUCs is positively correlated with the degree of land use conversion; and (4) in the future, particular attention should be paid to areas around the city center, the Caoshan Development Zone in the northwest, and Nanshan Bamboo Sea in the south, where high-intensity land use conflicts may occur.

Keywords: land use simulation; CLUMondo model; land use/cover change (LUCC); land use conflicts (LUCs)

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1. Introduction

As a non-renewable resource necessary for human survival, land is the most basic material for human production and life. It serves as the foundation for the development of a country and society as a whole. As the world's population grows rapidly and urbanization accelerates, limited land resources are supporting larger and more intensive human activities [1]. Inappropriate development and land use have caused a number of significant global problems, such as vegetation destruction, land degradation, and biodiversity loss [2]. Therefore, effectively resolving the conflict between urban development and land resources in order to achieve sustainable land use and maintain regional ecological stability has become an important issue in today's world [2,3]. Land use/cover change (LUCC) refers to changes in the land surface caused by human activities [3]. It reflects the interaction between human activities and natural factors in the regional ecological environment [1], and it is an important factor influencing ecological processes on the Earth, such as biochemical cycling, energy exchange, and soil erosion and deposition [4,5]. In 1992, the United Nations issued "Agenda 21", in which LUCC research was clearly identified as a priority for the 21st century [6]. In 1995, the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme (IHDP) on Global Environmental Change jointly proposed the "Land Use/Cover Change Science Research Program", making LUCC-related issues a research priority in countries around the world [7]. In 2005, the

Global Land Project (GLP) was launched jointly by IGBP and IHDP to better continue the LUCC program that started a decade earlier [8]. This project emphasizes the integration of LUCC research, which requires a comprehensive consideration of the coupling relationship between human and natural factors, with research on the interaction between social and ecological systems and on the connections across regions and urban-rural areas. In 2016, the Global Land Project was changed to the Global Land Programme, which continues as a research initiative aimed at understanding, measuring, and modeling the changes in the coupled human-environment system [9]. After almost 30 years of development, research on LUCC has made great progress in theory, methodology, and practice. The main research directions include LUCC monitoring, driving mechanisms, environmental impacts, and simulation. These fields are interrelated and complementary and together form the basic framework of land use and land cover change research [2,10,11].

To respond in a timely manner to the environmental pressures brought by urban development and human demands for land, land use simulation can predict future land change trajectories and development patterns, as well as identify the most appropriate spatial patterns of land use under different future development scenarios. This can provide guidance to urban planning and land policy making [12,13]. At present, the main land use change models are the Markov model, SLEUTH model, system dynamics (SD) model, agent-based model (ABM), cellular automata (CA) model, CLUE-S model, etc. [14]. Each of these models has its own unique characteristics and scales of applicability. The Markov model can quantify the conversion state and conversion rate of land use types, but it cannot describe spatial changes. The SLEUTH model is suitable for urban growth simulation and long-term forecasting, but it takes less account of social and economic factors. The SD model can reflect the interrelationships among the structure, function, and dynamic behavior of complex systems, but it is difficult to handle spatial information and lacks the ability to describe the spatial pattern of land use. The agent-based model (ABM) is limited in its applicability to certain regions and scenarios and has difficulty representing the spatial behavior of a subject [15,16]. The CA model is better at representing the neighborhood effects, but its conversion rules are based on empirical statistics or expert knowledge, making it susceptible to human factors. The CLUE-S model can simulate the changes in multiple types of land use and reflect the situation of land use change in terms of time, space, and quantity. It is particularly suitable for studying land use/cover change in small-scale regions. The CLUMondo model is the latest improved version of the CLUE-S model. It has inherited all the advantages of the CLUE-S model and addresses the shortcomings of its inadequate consideration of macro and non-spatial factors [17]. The CLUMondo model can convert macro factors, such as policies into land use demand parameters, comprehensively considering direct and indirect demand for different types of land area. It can also spatially allocate different intensities of land service demand based on land suitability and select the allocation order according to the strength of competition. The study case in this paper is Liyang, a county-level city in China, which is a small-scale region currently facing the challenge of balancing the conflicting objectives of economic, environmental, and social benefits while undergoing rapid urbanization. Therefore, the CLUMondo model was selected for the city to perform multi-scenario land use prediction in order to explore the possibilities of future land use changes and spatial patterns in the study area.

During the process of land use, disagreements among stakeholders over the use, allocation, quantity, and distribution methods of the land can result in land use conflicts (LUCs) [1]. They reflect the discordance and imbalance between the allocation of land use and the needs of social development in human-environment relationships, such as conflicts between urban expansion and the protection of basic farmland or ecological conservation. Severe LUCs can pose a threat to ecological and food security, thereby limiting regional sustainable development [18]. They can also lead to disputes over land rights and interpersonal conflicts, and they can even become important factors affecting social stability [19]. Scholars have analyzed LUCs from the perspectives of economics, geography, ecology, and sociology. Qualitative analysis methods commonly used include participatory survey methods, logical framework approaches, and game theory analysis. While these methods assist researchers in understanding the mechanisms behind and finding solutions to land use conflicts, quantitatively measuring such conflicts remains a challenge [20]. Commonly used quantitative analysis methods include suitability assessment [21,22], multicriteria analysis [23–25], ecological risk assessment [1,20], and the pressure-state-response (PSR) model [18,26–28]. Based on the theory and methods of landscape ecological risk assessment, ecological risk assessment is a model for measuring conflicts. It constructs a conflict index by considering risk sources, risk receptors, and risk effects. The model creates a "comprehensive spatial conflict index = spatial complexity index + vulnerability index − stability index" equation to quantify spatial conflicts. This method can accurately identify conflict locations and spatial characteristics, as well as reveal regional ecological risks caused by inappropriate spatial structures of land use. Due to various ecological problems in Chinese cities caused by rapid urbanization, and the fact that this method can objectively and effectively characterize the pressure of human interference and natural degradation, this study selected the ecological risk assessment model to measure land use conflicts in the study region.

Currently, research on land use simulation is mostly focused on revealing the characteristics of land use conversion [29,30], exploring future development scenarios [31–33], and evaluating future ecosystem services [16,34,35]. The research on land use conflict is mainly focused on identifying the spatiotemporal evolution characteristics [36–38] and driving factors of current land use conflicts [39,40]. Few studies have explored the possible development trends of LUCs by land use simulation and prediction. This limits the comprehensive and profound analysis of land use conflict issues and also has a restrictive effect on the formulation of future land use management policies. Especially for China, where development is rapid and land resources are extremely scarce, spatial planning strategies that are forward-looking and can predict land use issues are particularly important. Since 2019, territorial spatial planning has become an important development strategy in China. Its main purpose is to coordinate land use and development intensity among different regions based on their resource endowments and comparative advantages, so as to avoid the escalation of regional land use conflicts and contradictions caused by the different positioning of planning functions [41,42]. Therefore, government policies need to consider future land management, and research on land use conflicts (LUCs) should expand to include simulations of potential future changes.

In light of the limited focus on future land use conflicts in academic research, this paper uses the Liyang in Jiangsu Province as a case study to provide empirical evidence for predicting potential future trends in land use conflicts through multi-scenario land use simulations. This paper also suggests strategies for spatial governance and optimizing land use patterns to address and reduce land use conflicts. The research provides a valuable reference for future studies on the sustainable use of regional land resources and territorial spatial planning. The study's specific research objectives include (1) studying land use changes in Liyang in 2030 under different scenarios; (2) examining the spatial characteristics of future land use conflicts (LUCs) in Liyang; and (3) determining strategies and key areas for spatial optimization in Liyang.

2. Materials and Methods

2.1. Study Area

Liyang is a city at the county level in Jiangsu Province, situated between 31°09′–31°41′ north latitude and 119°08′–119°36′ east longitude. It is located at the intersection of three provinces in the Yangtze River Delta region. It has a variety of topographical features, including low mountains, hills, plains, and polders, and has a total area of 1535 km^2. The city is interwoven with rivers and lakes; it has low mountains and hills in the south and northwest and plains and polders in the center (Figure 1). Since the early 1990s, tourism has become an important industry in Liyang, not only solving people's food and clothing problems but also driving rapid economic and urban development. By 2020, Liyang's urbanization rate had risen from less than 10% in the 1980s to 63%, and its total GDP had increased from 28 million in the 1980s to 108.6 billion (Figure 2). In the past 40 years of its development, Liyang's tourism industry has become a breakthrough point for deepening economic reform in the city. In form, the industry has transformed from scenic-spot tourism to all-for-one tourism, emerging as a new model for tourism development. This has led to the rapid development of the city's tertiary industry, which increased from 15% in the 1980s to 45% in 2020. Liyang was selected in the second batch of national all-for-one tourism demonstration zones in 2020. In the future, Liyang will continue to leverage all-for-one tourism as a catalyst for the city's high-quality development. Therefore, eliminating current and potential land use conflicts and forming a coordinated development system of urban development and an ecosystem in the region are key considerations in Liyang's land use planning.

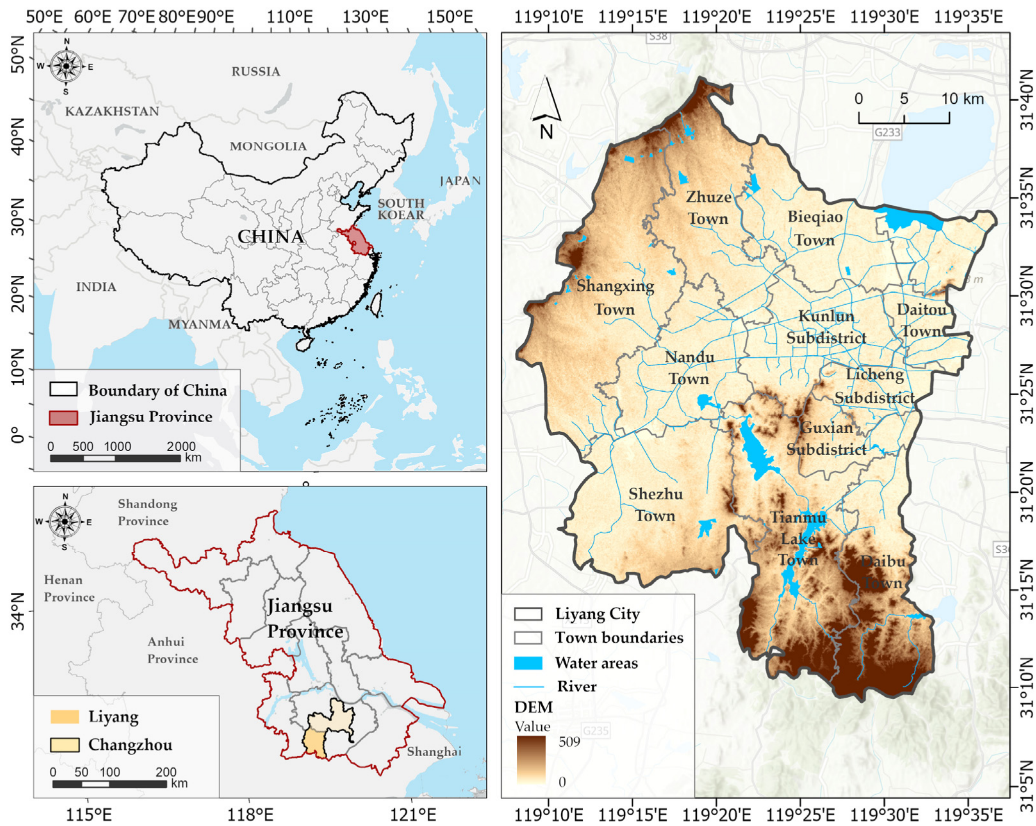
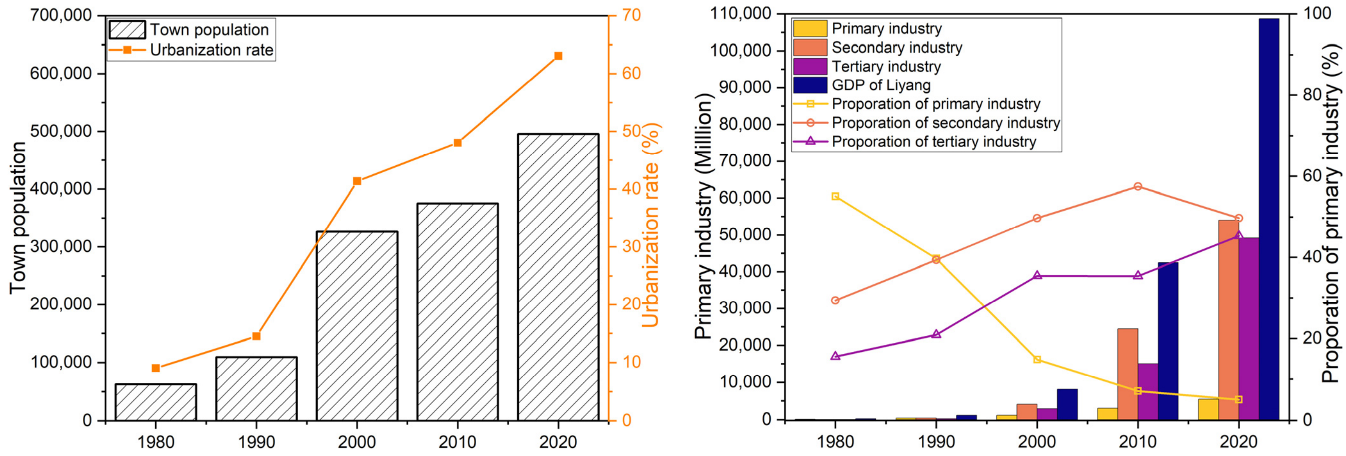


Figure 1. Location and digital elevation map (DEM) of Liyang.

2.2. Data Sources and Processing

The primary data used in this research were resampled to a 90 m precision raster graphic and georeferenced using the Albers Conical Equal Area projection in ArcGIS. These data included land use, topographic, meteorological, soil, position, and socio-economic data, as listed in Table 1. The remote-sensing images were analyzed using ENVI5.3 to identify seven types of land use: cultivated land, woodland, grassland, water area, rural settlements, urban, and other construction land and unused land. Meteorological data were initially obtained from meteorological stations and were converted into grid format by spatial interpolation using ArcGIS 10.6. For land use simulation, all data were converted into ASCII format in CLUMondo, and the ecological sources in the study area were set as restricted areas.



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

Figure 2. Development of Liyang from 1980 to 2020. (**a**) Urbanization process; (**b**) Industry development process.

Table 1. Data sources and description.

Category	Data	Unit	Year	Data Source
Land use	Remote-sensing images	-	2010, 2020	United States Geological Survey (USGS)
	Land use maps	class	2010, 2020	Interpreted from remote-sensing images
Topographic	DEM	m	2010, 2020	Geospatial Data Cloud
	Slope	°	2010, 2020	Extracted from DEM data
	Aspect	-	2010, 2020	
Meteorological	Annual total precipitation	mm	2010, 2020	China Meteorological Data Service Centre
	Annual average temperature	°C	2010, 2020	
Soil	Soil water content	m^3	2010, 2020	National Tibetan Plateau Data Center
	Soil salinity	%	2010, 2020	World Soil Information (ISRIC)
Position	Distance to major rivers	km	2010, 2020	OpenStreetMap
	Distance to main traffic	km	2010, 2020	
	Distance to township centers	km	2010, 2020	
Socio-economic	Population density	people/km^2	2010, 2020	Statistical Yearbook of Liyang City
	Per capita GDP	10^4 yuan	2010, 2020	
	Fixed assets investment	10^8 yuan	2010, 2020	
	Nighttime light	-	2010, 2020	National Tibetan Plateau Data Center

2.3. Methods

Figure 3 illustrates the overall research structure. The study area's land use in 2030 was projected using the CLUMondo model under various scenarios. The ecological risk assessment model was used to evaluate the LUCs in the region from 2010 to 2030. Some spatial analysis approaches, such as standard deviational ellipse and hot spot analysis, were used to quantitatively describe land use features. Based on these analyses, strategies for land management and planning were proposed.

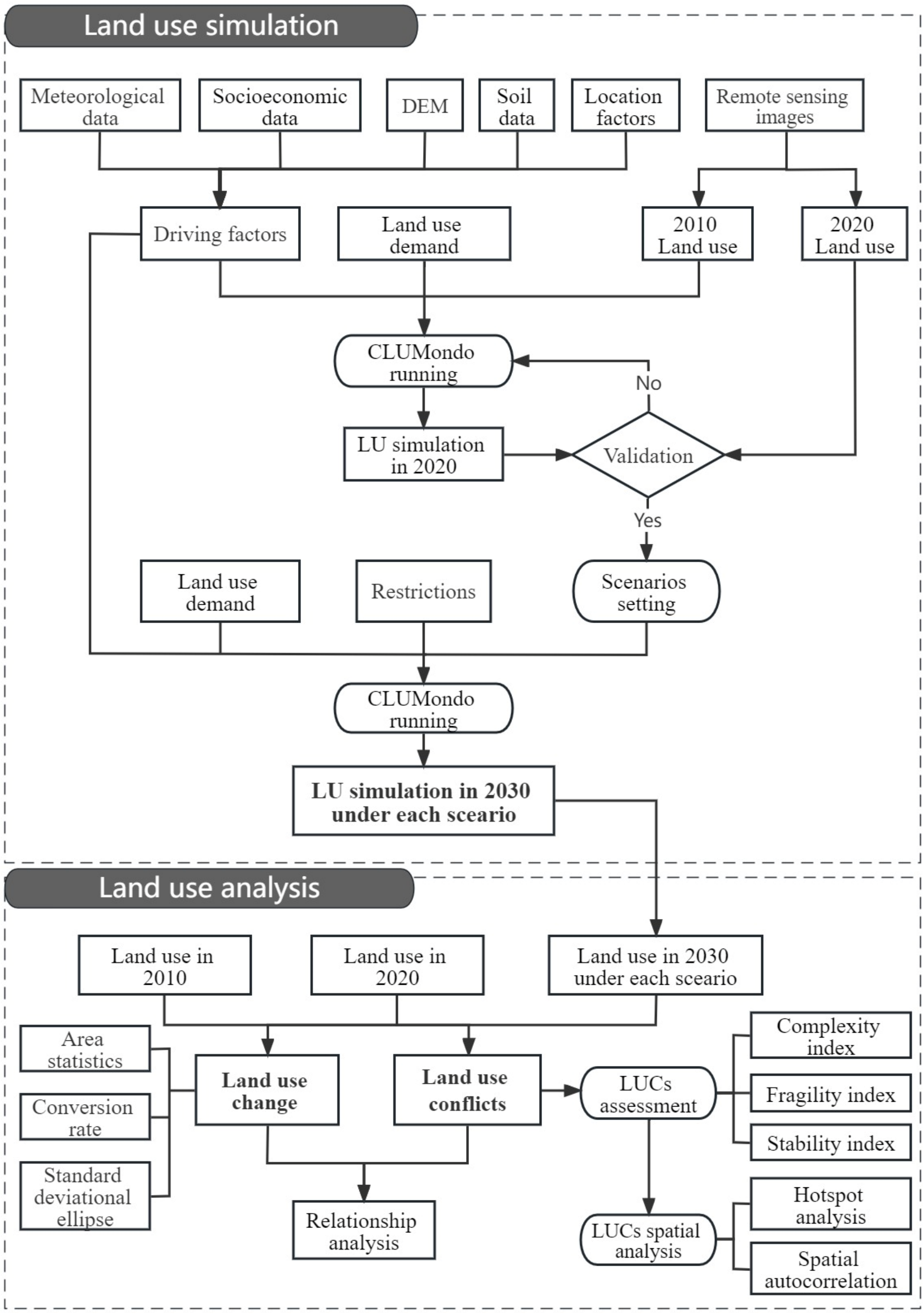


Figure 3. Technical flow chart.

2.3.1. Dynamic Degree of Land Use

The dynamic degree of land use reflects the conversion rate and intensity of land use change in the study area [43]. The single dynamic degree indicates the conversion rate of a certain type of land during the conversion period [44]. The calculation formula is as follows:

$$K_i = \frac{S_b - S_a}{S_a} \times \frac{1}{T} \times 100\% \quad (1)$$

where K is single land use dynamic degree; i is a certain land use type; S_a is the area of a certain land use type before the conversion; S_b is the area after the conversion; and T is the conversion period.

The comprehensive dynamic degree represents the change rate of all land use types and reflects the overall land use stability in the study area [45]. A higher value indicates more active land use changes and poorer overall stability. The formula is as follows:

$$S = \left[\sum_{i=1}^{n} \left(\frac{\Delta S_{i-j}}{S_i} \right) \right] \times \frac{1}{T} \times 100\% \quad (2)$$

where S is the comprehensive land use dynamic degree; S_i is the total area of land use type i; ΔS_{i-j} is the total area of land use type i converted in and out; and T is the transfer period.

2.3.2. Land Use Conflict Assessment Model

When a land ecosystem experiences a significant disruption, its spatial pattern alters, leading to disruptions in natural processes, reduced biodiversity, and harm to the region's ecological security [46]. This occurrence demonstrates the clash between the spatial arrangement of land use and the natural environment. Typically, the lower the ecological risk posed by a land use structure, the less severe the land use spatial conflict [18]. As a result, the land use conflict assessment model was developed by drawing on the "risk source-risk receptor-risk effect" ecological risk evaluation model. The formula is as follows:

$$LUCI = CI + FI - SI \quad (3)$$

where $LUCI$ is the index of land use conflict; CI is the complexity index; FI is the fragility index; and SI is the stability index. As a reliable measure of risk sources, landscape complexity reflects external pressures from human activities and intensive land use. The area-weighted mean patch fractal dimension (AWMPFD) [20] is employed to describe the intricacy of land use patches and indicate the extent to which neighboring landscapes affect current landscape units. A higher value signifies a more complex landscape patch boundary and a greater likelihood of disturbance from human activities [20,47]. The calculation formula is as follows:

$$CI = AWMPFD = \sum_{i=1}^{m} \sum_{j=1}^{n} \left[\frac{2\ln(0.25P_{ij})}{\ln(a_{ij})} \times \left(\frac{a_{ij}}{A} \right) \right] \quad (4)$$

where P_{ij} is the perimeter of the j-th patch of the i-th land-use type; a_{ij} is the patch area of the j-th patch of the i-th land use type; A is the total landscape area; m is the number of patches; and n is the number of land use types. The index values have been linearly adjusted to fall within the [0, 1] range in order to simplify subsequent calculations. The fragility index measures the responsiveness of spatial patches to external pressures and indicates the risk receptors' carrying capacity [47]. The lower the resilience of receptors, the more vulnerable the spatial patch is to external disturbance and the higher the level of land use conflict [48]. According to the previous studies [48–51] and the characteristics of regional urbanization, the fragility values of seven land use types in the study region were determined to be: urban and other constructed land (7), rural settlements (6), unused (5), grassland (4), water (3), farmland (2), and woodland (1). The calculation formula is as follows:

$$FI = \sum_{i=1}^{m} \sum_{j=1}^{n} F_{ij} \times \frac{a_{ij}}{A} \quad (5)$$

where F_{is} is the fragility degree of the j-the patch of land-use type i; a_{ij} represents the area of the j-th patch of land use type i; A represents the total area of the landscape; m is the number of patches; and n stands for the number of land use types. To make calculations easier, the results were linearly adjusted to fall within the [0, 1] range. As a key measure of the risk effect, landscape stability is assessed using the patch density index (PD), which indicates the degree of landscape fragmentation. A higher value signifies a more fragmented landscape, poorer land stability, and more severe land use conflict [1,20]. The calculation formulas are as follows:

$$SI = 1 - \frac{PD - PD_{min}}{PD_{max} - PD_{min}} \tag{6}$$

$$PD = \frac{n_i}{A} \tag{7}$$

where PD is the index of patch density; PD_{min} and PD_{max} represent the minimum and maximum values of PD; n_i is the number of landscape patches of land use type i; and A is the total area of the landscape.

2.3.3. Simulation of Future Land Use

As the latest iteration in the series of Conversion of Land Use and its Effect (CLUE), CLUMondo is a dynamic and spatially explicit land use model capable of simulating changes in both land cover and land use intensity [52]. Its land use simulation is based on a combination of an empirical analysis of location suitability and a dynamic assessment of the interactions between land use systems [53]. The demand for goods and services, spatial restrictions, and competition between different land use types are comprehensively considered in the CLUMondo model, effectively improving on previous land use simulation methods that focused only on the quantity of land conversion [54,55].

1. Scenario settings

Three simulation scenarios were established to examine the future development trend of land systems in the study region under different conditions, based on government planning, economic development objectives, and environmental protection demands [56–58].

The natural growth scenario (NGS) refers to a situation where the study area would not experience sudden natural disasters, such as droughts and floods, in the next decade or so, and was not strongly interfered with by external factors. The future transformation followed the trend of land use change in the past (2010 to 2020). According to the government's plan, the urbanization rate will reach 80% by 2030 (17% higher than in 2002), and the city's GDP will need to increase by about 250 billion yuan (about 140 billion yuan higher than in 2020) (Table S1).

The economic development scenario (EDS) focused on economic benefits by expanding the area of built-up land, especially the urban area, traffic land, and industry land. As a result, under this scenario, the growth rate of rural areas was set to be roughly equivalent to that under the NGS, while the growth rate of urban and other construction land was increased by 30% compared to the NGS.

The ecological protection scenario (EPS) aimed to enhance the ecological environment and the services it provides. It took into account the need for strict ecological boundaries and restoration efforts in government planning. This scenario assumed that the area of ecological land in the study area would increase by 10% by 2030. In addition, important ecological sources in this study area include the planned ecological red line area, so these large ecological patches were set aside as conservation areas that could not be converted.

The simulation of different scenarios was realized by different parameter settings, including by adding constraint conditions and defining the conversion matrix and conversion resistance coefficient.

2. Parameter setting for CLUMondo model

Based on previous studies [1,14,32,34,43,59–63] and data availability, 14 independent variables were selected to explain the location suitability of land use (Table S2). A total of 2 factors with high correlation values (above 0.8) were eliminated, and a total of 12 driving factors of LUCC were determined, as shown in Figure S1. Logistic regression analyses were carried out for each land use type and driving factor to obtain "AUC" values, which represent the accuracy of the calculated regression (Table S3).

Six land use service demands (crop production, woodland area, grassland area, water area, rural settlements area, and urban and other construction land area) were calculated independently under different scenarios (Table S4). The annual changes in each service were determined by linear interpolation between the corresponding data in 2010 and 2020. The NGS projected the future land system using the same trend as before. The grey theory is known for its unique ability to make accurate predictions using limited data and uncertain factors [64]. The GM (1.1) model is often used as a forecasting tool within the grey theory and was used in this scenario to calculate the demand for land use services. In EDS, the change rate of rural settlements was set according to the previous decade. The change rate of urban and other construction land was set 30% higher than before, as the construction of characteristic towns, tourism facilities, and transport networks will be greatly developed for all-for-one tourism in the future. In EPS, the areas of woodland, grassland, and water in 2030 were set to increase by 10%. Ecological sources are large patches that provide important ecosystem services, and these should be well-conserved. Identified in a previous study [65], they were determined to be spatial restrictions for the land use simulation under the EPS (Figure S2).

Conversion resistance is a measure of how easily land can be converted. It ranges from 0, which means easy conversion, to 1, which means the change is irreversible. This reflects the convertibility of the land. Each land use type was assigned a specific resistance value under different simulation scenarios, as shown in Table S5. The conversion matrix shows the potential for different types of land use to be converted into one another. The values in the matrix are defined as '1' for allowed conversion, and '0' for not allowed conversion. In this study, the simulations under the NGS and EDS had the same conversion matrix, with the matrix having different values of ecological land than those of the matrix under the EPS, as shown in Table S6.

3. Model validation

The accuracy of the CLUMondo model was checked by comparing its 2020 simulation with the actual land use map from 2020. First, based on the 2010 land use map and the natural growth scenario parameter setting, the 2020 land use simulation was carried out. Then, the Map Comparison Kit (MCK) was used to perform a cell-by-cell comparison using the Kappa algorithm. Kappa statistics, including Kappa, Kappa Histo (KHisto), and Kappa Location (KLoc), were calculated for the whole map and each land use type. Generally, a Kappa value greater than 0.75 indicates good agreement between the two maps and high reliability of the land use simulation. A Kappa value between 0.4 and 0.75 indicates fair agreement, while a value less than 0.4 indicates poor agreement [66,67].

2.3.4. Spatial Autocorrelation Analysis

Spatial autocorrelation analysis was used to determine the heterogeneity of the spatial distribution of LUCs, including the global spatial autocorrelation index Moran's I and the local spatial autocorrelation index LISA [68–70]. Moran's I indicates the extent to which similar values of a variable are clustered together in space. The value range of Moran's I is −1–1. If a Moran's I value is greater than 0, the spatial correlation is positive, meaning that the locations with similar attributes of the variable are clustered together. When Moran's I is less than 0, it indicates that there is a negative spatial correlation, meaning that locations with similar values for a variable are spread out or dispersed in space. If Moran's I is equal to 0, it means that there is no spatial correlation. LISA measures the degree of spatial clustering of a specific location surrounded by similar or dissimilar values. The result is shown in a map of high and low clustering, which is useful for identifying the spatial pattern of local autocorrelation. The calculation formulas are as follows:

$$Moran's\ I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \overline{x})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (8)$$

$$LISA = \frac{n(x_i - \overline{x})}{\sum_i (x_i - \overline{x})^2} \sum_i W_{ij}(x_i - \overline{x}) \quad (9)$$

where n is the total number of conflict cells; x_i and x_j represent the values of a variable x at two different spatial locations i and j; $\overline{x}$ represents the average value of the variable; and W_{ij} is the spatial adjacency matrix.

3. Results

3.1. Validation of CLUMondo Model

The land use status in 2020 and the land use simulation of the study region in 2020 are shown in Figure 4. The Kappa coefficients are shown in Table S7. With the exception of the unused land, the Kappa coefficient of each land use type was greater than 0.6. This is because the unused land represented only 2.2 percent of the area and was scattered and susceptible to human behavior, resulting in high simulation difficulty and low simulation accuracy. In general, the overall Kappa coefficient was greater than 0.75, and it can therefore be considered that the CLUMondo model was reliable for simulating future land use changes in the study area.

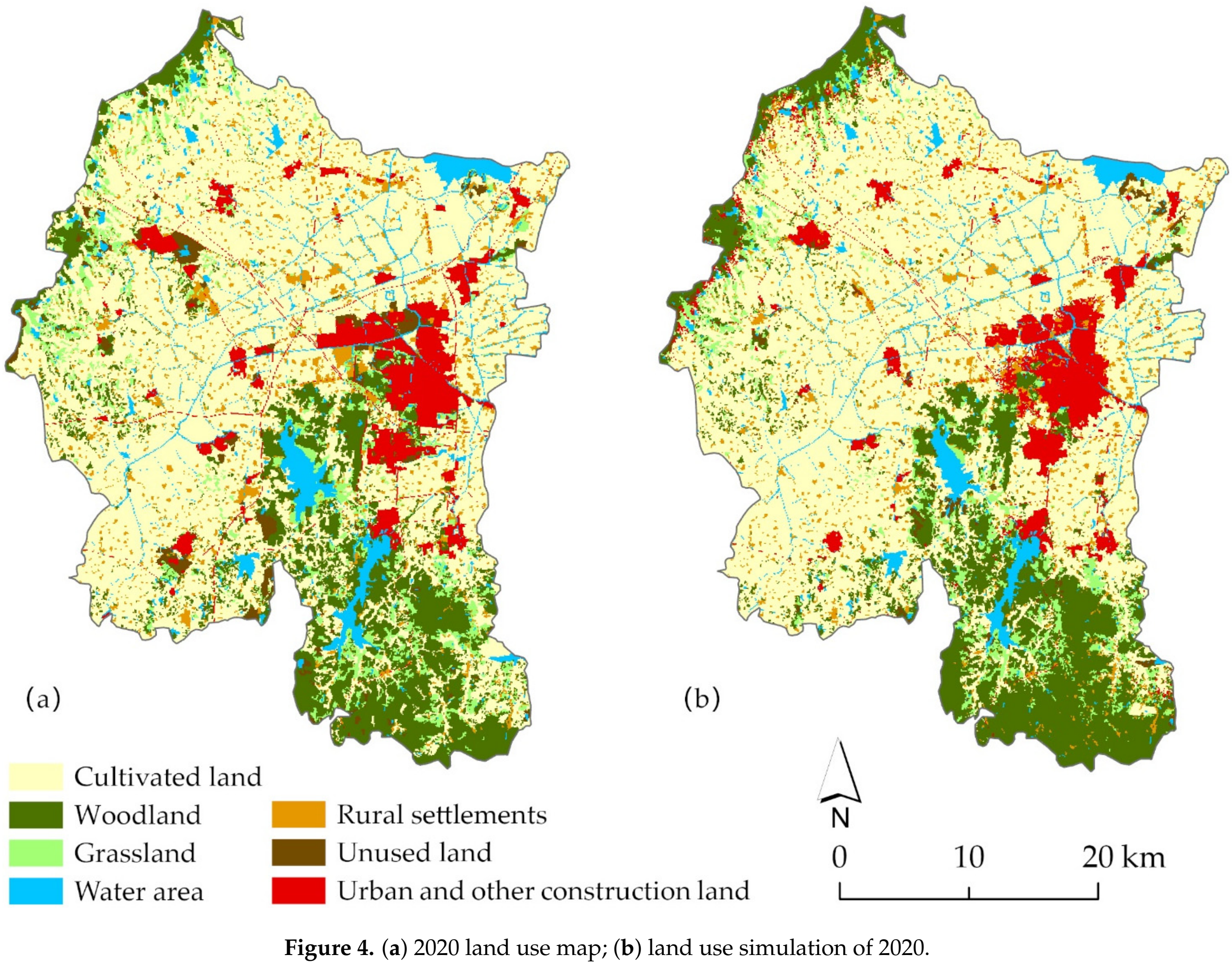


Figure 4. (**a**) 2020 land use map; (**b**) land use simulation of 2020.

3.2. Simulation Results of Future Land Use

The spatial distributions of the land use simulation for 2030 are shown in Figure 5. The land use areas and change rate are shown in Figure 6. The area conversion graphs of each land use type under the defined scenarios are shown in Figure 7. Generally, the water area and rural settlements changed slightly under the three scenarios. Significant changes occurred in the cultivated land, grassland, unused land, and urban and other construction land. In all scenarios, there was a large decrease in cultivated and unused land, while urban and other construction land increased significantly.

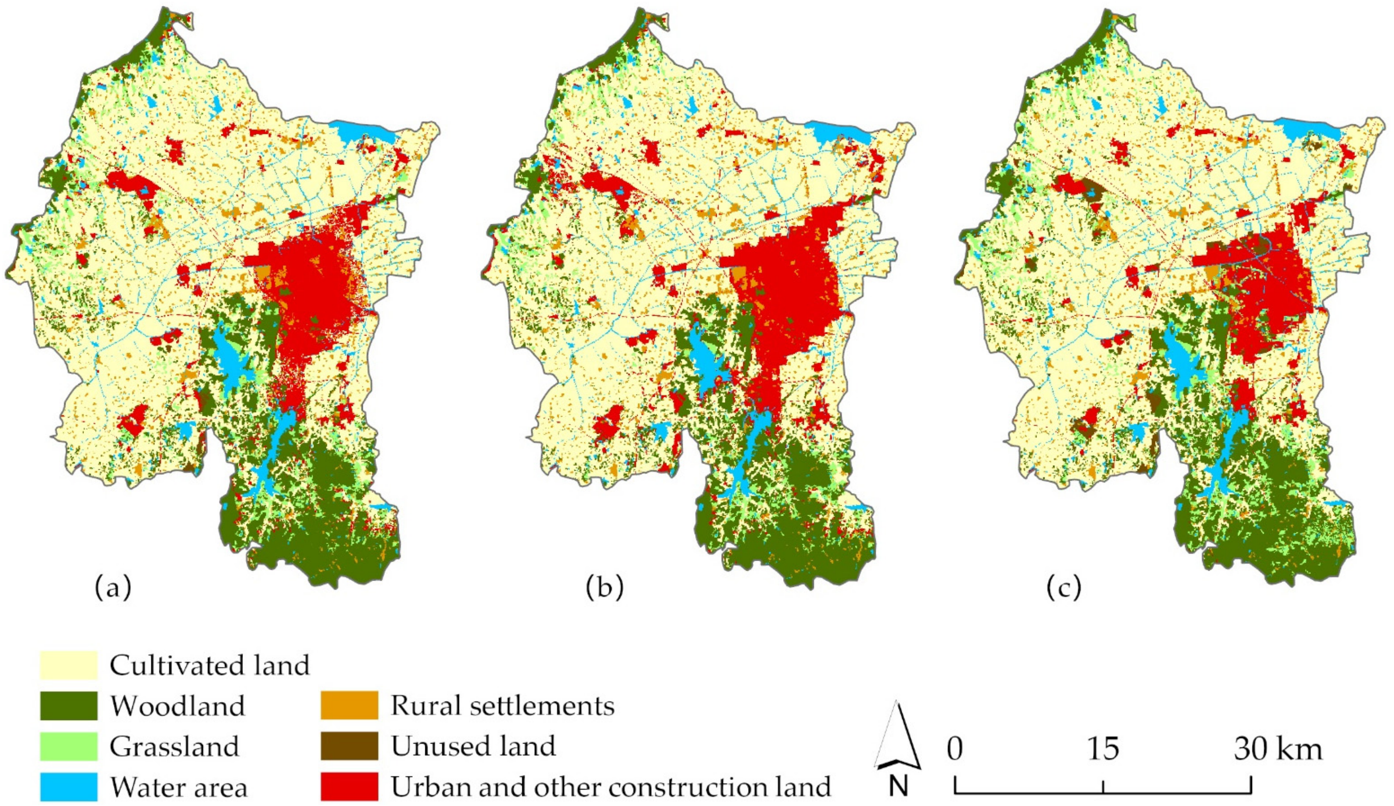


Figure 5. Results of land use simulation in 2030 under different scenarios. (**a**) NGS; (**b**) EDS; (**c**) EPS.

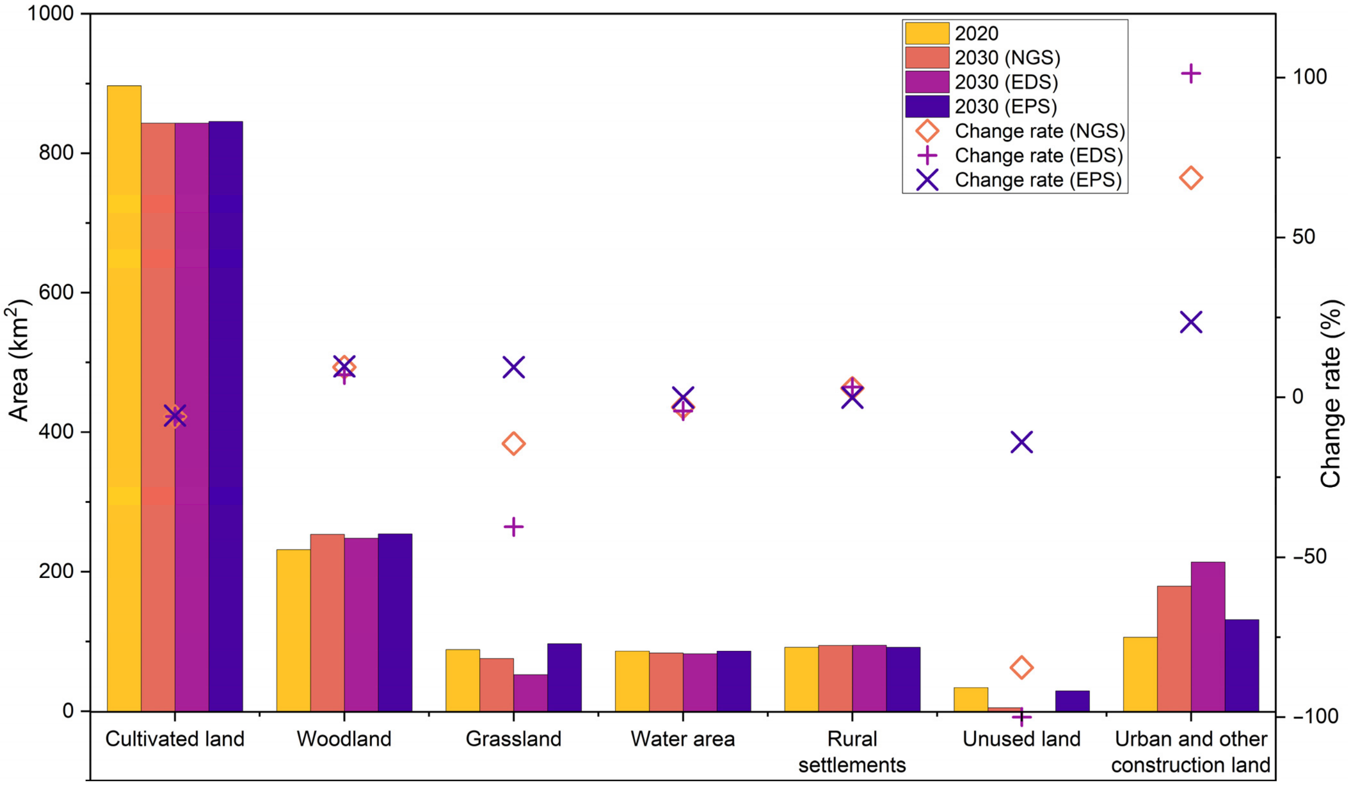


Figure 6. Land use changes under different scenarios for 2030.

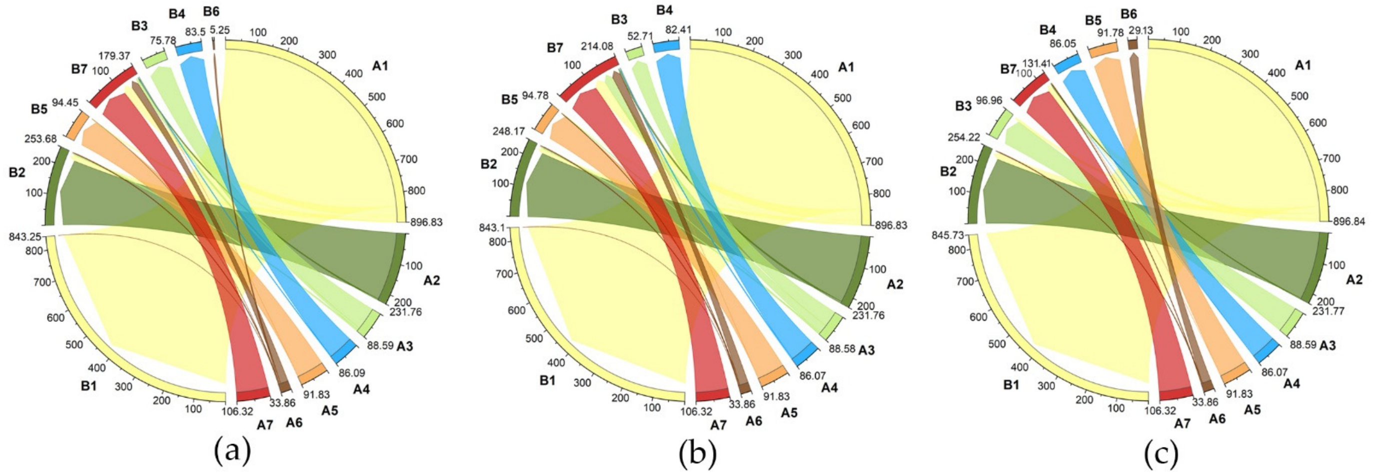


Figure 7. Land use conversion area chord diagrams. (**a**) NGS; (**b**) EDS; and (**c**) EPS. A1–A7 are the land use types in 2020; B1–B7 are the land use types in 2030; 1–7 represent cultivated land, woodland, grassland, waters, rural settlements, unused land, and urban and other construction land.

Under the NGS, the urban and other construction land expanded mainly around the original urban center, recording an area of 73 km^2 and a growth rate of 68.69%. These conversions were mainly derived from the cultivated land and unused land, which accounted for 44.13% and 34.66%, respectively. A total of 53.74 km^2 of the cultivated land was converted into urban and other construction land (59.98%), woodland (34.34%), and rural settlements (5.68%). A total of 28.61 km^2 of the unused land was converted, of which 88.51% was converted to urban and other construction land, 10.9% to woodland, and 0.59% to cultivated land and rural settlements. The woodland increased by 9.46% and the grassland decreased by 14.46%, while the change rates of the rural settlements and water area were no more than 5%. Premised on the economic development of the EDS, the expansion of built-up land around the urban center rapidly led to the formation of one large area, with a newly added area of 107.77 km^2 and a high growth rate of 101.33%. The conversions were derived from every land use type, of which the cultivated land, grassland, and unused land accounted for more than 90%. A total of 53.96 km^2 of the cultivated land was converted to the urban and other construction land (71.71%), woodland (27.8%), and rural settlements (0.5%). Nearly 87% of the converted grassland became built-up land, amounting to an area of 31.23 km^2, while the remaining 13% became woodland. All of the unused land with an area of 33.86 km^2 was converted, 84.5% of which to the urban and other construction land, 9.23% to woodland, 5.57% to rural settlements, and 0.7% to cultivated land. The woodland and rural settlements increased by 7.08% and 3.2%, respectively, while the water area decreased by 4.25%. The scale of built-up land expansion under the EPS was significantly smaller than that of those under the other two scenarios. It was because the amount and distribution of built-up land were well-controlled for the sake of ecological protection. Further, the urban and other construction land increased by only 25.1 km^2, with a change rate of 23.58%. The conversions mainly derived from the cultivated land (78.33%), woodland (12.96%), and unused land (8.46%). Both the woodland and grassland increased by around 10%, while the unused land decreased by around 14% and the cultivated land decreased by around 6%. The water area and rural settlements remained almost unchanged.

3.3. Characteristics of Land Use Conflicts

The spatial distributions of the LUCs and the proportion of the area occupied by each conflict level are shown in Figure 8 and Table 2. The average conflict index increased in 2030 compared to 2020 in all scenarios, with the highest increase observed under the EDS. In 2020, high-level conflict areas accounted for 34.3%, were mainly scattered along rivers and traffic arteries, and were locally mixed with higher-level conflict areas, which accounted for 2.16%. The LUCs in 2030 under the EPS remained basically unchanged, while there were significant changes under the NGS and EDS. The area of high-level LUCs under the NGS increased slightly by 0.39%. The area of higher-level LUCs increased by about 1%, forming a ring-shaped pattern around the city center. Under the EDS, the area of high-level and higher-level LUCs increased by 1.33% and 4.7%, respectively. In terms of the spatial distribution of the LUCs, the area of the city center changed the most. Its inner area increased from a low to a moderate level, and its outer ring-shaped higher-level area was more significant than it was under the NGS. In addition, the originally scattered higher-level areas became more aggregated, and new agglomeration centers developed on the northwestern and southern sides of the study area.

Table 2. Statistics for LUCs index measurement.

Conflict Level	Conflict Index Range	Area Ratio (%)			
		2020	2030		
			NGS	EDS	EPS
Lower	0–0.2	10.61	11.00	11.82	10.30
Low	0.2–0.4	19.59	16.90	16.30	19.19
Moderate	0.4–0.6	33.33	34.27	29.39	33.22
High	0.6–0.8	34.30	34.69	35.63	34.78
Higher	0.8–1	2.16	3.15	6.86	2.52
Average conflict index		0.492	0.500	0.508	0.498

Figure 9 illustrates the area of each land use type in the different levels of land use conflict. In 2020 and 2030, more than 90% of both the woodland and water area occupied the low and lower LUC levels, indicating that these two land use types were in a stable state. Apart from its absence under the EDS, the unused land remained in the low and lower LUC levels in both 2020 and 2030. Over 90% of the grassland occupied the low and moderate LUC levels, except for under the EDS, where it was around 80%. The areas of these two types of land were small in size within the study area, so even if their changes were significant, they did not have a great impact on the LUCs. More than 90% of the cultivated land was distributed in the moderate and above LUC levels, with more than 50% being distributed in the high and higher levels, indicating that the cultivated land was highly variable. The distribution of built-up land varied greatly across the different LUC levels. In 2020, 74% of the rural settlements occupied the moderate LUC level. By 2030, more than 50% were in the high and higher LUC levels in all scenarios, with more than 90% occupying these levels under the EDS. The urban and other construction land accounted for only about 6% of the high and higher LUC levels in 2020, while it increased in 2030 to 42% under the NGS, 58.85% under the EDS, and 19.42% under the EPS.

The global spatial autocorrelation test was performed for the LUCs in 2020 and 2030, as shown in Table 3. The p-values were all less than 0.01, and the z-scores were all greater than 2.58, indicating that the results of the spatial autocorrelation confidence test were reliable, i.e., the conflict levels of the different spatial units were not randomly distributed. The value of Moran's I was 0.76 in 2020 and increased to more than 0.8 in 2030, indicating that the clustering of LUCs will increase in the future and that the EDS recorded the strongest clustering effect among the three scenarios. The calculation results of the local index of spatial autocorrelation (LISA) for the LUCs are shown in Figure 10. In 2020, hot spots were scattered in the study area, mainly along rivers and traffic arteries. In 2030, there were no major changes under the EPS. Under the NGS and EDS, there was an obvious belt-shaped hot spot aggregation area around the city center, and the original hot spot areas had all expanded. Compared to the EPS, there were also significant hotspot clustering areas on the northwest and south sides of the city under the EDS. The cold spots were clusters of low-level conflict, and these were mainly concentrated in large areas of water and woodland; the overall change from 2020 to 2030 was not significant. However, the cold spot areas within the city center had greatly reduced by 2030 and had almost disappeared under the NGS and EDS.

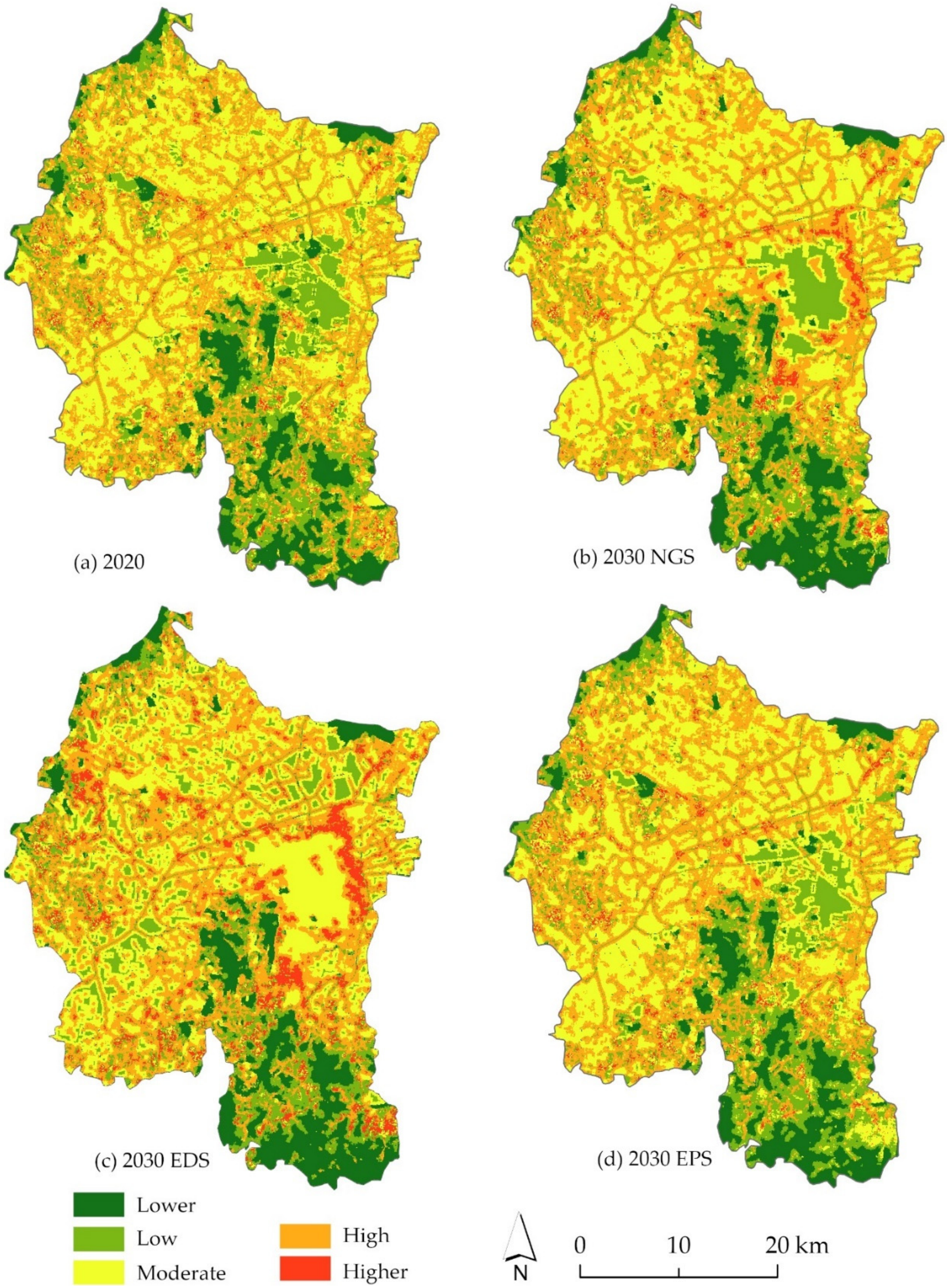


Figure 8. Spatial distribution of land use conflicts.

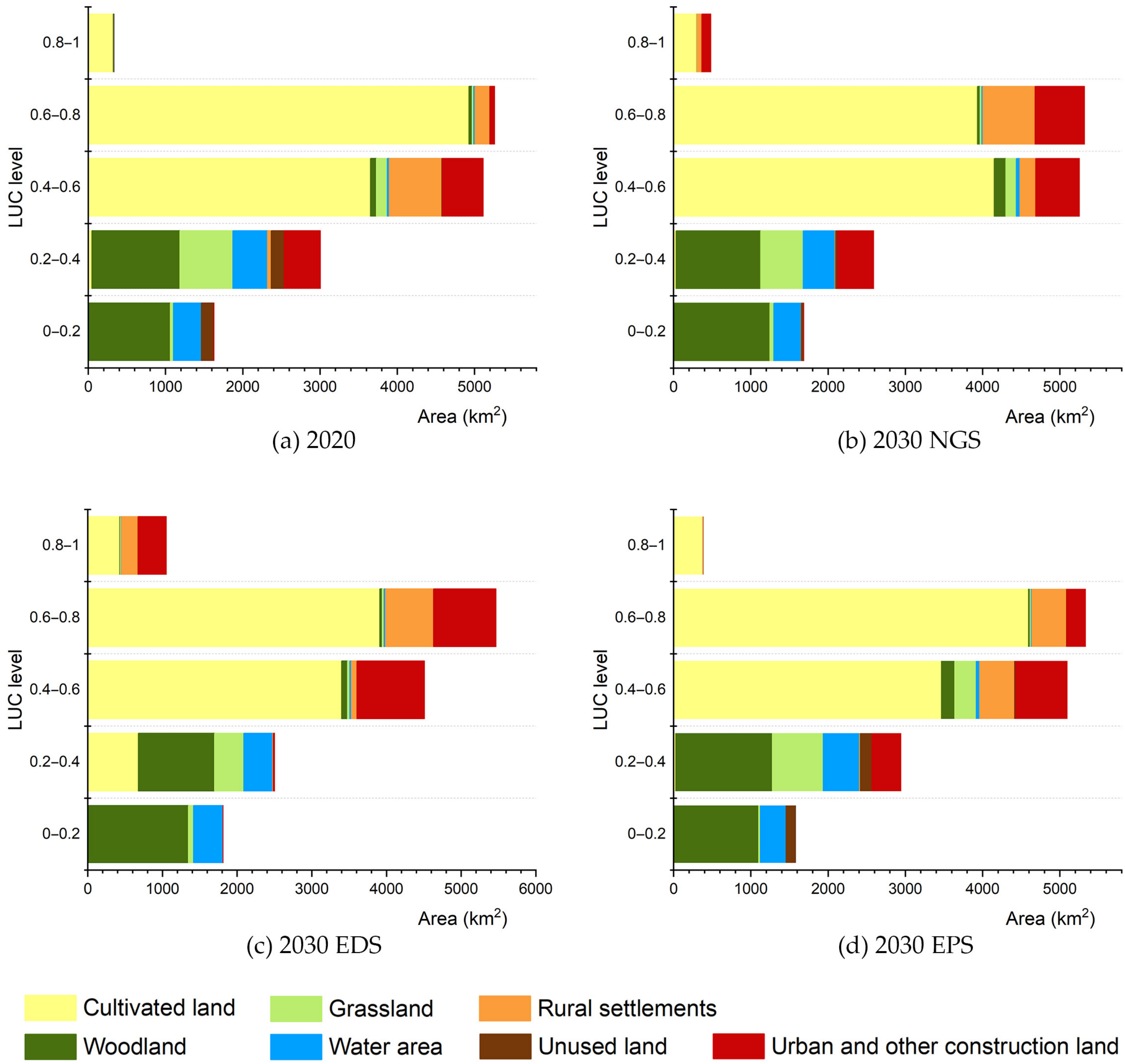


Figure 9. The land use area for each level of land use conflict.

Table 3. Global Moran's I index of LUCs.

Spatial Autocorrelation	2020	2030		
		NGS	EDS	EPS
Moran's I	0.76	0.874	0.884	0.866
z-score	466.102	536.148	541.98	531.312
p-value	0.000	0.000	0.000	0.000

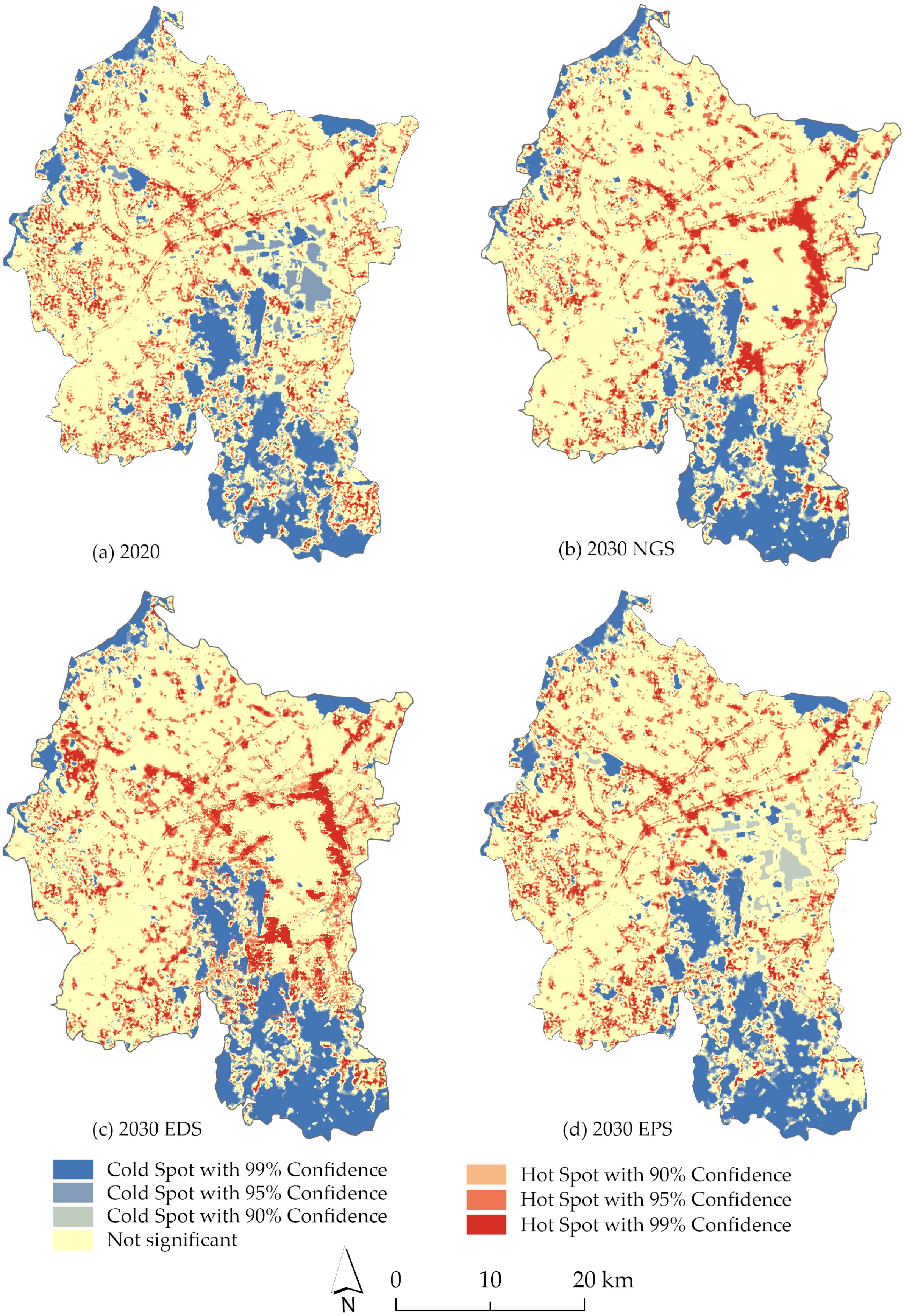


Figure 10. Analysis of local spatial autocorrelation of LUCs.

3.4. Comparison among the Three Scenarios

A statistical analysis of the areas of different land use types (shown in Figure 6) revealed that the areas of cultivated land, woodland, water, and rural settlements were relatively similar across the three scenarios. The grassland, unused land, and urban and other construction land varied considerably in terms of area. In 2020, the area of unused land was 33.86 km^2, and by 2030, all of this had been completely converted under the EDS, only 5.25 km^2 was left under the NGS, and 29.13 km^2 remained under the EPS. The grassland occupied 88.59 km^2 in 2020, and by 2030 it had increased by about 8 km^2 under the EPS, decreased by about 13 km^2 under the NGS, and decreased by about 36 km^2 under the EDS. The area of urban and other construction land increased in all scenarios: 25 km^2 (EPS), 73 km^2 (NGS), and 107.76 km^2 (EDS) respectively. Woodland, grassland, and water are types of ecological lands that can provide ecosystem services, with a total of 406.41 km^2 in 2020 in the study area. They recorded a slight increase of 6.5 km^2 under the NGS, an increase of 30.8 km^2 under EPS, and a decrease of 23.12 km^2 under the EDS. The built-up land, including the rural settlements and urban and other construction land, increased under all scenarios. Its smallest increase was 25 km^2 under the EPS, while its largest increase was under the EDS, which was 4.4 times that under the EPS. Its increase under the NGS was three times that under the EPS. It can also be seen from the comparison of the land use comprehensive dynamics (Table 4) that the overall average index of the EDS was the highest, indicating that land use conversion was most active under this scenario. For each type of land use, the highest value was 8.748, meaning that the conversion of the urban and other construction land under the EDS was the most active. Land use types with relatively high values also included the unused land under the NGS and EDS, the urban and other construction land under the NGS, and the grassland under the EDS, indicating that these land types were also highly converted. Under the EPS, the indices for all land-use types except urban and other construction land, unused land, and woodland were less than one. This suggests that land use change was most stable under this scenario.

Table 4. Land use comprehensive dynamic degree under different scenarios.

Scenarios	Comprehensive Dynamic Degree							
	Overall Average	Cultivated Land	Woodland	Grassland	Water Area	Rural Settlements	Unused Land	Urban and Other Construction Land
NGS	1.329	0.598	1.297	1.446	0.300	0.379	8.386	6.864
EDS	1.559	0.603	1.256	3.974	0.425	0.373	6.154	8.748
EPS	0.770	0.569	1.246	0.943	0.002	0.005	1.393	2.359

Further stand deviational ellipse analysis (Figure 11) showed that the expansion direction of built-up land in Liyang in 2030 was "northwest-southeast", which was consistent with 2020. As shown in Table 5, the X-axis distance, Y-axis distance, ellipticity, and ellipse areas all increased, indicating that there was an expansion of built-up land under all of the scenarios. The values of each parameter changed the least under the EPS, indicating that the expansion in built-up land was the lowest under this scenario. In addition, its mean center deviated from 2020 by only 0.31 km, indicating that the built-up land was in a relatively stable state under the EPS. The increase in ellipse area under the EDS was 6%, indicating that the built-up land tended to be dispersed in the expansion direction, and its mean center was shifted 0.93 km to the southwest. The increase in ellipse area under the NGS of 7.9% was the highest among all the scenarios, and the ellipticity of 0.3 was also the highest, indicating that the built-up land was most discrete in the expansion direction, with its center shifting 0.73 km to the south.

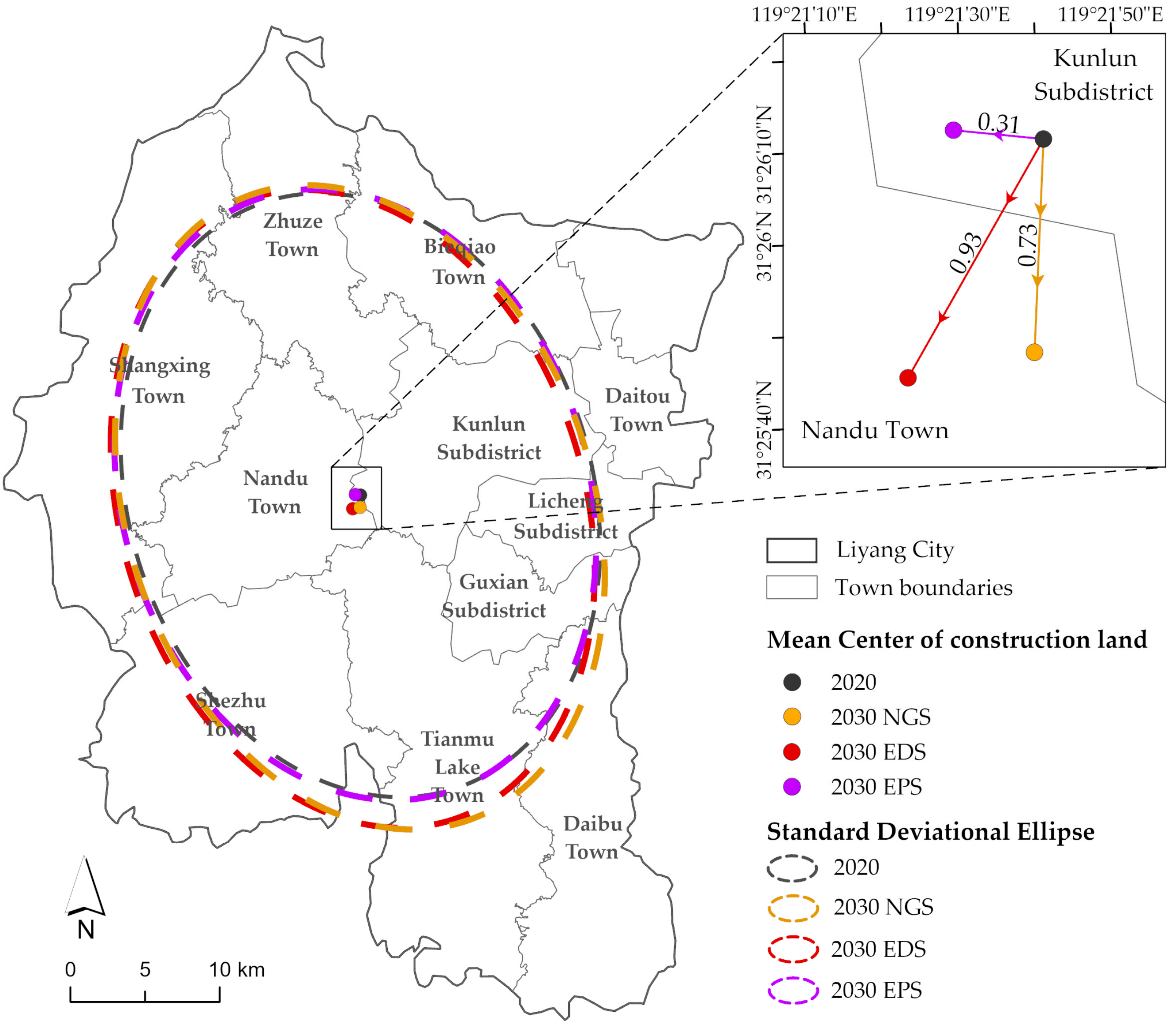


Figure 11. The standard deviational spatial distribution of construction land in 2020 and 2030.

Table 5. Parameter values of standard deviational ellipse.

Year	Scenario	X Distance (km)	Y Distance (km)	Rotation (°)	Ellipticity	Area (km^2)	Central Deviation Distance (km)
2020		13.78	18.36	156.27	0.249	794.85	
	NGS	13.85	19.72	155.09	0.300	857.71	0.31
2030	EDS	13.79	19.45	156.30	0.291	842.41	0.93
	EPS	13.88	18.55	157.00	0.251	808.73	0.73

3.5. Relationship between Land Use Conflicts and Land Use Change

Table 6 shows the quantitative changes in land use conversion from 2020 to 2030 at each level of LUCs under different scenarios. The total areas of land use conversion were 239.36 km^2 under the EDS, 203.98 km^2 under the NGS, and 118.14 km^2 under the EPS. The conversion area in the high and higher levels was 68.21% in the EDS, while this was 46.07% in the NGS and 12.87% in the EPS. As noted in Section 3.2, the average conflict index for the EDS was 0.508, which was higher than the values for the other two scenarios, 0.500 for the NGS and 0.498 for the EPS. This indicates that the degree of land use conversion was closely related to the intensity of land use conflict. Overall, the more land use conversion that occurred in the region, the more intense the land use conflict was.

Table 6. Land use conversion area at each LUC level under different scenarios.

Land-Use Conflict Level		NGS		EDS		EPS	
		LU Conversion Area (km^2)	Ratio (%)	LU Conversion Area (km^2)	Ratio (%)	LU Conversion Area (km^2)	Ratio (%)
L1	Lower	30.61	15.01	32.48	13.57	16.42	13.90
L2	Low	37.07	18.17	18.01	7.52	43.68	36.97
L3	Moderate	42.33	20.75	25.60	10.70	42.84	36.26
L4	High	73.63	36.10	100.27	41.89	15.08	12.77
L5	Higher	20.34	9.97	63.00	26.32	0.12	0.10
SUM		203.98	100	239.36	100	118.14	100

Figure 12 displays the area of each land use type that was converted at each level of land use conflict (LUC) under different scenarios. In all scenarios, a considerable portion of the converted area was attributed to the built-up land, woodland, and cultivated land, while grasslands and unused land came next in terms of their contribution. The proportion of converted cultivated land was most stable under the EPS, remaining between 30% and 50% for all LUC levels, while it was more variable under the other two scenarios, ranging from less than 10% to more than 40%. Under the EPS, the proportion of converted woodland was the highest at 43.2%; this was much higher than that under the other two scenarios, namely, 26.3% under the NGS and 22.61% under the EDS. From L1 to L5 of the land use conflict, the converted area of woodland decreased, and this was mainly concentrated in L1 and L2. The converted area for the urban and other construction land showed the opposite trend. From L1 to L5, the proportion of converted area for the urban and other construction land under the EPS increased from 0.2% to 47.6% at L4 and then decreased to 13.35% at L5. Under the NGS, it increased from 6.9% at L1 to 47% at L3 and then remained stable. Under the EDS, it increased from 1.68% at L1 to 49% at L5. This suggests that the intensity of conversion for urban and other construction land was closely related to the level of land use conflict. The most typical area, in this case, was the urban-rural interface area around the city center, which recorded the highest level of land use conflicts (Figure 8) and significant hotspots (Figure 10). This was because this area was the main region for future construction and expansion (Figure 5), and frequent and intense land use changes often generate severe land use conflicts. Even though the area of other land use types that was converted was relatively small, there was still some relationship between the amount of land use conversion and the level of conflict over land use. The land use dynamic degree is a measure of the intensity of change in land use. The Pearson correlation between the dynamic values for each land use type and the average land use conflict index is shown in Figure 13. Overall, there was a positive correlation between the land use dynamic degree and the average land use conflict, with a correlation coefficient of 0.84 recorded. For each land use type, there was also a positive correlation between land use dynamism and conflict, with the exception of the woodland.

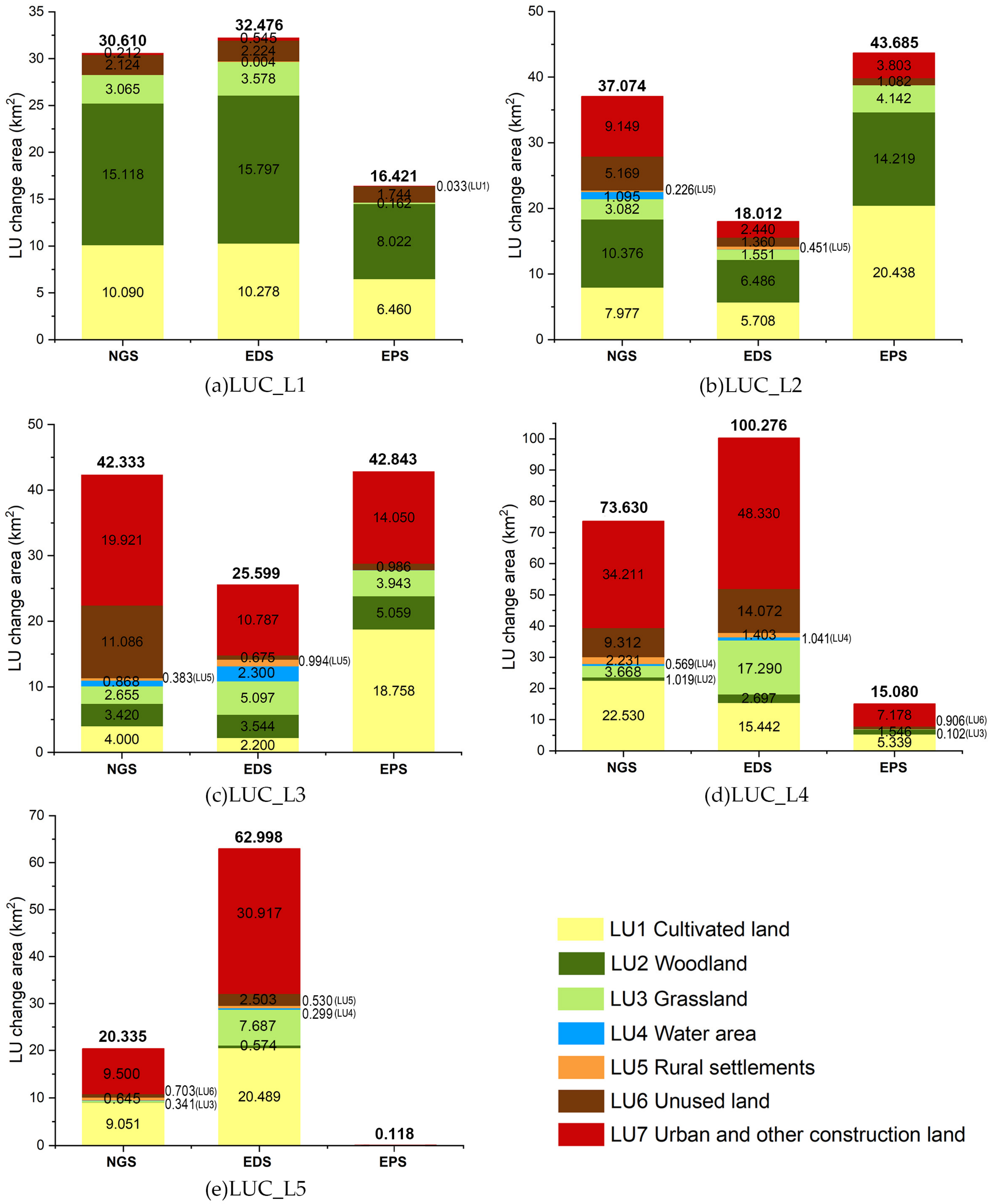


Figure 12. Land use transition area at each LUC level under different scenarios.

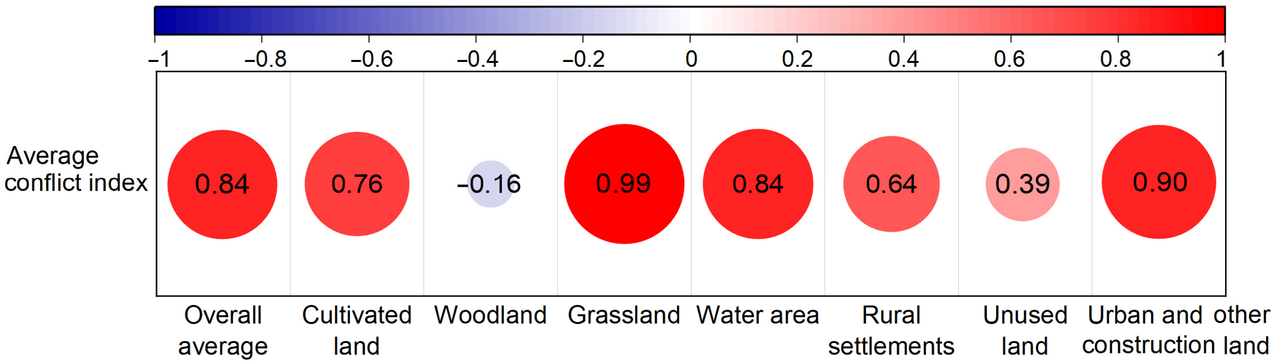


Figure 13. Pearson correlation coefficients between average conflict index and land use comprehensive dynamic degrees.

4. Discussion

4.1. Practical Implications for Land Use

The three simulation scenarios represented different development needs. The NGS continued the trend of previous years without external intervention. The EDS focused on economic profit, with an emphasis on industrial development and urbanization. The EPS focused on ecological conservation, with the setting of restricted areas. Both NGS and EDS were characterized by an increase in land use conflicts. Considering that Liyang has all-for-one tourism as one of its long-term development goals, the EPS may be the most suitable choice in the future, as it can better maintain good natural resources and the ecological environment. Multi-simulation of future land use can only provide some reference value for policy-making; scientific strategies should also be developed from a practical perspective and tailored to local conditions. The matters that need attention include the following:

(1) In addition to protecting Liyang's ecological sources as restricted areas, ecological restoration should also be carried out in conjunction with the distribution of ecological corridors and nodes, and ecological monitoring should be conducted in a timely manner to ensure the ecological security pattern of Liyang is well preserved. During the development and operation of tourism projects, tourist capacity should be reasonably controlled, and an environmental impact assessment of tourism behavior should be carried out, so as to achieve the coordinated development of ecological protection and tourism in the city.

(2) The cultivated land, which accounts for more than 50% of the city, is a key area for regulating land use conflicts between urban and rural areas. In this study, under all scenarios, the area of the converted cultivated land was more than 50 km^2. It is inevitable that urban sprawl will occupy a large amount of arable land. The resulting year-on-year decline in grain production will put enormous pressure on maintaining food security in the region. Therefore, it is necessary to strictly define a red line for basic farmland protection, improve the level of agricultural mechanization, actively promote smart agriculture, and improve the quality of existing farmland in Liyang.

(3) As shown in the previous analyses, there was a significant positive correlation between the dynamism of built-up land and the intensity of land use conflict. Regions with high levels of conflict tended to have large amounts of built-up land being converted. This was most typical for areas around the city center, where urban expansion led to serious land use conflicts. As a result, it is important to strictly control the urban growth boundary and establish an ecological buffer zone to prevent uncontrolled urban expansion. In addition, the expansion direction of the built-up land was found to be northwest-southeast. The Caoshan Development Zone in the northwest, Tianmu Lake, and Nanshan Bamboo Sea in the south are the driving force of built-up land expansion, and construction in these areas needs to be carefully managed to avoid serious land use conflicts.

4.2. Methodological Advantages

The research idea of this paper is to carry out a dynamic analysis of current and future land use conflicts, based on land changes from the past to the present and multi-scenario simulations of future land use. As an empirical study, this paper complements the lack of consideration of the future development trend of LUCs in the current research. It also provides forward-looking strategies for territorial spatial planning that are in line with China's national conditions of scarce land resources and a pronounced contradiction between people and land under rapid development.

This paper further explored the relationship between the intensity of land use changes and land use conflicts by analyzing their characteristics. While previous studies have mostly analyzed the relationship qualitatively, this study used Pearson's correlation analysis to show quantitatively and precisely that the more land use talked about, the more intense the land use conflict.

From the perspective of dynamic land use conflict, the areas to focus on in Liyang are suggested so that city leaders can better formulate policies and strategies when carrying out land development. This case can also provide a reference and ideas for territorial spatial planning at the county level.

4.3. Limitations and Future Directions

In terms of selecting drivers of land use change, this paper draws on previous studies and selects variables that can be spatially quantified, covering geographic, meteorological, soil, location, and socio-economic factors. However, land use change is also influenced by many factors that are difficult to collect and quantify, such as politics, land rights, and cultural practices. Future research should consider how these factors can be incorporated into land use simulation models.

The configuration of the parameters of land use simulation has a direct impact on the simulation results. In this study, although the accuracy verification met the required threshold, there is still potential room for further refinement. For example, various policy factors were not taken into account in the parameter settings. Further, the land use simulation under the EPS defined only ecological land as restricted areas, ignoring the fact that cultivated land can also provide a habitat for wildlife. In addition, the simulation was based solely on the CLUMondo model, and future multi-platform verification in conjunction with other models is required to improve the accuracy of the land use simulation.

This study measures land use conflict from a landscape ecology perspective by evaluating a region's complexity, fragility, and stability. However, land use conflict is a multifaceted concept that encompasses not only ecological considerations but also social, institutional, cultural, land tenure, and structure-function conflicts [71]. The mechanisms and manifestations of land use conflicts are highly complex, and some conflicts cannot be spatially represented. Therefore, it is necessary to develop a comprehensive, multi-indicator evaluation system that combines qualitative and quantitative evaluations from different perspectives to measure land use conflict objectively and comprehensively.

5. Conclusions

Due to the acceleration of urbanization, human demand for land resources has continued to grow. Coupled with the growing problems of global climate change, population growth, and environmental pollution, the globe's limited land resources are under great pressure. Land use conflicts reflect the mismatch and imbalance between land use allocation and societal development needs. By predicting and analyzing regional land use conflicts, the contradictory relationship between future urban development and land resources can be identified, the intensification of conflicts can be prevented in a timely manner, and the rational use of land resources can be realized. Liyang, a county-level city in China which has adopted the all-for-one tourism approach as its development engine, is facing conflicting trade-offs between economic, environmental, and social benefits in the process of urbanization. Presenting Liyang as a research case, this paper used the CLUMondo model to simulate land use in 2030 under three scenarios, namely, the NGS, EDS, and EPS, based on the land use map of 2020. Then, the land use conflicts under the different scenarios were measured by calculating the complexity, vulnerability, and stability of the region. Finally, by comparing and analyzing the characteristics of land use conversion and land use conflict, and discussing the relationship between the two, strategies and key areas for future land use planning were provided. The findings of the study were as follows:

(1) Under the three scenarios, there were only slight changes to the water area and rural settlements, while the cultivated land experienced a significant decrease, and the urban and other construction land showed a remarkable increase. Regarding their total amount of land conversion and total dynamic degree of land use, the scenarios were ranked as follows: EDS > NGS > EPS. The largest converted areas among all land use types were cultivated land, woodland, unused land, and urban and construction land. The higher land use dynamic degree included the urban and other construction land under all the scenarios, the unused land under the NGS and EDS, and the grassland under the EDS.

(2) All of the average land use conflict indices under the three scenarios were higher than the 2020 value, with the highest recorded under the EDS and the lowest under the EPS. The spatial distribution of LUCs showed little change under the EPS, but significant intensity under the NGS and EDS. Under the NGS, the most obvious high-level land use conflict occurred around the city center area. Under the EDS, besides the city center's surroundings, the most obvious high-level conflict areas also included the area around the Caoshan Development Zone in the northwest and the Nanshan Bamboo Sea in the south.

(3) The land use conflicts were found to be closely related to the land use change. In general, the more intensive the land conversions, the higher the land use conflicts. The Pearson correlation analysis showed that the average land use conflict index in the study area was significantly positively correlated with the overall average land use comprehensive dynamic degree. For each land use type, the correlation between the land use dynamics and the average land use conflict index was positive, except for the woodland.

(4) The EPS was found to be the most suitable for the development of all-for-one tourism in Liyang, as it recorded the least land use conflicts among the three scenarios. In the future, particular attention should be paid to the areas around the city center, Caoshan Development Zone, and the Nanshan Bamboo Sea, where high-intensity land use conflicts are likely to occur. It is also necessary to protect and restore the key areas of ecological security patterns and to ensure the quantity and quality of arable land in order to maintain food security in the city.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12040917/s1, Table S1: Policy reference for scenario setting; Table S2: Correlation matrix of driving factors; Figure S1: Driving factors of land use change; Table S3: Regression analysis; Table S4: Change rate of demand for land use services under different scenarios; Figure S2: Spatial restrictions for land use simulation; Table S5: Conversion resistance of land use types under different scenarios; Table S6: Conversion matrix under different scenarios; Table S7: Kappa coefficients of simulation validation.

Author Contributions: Conceptualization, X.F. and Y.C.; methodology, validation, data curation, writing—original draft preparation, X.F.; project administration, Y.C.; software, X.F.; writing—review and editing, supervision, X.F. and Y.L. All authors have read and agreed to the published version of the manuscript.

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Multiscenario Simulation of Land-Use Change in Hubei Province, China Based on the Markov-FLUS Model

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Abstract: A goal of land change modelers should be to communicate scenarios of future change that show the variety of possible future landscapes based on the consequences of management decisions. This study employs the Markov-FLUS model to simulate land-use changes in Hubei Province in multiple scenarios that consider social, economic, and ecological policies using 18 driving factors, including point-of-interest data. First, the Markov-FLUS model was developed and validated with historical data from 2000 to 2020. The model was then used to simulate land-use changes from 2020 to 2035 in four scenarios: natural development, economic priority, ecological protection, and cultivated land protection. The results show that the Markov-FLUS model effectively simulates the land-use change pattern in Hubei Province, with an overall accuracy of 0.93 for land use simulation in 2020. The Kappa coefficient and FOM index also achieved 0.86 and 0.139, respectively. In all four scenarios, cultivated land remained the primary land use type in Hubei Province from 2020 to 2035, while construction land showed an increasing trend. However, there were large differences in the simulated land use patterns in different scenarios. Construction land expanded most rapidly in the economic priority scenario, while it expanded more slowly in the cultivated land protection scenario. We designed the protection scenario to restrict the rapid expansion of construction land. In the natural development and economic priority scenarios, construction land expanded and encroached on cultivated land and forests. In contrast, in the ecological protection scenario, forests and water areas were well-preserved, and the decrease in cultivated land and the increase in construction land were effectively suppressed, resulting in a large improvement in land use sustainability. Finally, in the cultivated land protection scenario, the cultivated land showed an increasing trend. The spread and expansion of construction land were effectively curbed. In conclusion, the Markov-FLUS model applied in this study to simulate land use in multiple scenarios has substantial implications for the effective utilization of land resources and the protection of the ecological environment in Hubei Province.

Keywords: land-use change; multiscenario simulation; Markov-FLUS model; regional sustainability; natural development; ecological protection; economic priority; cultivated land protection

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1. Introduction

Urbanization is a natural outcome of social and economic progress, enhancing the quality of human life but also transforming the land's surface environment [1]. However, some unsustainable land use practices in the rapid urbanization process have resulted in severe ecological damage, including soil erosion, grassland degradation, and wetland shrinkage, posing a threat to ecological security. The rapid expansion of urban land use has encroached upon a substantial amount of ecological space, further exacerbating ecological issues [2]. Therefore, promoting sustainable land use patterns that balance economic growth with environmental protection is critical.

Land use is a cornerstone of resource, environmental, and ecological research, as well as scientific management. It provides crucial data for land resource planning and ecological environment monitoring [3]. Land-use change is a complex process influenced by various social, economic, and environmental factors that operate over time and space [4]. Land-use change models play a vital role in examining the driving forces, evolutionary processes, impacts, and prospects of land-use change [5]. Therefore, simulating land-use change at different spatiotemporal scales is essential for understanding the impact of human activities on regional ecological environments and supporting decision-making processes [6]. By modeling and simulating land-use change, we can gain a better understanding of the processes and trends of land-use change and formulate appropriate land policies [7,8].

In recent years, a considerable amount of scholarly effort has been devoted to the design and implementation of models for land-use change, resulting in the development of a variety of models [9–12]. The commonly utilized land-use change simulation models can be classified into two main types. The first type is quantity simulation models, which primarily focus on quantifying land demand. These models analyze changes in the areas of different land cover types, as well as their rates of change, but do not consider spatial distribution. Examples of such models include Markov models [13], gray system models [14], regression analysis models [15], and system dynamics (SD) models [16]. The second type is spatial simulation models, which are mainly used to simulate the spatial distribution and pattern characteristics of land use and to analyze the spatial differences in land-use change driven by natural and human factors. Examples of such models include cellular automata (CA) [17], multiagent systems [18], and CLUE/CLUE-S models [19]. Based on the causal relationship between past land-use change and related driving force factors, researchers have computed land use demand and distribution probability to simulate future spatiotemporal land use patterns in targeted scenarios.

The present mathematical models used for simulating changes in land use quantity can reasonably predict future land use quantity based on past and current land cover data [10]. However, due to their lack of capability to simulate changes in land use spatial patterns, these models are unable to meet the needs of national land use planning and management [20]. In contrast, land use spatial change simulation models exhibit outstanding advantages in simulating the spatiotemporal dynamics of complex land use systems. Currently, the CA model has been successfully applied to simulate land-use changes and urban expansion processes [21]. Nevertheless, conventional CAs usually assume that each cell has only one land use type at each time step, ignoring the mixed land use structures that are often found in land units [22,23]. On the other hand, the SLEUTH model can adjust constraint conditions by configuring different parameters to control the type of urban growth and simulate the process of urbanization through cellular allocation [24]. Nonetheless, this model is mainly suitable for simulating urban expansion and does not consider the impact of macro land supply and demand and relevant land policies on land-use changes [25]. The multiagent model can simulate land-use changes based on the decision-making interactions of multiple agents and the influence of the external environment. However, characterizing the rules for different land-use change decision-making processes is complex, and collecting sufficient data at the individual level to verify the model is difficult. The CLUE/CLUE-S model is an empirical statistical model that can simultaneously simulate changes in multiple land use types due to its application of a system theory approach to address the competitive relationships between different land use types [26,27]. However, during the land cover allocation process, this model only assigns the dominant land use type with the maximum joint probability to the grid cell, neglecting the possibility of other nondominant land use types transitioning, thus lacking the ability to simulate sudden and dramatic land-use changes [28–30].

Coupled simulation models that balance land use demand quantification and spatial allocation simulation have become the mainstream choice [31,32]. The Markov-FLUS model is a new type of land-use change simulation model that overcomes the aforementioned limitations [15,33]. It integrates a "top-down" SD model and a "bottom-up" CA model to simultaneously simulate changes in multiple land use types [34]. Its land cover selection mechanism, based on roulette wheel selection, allows nondominant land use types to be allocated to grid cells, reflecting the uncertainty of actual land-use changes and enabling the model to simulate sudden and dramatic changes in land use. In contrast, most current models, such as CLUE-S, assign the land use type of a specific grid cell to the primary cell with the highest conversion probability, controlled by predefined thresholds that only consider dominant land use types, neglecting competition with other types and reducing opportunities for nondominant types [35,36]. Although the dominant land use type with the highest combined probability is prioritized in grid cell allocation, other types with relatively lower probabilities still have a chance of being allocated [37–39]. The roulette wheel selection mechanism allocates land use types in proportion to their combined probabilities, increasing the likelihood of being selected for land use occupation with higher combined probabilities, while lower combined probabilities still offer allocation opportunities. This stochastic mechanism reflects real-world land-use change uncertainty, making it suitable for leapfrogging land use simulations.

The Markov-FLUS model is widely used in land use research and is a powerful analytical tool for land use planning and management. This study employs the Markov-FLUS model and applies it to Hubei Province, China. The contributions of this paper are as follows:

- Historical land use data from 2000 to 2015 and 18 driving factors, including 10 points-of-interest data, were used to simulate future land use patterns in Hubei Province, China.
- The improved model simulated and analyzed four different future land use scenarios, providing valuable insights for decision making on sustainable land use and planning management in Hubei Province, China.

2. Materials and Methodology

2.1. Case Overview

Hubei Province, located in Central China, boasts a unique geographic location, diverse terrain, and a mild and humid climate, which have endowed it with abundant natural resources and unique natural environments [40]. Geographically, Hubei Province is situated in the middle reaches of the Yangtze River and features a mountainous landscape, making it one of the most prominent water and electricity supply and industrial bases in China [41,42]. The Three Gorges Dam, which is one of the world's largest hydraulic projects, has made important contributions to the power supply in southern China. The Dabie and Wudang mountain areas are also noteworthy natural landscapes in Hubei Province, and these topographical features have had a profound impact on the province's economic and cultural development. Furthermore, Hubei Province accords great importance to the preservation and development of its cultural heritage, such as the Chu culture, Jingchu culture, and Han culture in the Han River Basin, which has had a profound influence [43]. Figure 1 shows the geographical location of Hubei Province [44,45].

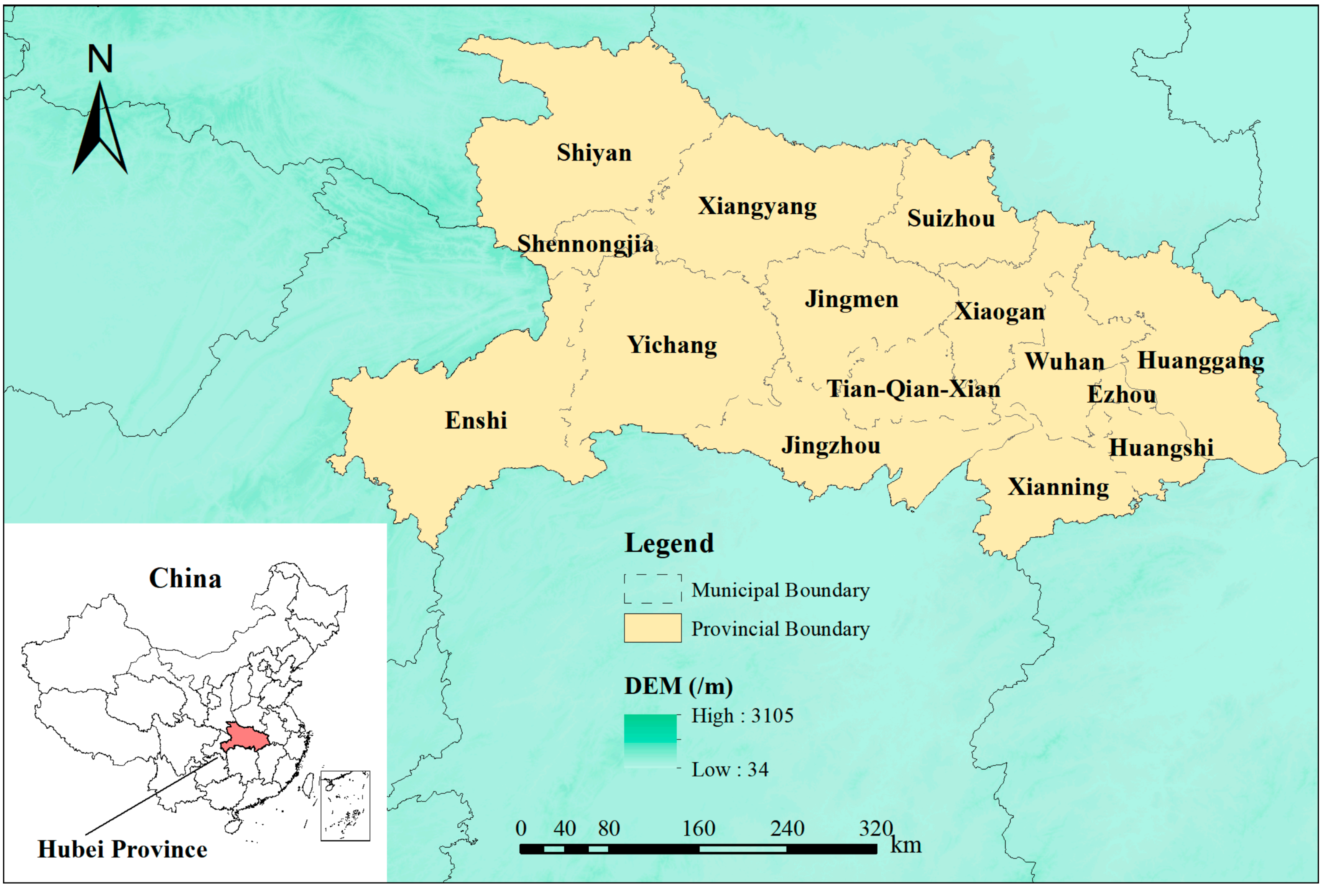

Figure 1. The location of the target study area.

Hubei Province is the largest province in Central China and has various unique characteristics. From the perspective of the natural environment, Hubei Province has a rich and diverse ecological environment, and the protection and utilization of natural resources are of paramount importance for the province's sustainable development. For instance, the natural beauty of the Dabie Mountains, the Enshi Grand Canyon, and other locations in Hubei Province has attracted a large number of tourists. It has diverse land use types, a vast mountainous region in the northwest, and the largest interbasin water transfer project in China [46]. Moreover, it is known as the "Province of Thousand Lakes" and is home to Wuhan, one of China's most developed cities, and the provincial capital. However, its urban development is notably uneven, which makes it an intriguing area of research. The Hubei Provincial Government has outlined a future planning goal of achieving "one main lead, two wing drives, and coordinated development across the region" by 2035. This study is expected to provide valuable support toward realizing this objective.

In summary, the plentiful natural resources and unique natural environment of Hubei Province provide strong support for its economic, cultural, and social development, making it a crucial field for academic research. Therefore, enhancing research on land-use change simulation under different scenarios in Hubei Province and investigating ways to balance natural resource protection with economic and social development have great academic and practical significance.

2.2. Research Design

This study utilizes a Markov-FLUS model to develop four future scenarios and simulate future spatial patterns in response to a given land use demand determined by the model. First, we use ANN to estimate the probability of each land use type occurring in a specific grid cell. Second, we incorporate complex adaptive inertia and competition mechanisms to account for the competition and interactions between different land use types. During the CA iteration, we estimate the dominant land use type by combining the probabilities of all land use types at each grid image element and assign it using a roulette selection process. The proposed method captures the complex land use dynamics in the simulation of future land-use changes. Figure 2 illustrates the research design of this study.

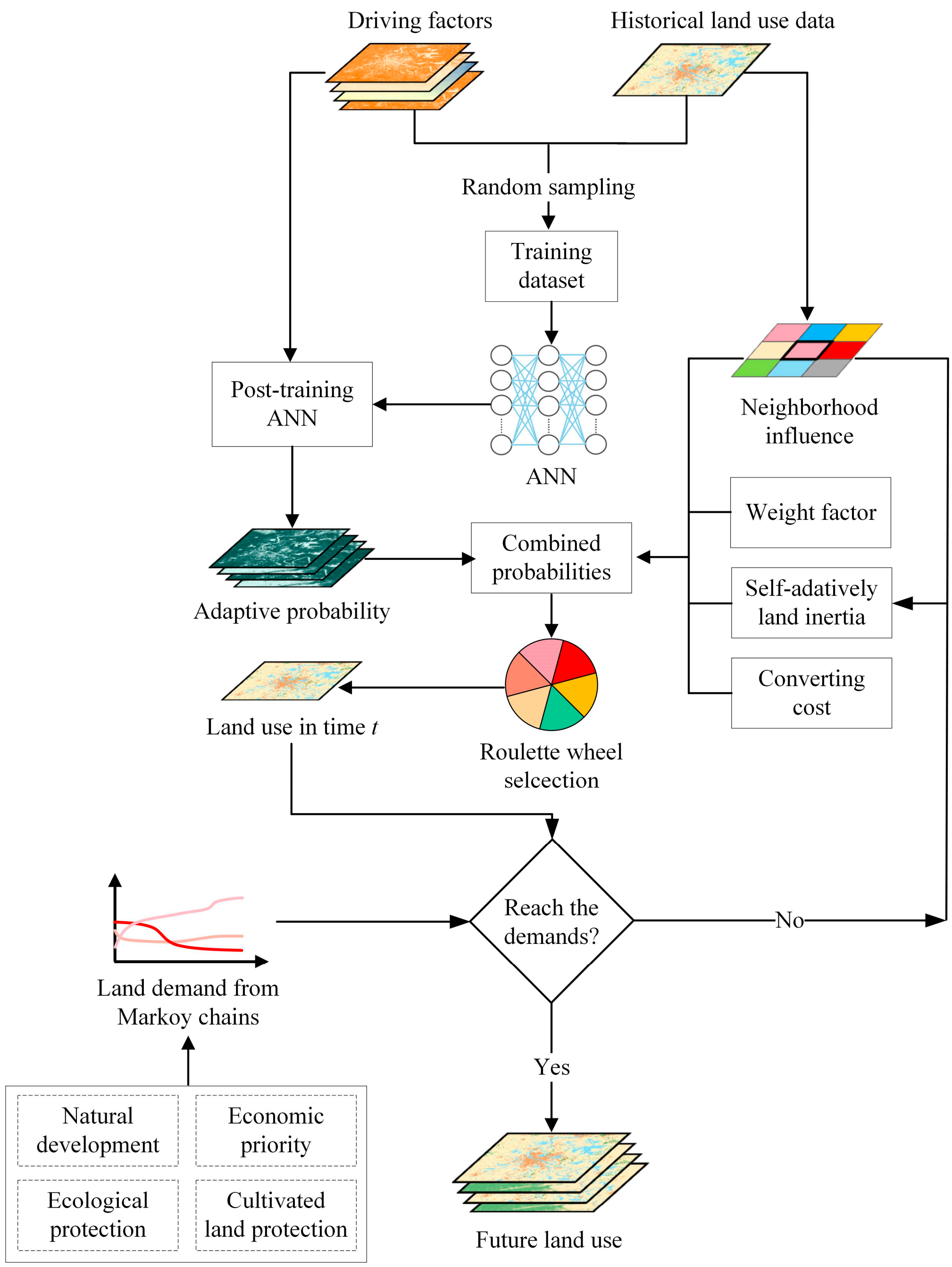

Figure 2. Research design for this study.

2.3. Data and Preprocessing

This study employs land use status data (annual China Land Cover Dataset, CLCD) from 2000, 2005, 2010, 2015, and 2020, obtained from the dataset published by Yang et al. The CLCD consists of 6 level-1 classes (cropland, forest, grassland, water, built-up area, and barren) and 25 level-2 classes [47,48]. The producers of the dataset assessed its overall accuracy through field surveys and achieved an accuracy rate of over 94.3% for the level-1 classes and 91.2% for the level-2 classes. Although the CLCD is updated every five years, its consistent regions can serve as potential training samples for long-term data analysis [47,49]. A further assessment based on 5131 third-party test samples showed that the overall accuracy of the CLCD outperformed that of MCD12Q1, ESACCI_LC, FROM_GLC, and GlobeLand30 [47,50]. The data have a spatial resolution of 30 m. Based on the land-use classification system and the characteristics of land use in Hubei Province, we chose to use the 6 level-1 classes of the CLCD produced by Wuhan University and renamed them as cultivated land, forests, grassland, water, architecture, and others (unused land). Social and economic data were procured from the Chinese Academy of Sciences Data Center (https://www.resdc.cn/, accessed on 21 November 2022) and the Hubei Statistical Yearbook, while the sources for other natural, transportation, and social economic data are listed in Table 1. The data were processed using ArcGIS software to ensure conformity with the requirements of the Markov-FLUS model [37,51,52] by converting, projecting, and resampling the data into the same projection coordinate system with a spatial resolution of 100 m.

2.4. Methodology

2.4.1. Principles of the Markov-FLUS Model

The Markov-FLUS model is constructed based on the system dynamics model and the cellular automata model. It integrates the artificial neural network (ANN) algorithm and the roulette wheel selection mechanism to enhance the accuracy of land-use change simulation [53,54]. This mechanism effectively handles the interplay of various driving factors, including natural, social, and economic factors, as well as the complexity and uncertainty associated with the interconversion among various land use types [55]. The FLUS model has been widely applied to solve geographical process simulations and complex spatial optimization problems, such as large-scale land-use change, urban expansion, zoning of nature reserves, and facility location selection [56,57].

The Markov-FLUS model employs a multilayer feedforward neural network algorithm (BP-ANN) to integrate various land use types and select multiple driving factors, such as natural, social, and economic factors, from the initial land use data [58]. By associating different land use types with various driving factors, this model generates a probability distribution map of land suitability for each type [59]. However, traditional CA models have some limitations in regard to simulating real-world changes in land use [60]. This is because traditional CA models often assume that the processes that drive land change are static and do not take into account the dynamic processes that can lead to changes in land use over time, such as urbanization and development [59].

To address these issues and improve the accuracy of the simulation, the Markov-FLUS model incorporates an adaptive inertia competition mechanism based on roulette wheel selection into the traditional CA model [61]. This enables better handling of the complexity and uncertainty of land use type conversions under the influence of natural and human activities [62,63].

This study couples the CA module and the Markov model in FLUS to dynamically simulate and predict the future land use distribution in Hubei Province. The CA module has the ability to handle the spatial interactions of land use [64,65], while the Markov model can predict changes in the sizes of land use types over time [66]. The model utilizes transition probabilities between distinct land use types to predict the likelihood of a parcel undergoing a change in land use type at a future time [67]. Through the application of these probabilities to the current distribution of land use types, the model can forecast alterations in the distribution over time [68].

The advantage of this approach lies in integrating the ability of the CA module to handle the spatial distribution of land use and the characteristics of the Markov model to predict the number of land use types [69]. This results in an exploration of dynamic information on land use types in terms of both space and quantity. In the coupling process, the simulation results of each stage are used as input for the next stage, along with the driving forces and demands of the next stage, thereby ensuring mutual feedback between the two models during the simulation process.

By modifying the input parameters of the FLUS model, this study estimated the land type area under four scenarios of Hubei Province in 2035.

Table 1. List of drivers selected for this study.

Types	Driving Factors	Data Sources
Geographical factors	DEM	Geospatial Data Cloud (https://www.gscloud.cn/)
	Slope	Geospatial Data Cloud ArcMap slope
	Aspect	Geospatial Data Cloud ArcMap aspect
	NDVI	Geospatial Data Cloud
Climatic factors	Average temperature	The National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)
	Average precipitation	The National Tibetan Plateau Data Center
Socioeconomic factors	Population density	Resource and Environment Science and Data Center (https://www.resdc.cn/)
	GDP	China National Bureau of Statistics (http://www.stats.gov.cn/)
	Restaurant distribution density	Resource and Environment Science and Data Center ArcMap Kernel Density
	Hotel distribution density	Resource and Environment Science and Data Center ArcMap Kernel Density
	Supermarket distribution density	Resource and Environment Science and Data Center ArcMap Kernel Density
Location factors	Distance to waters	OpenStreetMap (https://www.openstreetmap.org) ArcMap European distance tool
	Distance to expressway	OpenStreetMap ArcMap European distance tool
	Distance to primary roads	OpenStreetMap ArcMap European distance tool
	Distance to railroad	OpenStreetMap ArcMap European distance tool
	Distance to town center	OpenStreetMap ArcMap European distance tool
	Distance to city center	OpenStreetMap ArcMap European distance tool
	Distance to bus stops	OpenStreetMap ArcMap European distance tool

Note: The driving factors used for accuracy validation in this study (climate, socioeconomic, and locational factors) were from 2015, while those used in the scenario simulation processes were from 2020. The access date is 21 November 2022 in this table.

2.4.2. Drivers of Land-Use Change

Land-use change is the result of the interplay between the intrinsic physical and chemical conditions of various land types and external factors such as natural, social, and economic factors. Under the influence of natural factors, land-use change is relatively stable, as the transformation of land use types occurs under strict natural limitations. However, the rapid development of urbanization has made the situation of land-use change more complex, with the combined effects of various factors, including social, economic, and policy factors [28,28,70].

This study conducted a comprehensive review of the previous literature and identified four distinct categories of driving factors: geographical, climatic, socioeconomic, and locational factors [71]. These four categories represent the primary factors that influence land-use change. To enhance the comprehensiveness of our study, we incorporated some point-of-interest (POI) data into the socioeconomic and location factor categories, which had previously been overlooked in the literature. We employed various combinations of the driving factors in the Markov-FLUS model and evaluated their performance based on neural network model training and probability calculation. The combination consisting of 18 driving factors exhibited the lowest RMSE and high measurement accuracy. Table 1 presents the types and sources of all driving factors, with a spatial resolution of 100 m and a completely unified spatial range, mathematical basis, and format.

Figure 3 shows the raster images of all driving factors. Geographic and climatic conditions, as natural factors, determine the direction, mode, and trend of land-use changes. Therefore, DEM, slope, and aspect, which constitute the most critical terrain conditions, were selected as the driving factors to characterize geographic factors. Average precipitation and temperature, which constitute the most critical climatic conditions, were selected as the driving factors to characterize climatic factors. Accessibility, as an important location factor, affects the convenience and cost of land development and has a large impact on regional land-use change. This study mainly selected the distances of various land use types to water bodies, highways, primary roads, railways, town centers, city centers, and bus stops as driving factors to characterize location factors. Additionally, this study also selected driving factors to characterize economic factors, such as GDP, population density, restaurant density, hotel density, and supermarket density [72,73].

This study incorporated 10 POI data as part of our driving factor analysis, encompassing geographic information from various establishments such as hotels, restaurants, supermarkets, and bus stations. The utilization of these data points has not been extensively explored in previous studies. By incorporating these data points, we gained a more comprehensive understanding of land-use changes.

2.4.3. Model Accuracy Verification

Uncertainty in simulations is inevitable and emerges from various sources, such as the accuracy of the initial land use data used for simulation, the accuracy of driving factors, and simulation performance. Therefore, to acknowledge the uncertainty of simulations, we used historical land use data from 2010 and 2015 to predict land use demand for 2020. Data were imported regarding suitability probabilities and limiting factors for each individual land use type, and the Markov model was employed to predict land-use change in Hubei Province from 2015 to 2020. Figure 4 presents a comparison between the predicted outcomes and actual 2020 land use patterns, while Figure 5 shows a comparison of predicted versus actual land use type areas. The subtle differences observed between the predicted and actual datasets are because of a small amount of change during the validation time interval.

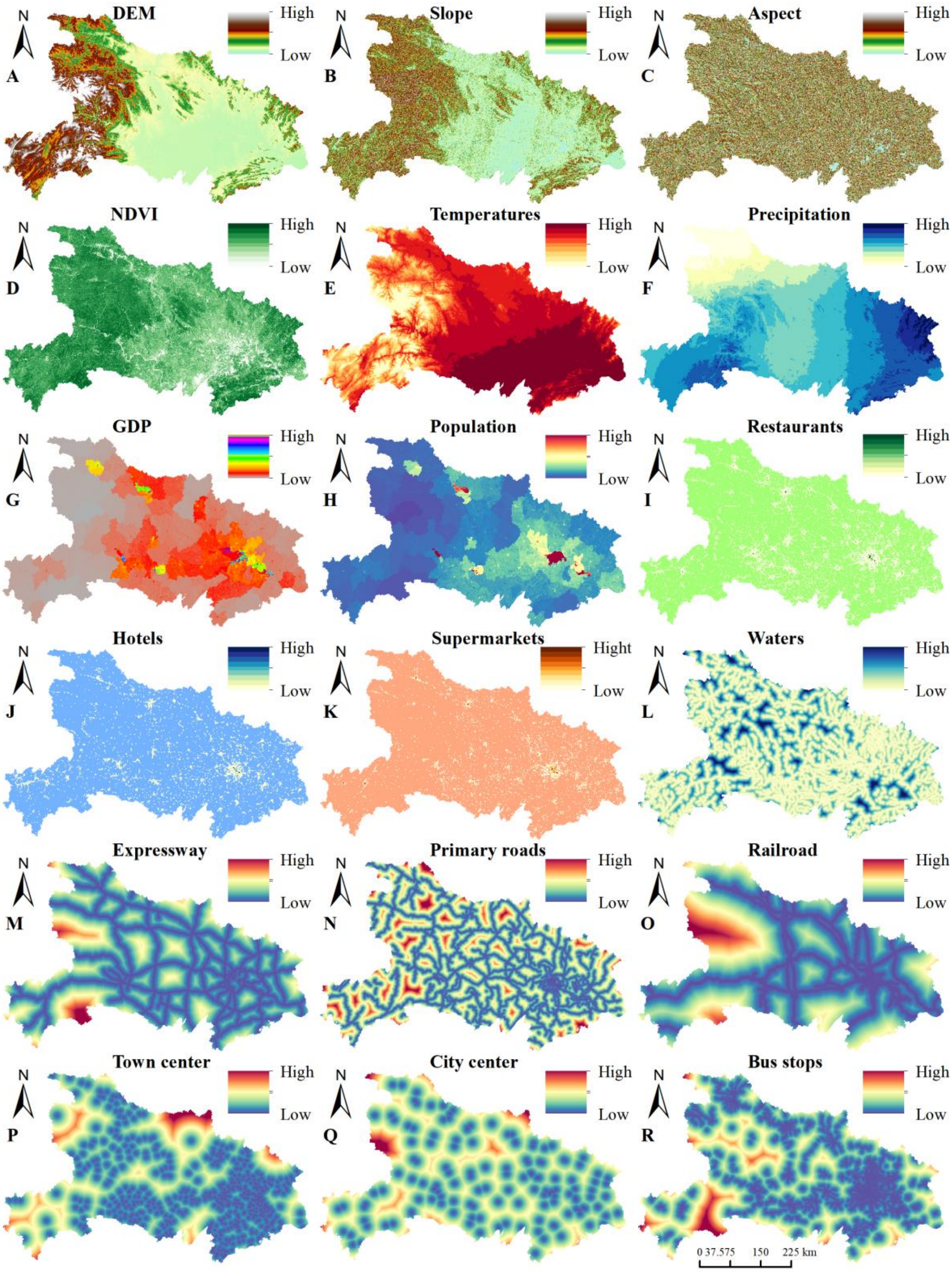

Figure 3. Drivers of land-use change. (**A**) DEM, (**B**) slope, (**C**) aspect, (**D**) NDVI, (**E**) temperatures, (**F**) precipitation, (**G**) GDP, (**H**) population, (**I**) restaurants, (**J**) hotels, (**K**) supermarkets, (**L**) waters, (**M**) expressways, (**N**) primary roads, (**O**) railroads, (**P**) town centers, (**Q**) city centers, (**R**) bus stops.

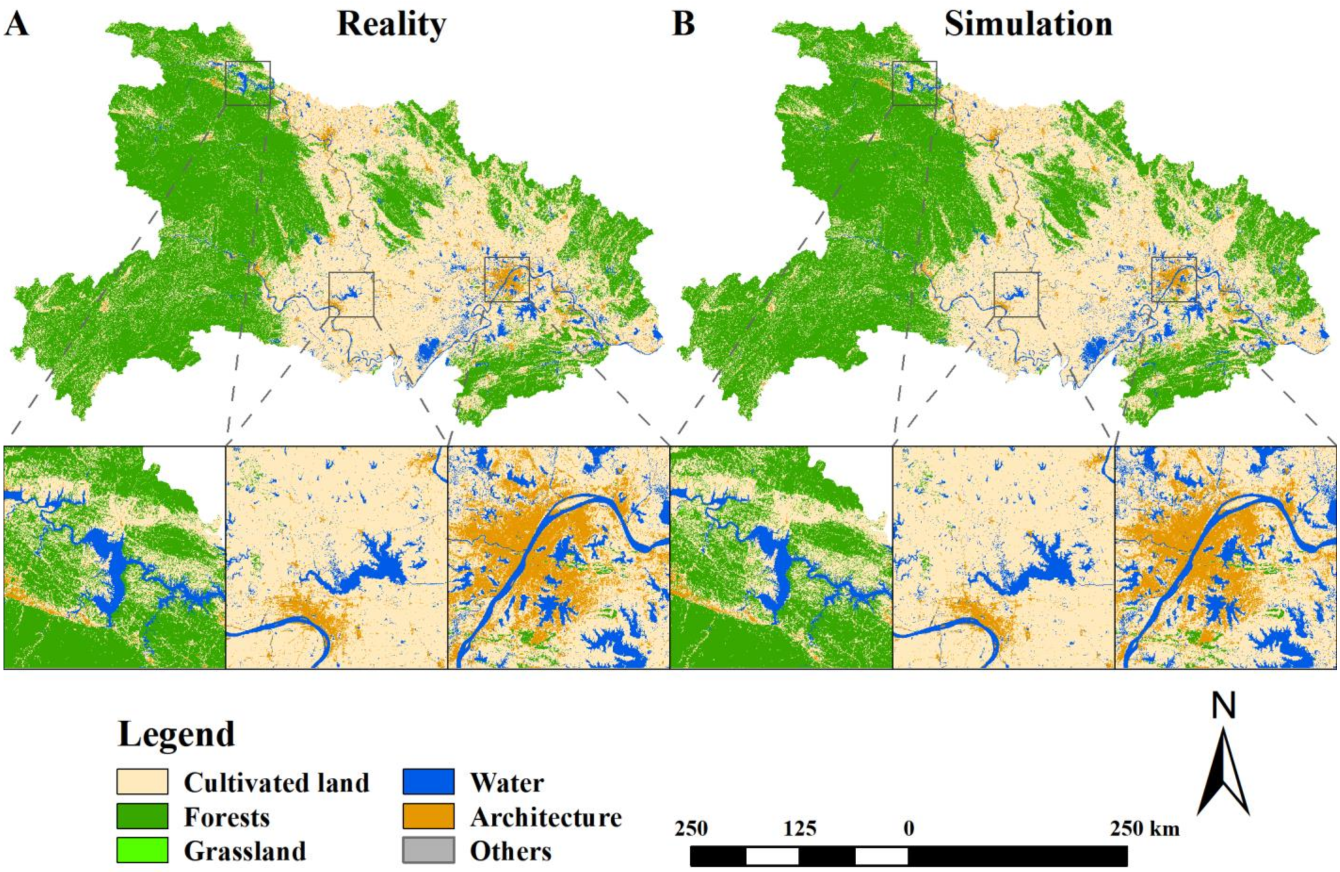

Figure 4. Comparison of reality and simulation details of land use in 2020. (**A**) Reality; (**B**) simulation.

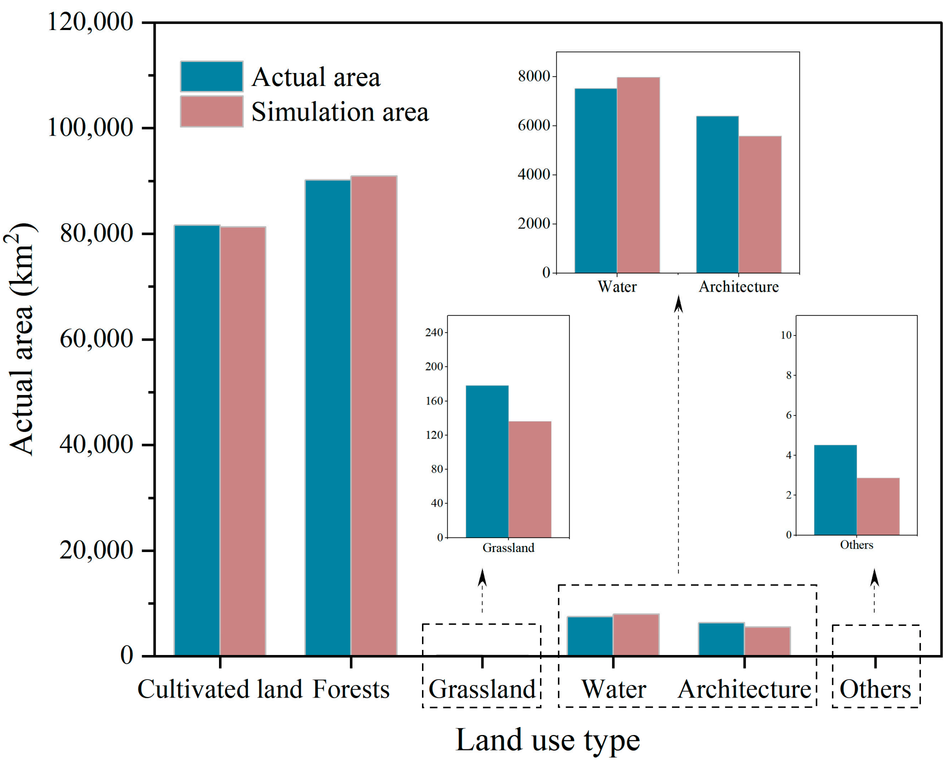

Figure 5. Comparison of reality and simulation of land use area in 2020.

Table 2 displays the overall accuracy, Kappa coefficient, and FOM index. The effectiveness of the model was validated through the application of overall accuracy (OA), the FOM index, and the Kappa coefficient. The values of OA and Kappa are typically between 0 and 1, with a higher value indicating a higher level of accuracy in the model simulation. When the Kappa coefficient is greater than 0.8, it indicates that the model simulation accuracy has reached a satisfactory level of statistical significance [29,74]. Additionally, this study employed the FOM coefficient to assess the accuracy of the model, which is a measure of the efficiency, sensitivity, or precision of a system. A larger FOM value indicates better simulation results and higher accuracy. The accuracy coefficient is the best test for the rationality of the driving factors, suitability probability maps, and other parameter settings used in the model, which jointly affect the simulation results. To further test the adaptability of the model in Hubei Province, we adopted a 20% random sampling strategy for comparison, and the calibration results are shown in Table 3. Based on the results of the three accuracy coefficients and random sampling, the FLUS model demonstrated good applicability in this study.

Table 2. FLUS model validation results.

Inspection	OA	Kappa	FOM
Results	0.93	0.85	0.139

Table 3. Validation results of random samples.

Land Use Type	Commission Error	Omission Error	Producer's Accuracy	User's Accuracy
Cultivated land	0.0750608	0.0785903	0.92141	0.924939
Forest	0.0511676	0.0434008	0.956599	0.948832
Grassland	0.681315	0.756484	0.243516	0.318685
Water	0.17362	0.126522	0.873478	0.82638
Architecture	0.140058	0.248898	0.751102	0.859942
Others	0.683333	0.788889	0.211111	0.316667

2.5. Multiple Scenario Simulations

2.5.1. Design of Multiple Scenario Simulations

The development of the socio-economic and natural environment is characterized by uncertainty. Scenario analysis provides a valuable tool for exploring and comparing the outcomes of different scenarios based on various assumptions that represent development goals. This approach enables the development of strategies that are best suited for future development. Based on the previous literature and considering the current development situation and future socioeconomic development plan of Hubei Province [35,37,75,76], this study used the Markov model to design four scenarios:

- The natural development scenario, also known as the recent trends scenario, is constructed based on the trajectory of past and current development in Hubei Province. The current trends for economic and population development and technological innovation are assumed to remain continually consistent. In this scenario, there is no human interference or restrictions on land use development, and it follows the natural changes in land use based on historical characteristics of land-use change and natural socioeconomic development factors, with transition probabilities maintaining the level between 2000 and 2020. In other words, the recent trends scenario assumes a continuation of historical patterns of land change.
- The economic priority scenario, which aims to maximize socioeconomic benefits, assumes that cities become attractive destinations due to rapid regional economic growth and technological innovation. The continuous rapid growth of the population and economy comes at the expense of natural resources (with a growth rate of approximately 0.9% to 8%), leading to drastic land-use changes. In this scenario, economic

development is prioritized and requires the rapid expansion of built-up land such as cities and roads, which are important signs of economic development. In this model, we increase the cost of conversion from built-up land to other land and reduce the probability of transfer from living space to ecological space.

- The ecological protection scenario focuses on protecting ecological land, with a cultivated land area of no less than that of the planned cultivated land retention and medium- to high-yield cultivated land area in 2020. The forest area is no less than the planned area in 2020. The area of urban land, rural residential areas, and other construction land does not exceed the planned area in 2020. The ecological protection red-line area is the restricted development zone. In other words, the ecological protection scenario refers to strengthening forests, grassland, water, and other ecological lands while weakening the expansion capacity of the other land types.
- The cultivated land protection scenario, which aims to simulate the impact and environmental effects of cultivated land protection policies and land reclamation activities, takes the key cultivated land protection areas (basic farmland protection areas) as the restricted development area, with a cultivated land area of no less than that of the planned cultivated land retention and medium- to high-yield cultivated land area in 2020. The area of urban land, rural residential areas, and other construction land does not exceed the planned area in 2020. The probability of cultivated land being converted to urban land, rural residential areas, and other construction land is reduced, while the probability of grassland, urban land, rural residential areas, and unused land being converted to cultivated land is increased.

2.5.2. Neighborhood Factors

Neighborhood factors can reflect the intensity of expansion of different land types, particularly the expansion potential of various land uses under external influences [77,78]. Parameters similar to neighborhood factors have been utilized in several large-scale land use simulation models, such as CLUE-S, FORE-SCE, and CLUMondo [35]. These models employ a static set of empirically derived parameters to represent the degree of difficulty associated with land-use conversion in specific regions.

These neighborhood factors range from 0 to 1, with higher values indicating a stronger expansion ability of the land use type. Neighborhood factors are estimated by analyzing historical land use data in the study area and incorporating expert opinions. These factors reflect the inherent properties of land use and are not influenced by changes such as technological advancements or human activities. In this study, after reviewing the previous literature and conducting multiple tests and adjustments, the parameters for neighborhood influence factors for each land type were finally determined and are presented in Table 4.

Table 4. Neighborhood factor parameters.

Scenarios	Cultivated Land	Forest	Grassland	Water	Architecture	Others
Natural development	0.5	0.7	0.3	0.4	1	0.01
Economic priority	0.2	0.3	0.2	0.3	1	0.01
Ecological protection	0.3	1	0.7	0.5	0.8	0.01
Cultivated land protection	0.8	0.5	0.3	0.5	0.8	0.01

2.5.3. Conversion Costs and Restricted Change Area Settings

Conversion cost is used to represent the degree of difficulty in converting from the current land use type to the desired type and is another factor shaping land use dynamics [79]. In this study, four different conversion costs were designed based on the four scenarios established, as shown in Table 5. In the table, a value of one represents that two land use types can be converted to each other, while zero indicates that they cannot be converted.

Table 5. Conversion cost coefficients between land use types.

Scenarios	Land Use Type	Cultivated Land	Forest	Grassland	Water	Architecture	Others
Natural development	Cultivated land	1	1	1	1	1	1
	Forest	1	1	1	1	1	1
	Grassland	1	1	1	1	1	1
	Water	1	1	1	1	1	1
	Architecture	1	1	1	1	1	1
	Others	1	1	1	1	1	1
Economic priority	Cultivated land	1	1	1	1	0	1
	Forest	1	1	1	1	0	1
	Grassland	1	1	1	1	0	1
	Water	1	1	1	1	0	1
	Architecture	1	1	1	1	1	1
	Others	1	1	1	1	1	1
Ecological protection	Cultivated land	1	0	0	0	1	1
	Forest	1	1	1	1	1	1
	Grassland	1	1	1	1	1	1
	Water	1	1	1	1	1	1
	Architecture	0	0	0	0	1	0
	Others	0	0	0	0	1	1
Cultivated land protection	Cultivated land	1	1	1	1	1	1
	Forest	0	1	1	1	1	1
	Grassland	0	1	1	1	1	1
	Water	0	1	1	1	1	1
	Architecture	0	1	1	1	1	1
	Others	1	1	1	1	1	1

The setting of restricted areas means that according to the actual situation of the study area, some areas are selected as exclusion zones and land-use conversion is prohibited [33]. This study presents four different constrained conversion areas designed based on four specific scenarios. In the natural development scenario, all land-use changes are permitted. In the economic priority scenario, the conversion of architectural land into other types is prohibited. In the ecological protection scenario, the conversion of cultivated land, forest, grasslands, and water areas into architectural land is forbidden. Moreover, conversion is also prohibited within ecological nature reserves and ecological protection red-line areas. In the cultivated land protection scenario, the conversion of cultivated land into other types is prohibited. Additionally, conversion is also prohibited within basic farmland protection areas.

3. Results and Discussion

3.1. Land-Use Changes from 2000 to 2020

Figure 6 illustrates the land use dynamics in Hubei Province from 2000 to 2020. The most substantial changes in land use occurred between 2000 and 2005, with an average change rate of 17.04% for the 6 land use categories. The observed trend was a general decline in cultivated land, grassland, and other land types, accompanied by an increase in forests, water areas, and construction land areas. Other land and grassland experienced the most dramatic reduction, declining by 43.23% and 39.42%, respectively, while the construction area exhibited the most notable increase, by 12.62%. The period from 2000 to 2005 marked a window of urbanization in Hubei Province, with a rapid increase in urban development and population density and a gradual expansion of construction land. As a result, farmland at the edges of urban areas decreased. To mitigate large-scale human activities, such as deforestation and lake reclamation, Hubei Province implemented ecological restoration projects, such as the "Grain for Green" and "Lake for Land" programs, to recover some ecological land areas, such as forests and water bodies. However, these actions also led to a rapid decrease in the cultivated land area.

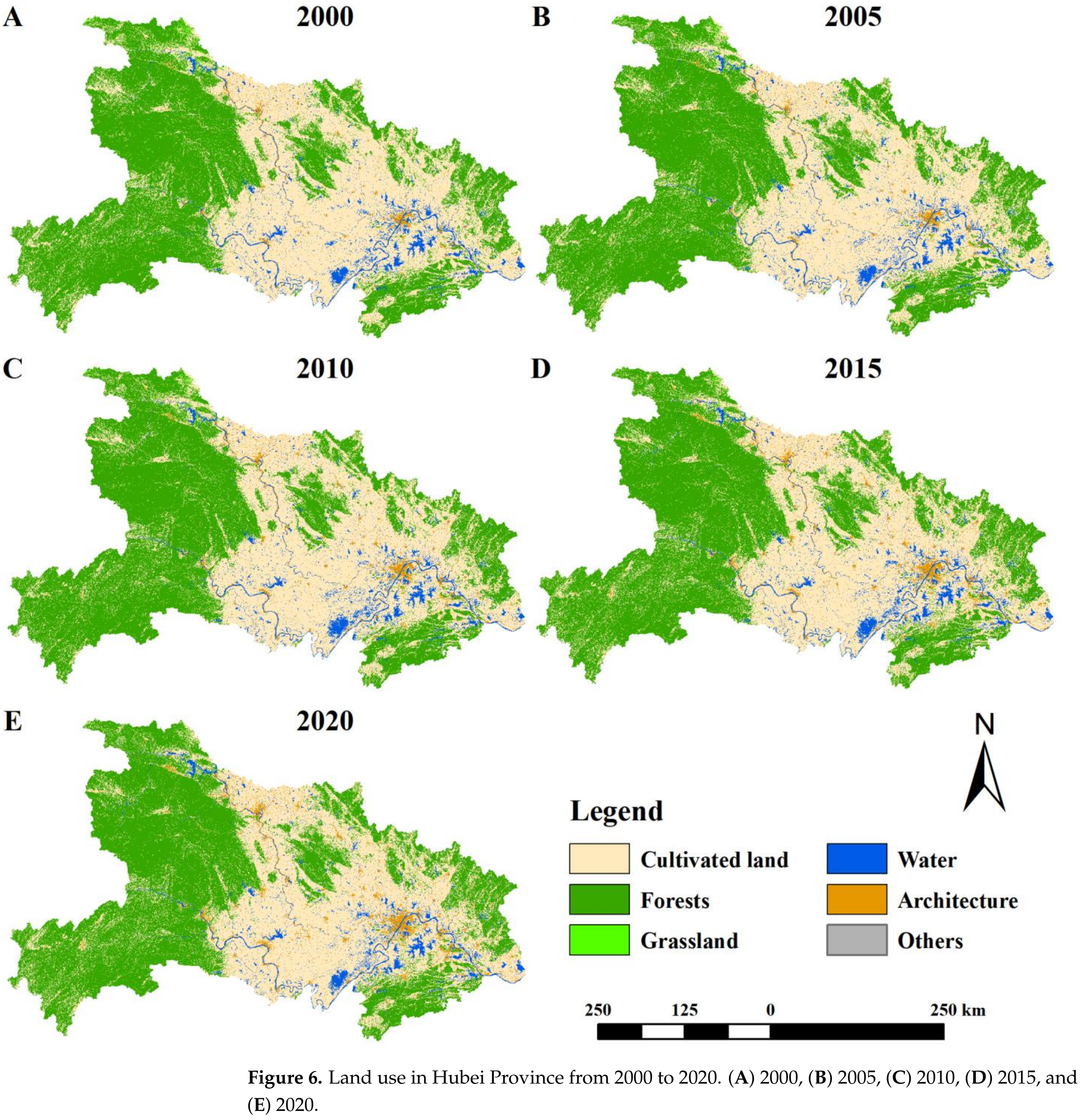

Figure 6. Land use in Hubei Province from 2000 to 2020. (**A**) 2000, (**B**) 2005, (**C**) 2010, (**D**) 2015, and (**E**) 2020.

Figure 7 shows the area changes of different land use types in Hubei Province over various time periods. Among the land use categories, forestland has the largest area in Hubei Province. It is primarily situated in the elevated regions of western Hubei Province, with the proportion of forestland accounting for 47.32% in 2000 and 48.52% in 2020, exhibiting a slightly increasing trend. Farmland, the second-largest land use category, is mainly distributed in the level terrains of the Jianghan Plain. The proportion of farmland area in Hubei Province decreased from 46.31% in 2000 to 43.90% in 2020, indicating a declining trend. Grassland and other land use types occupy smaller areas, yet their changes are more substantial. Specifically, the grassland area in 2020 decreased by 80.83% in comparison with that in 2000, and other land use types decreased by 76.63%. Meanwhile, the construction land use type displayed the most considerable growth rate, with a 91.60% increase.

The reason for this trend is the presence of the Yangtze and Hanjiang Rivers that flow through Hubei Province, endowing the region with unique advantages for water, land, and air transportation that have facilitated its economic development. The urbanization process that has taken place along the river in Hubei Province has rapidly developed, leading to an increased population density and an expanded urban area, resulting in a substantial increase in the area of construction land. However, the expansion of construction land has encroached upon some farmland, which has been partially compensated for by using grassland and other land use types. Consequently, the reduction in the area of cultivated land has been relatively small, while the decrease in grassland and other land use types has been more substantial. While compensating for the loss of cultivated land with grassland may offset the total area loss of arable land, it fails to consider the quality of farmland and the unit yield, which are crucial for ensuring food security.

Overall, from 2000 to 2020, the area of construction land in Hubei Province continuously increased, investment in public infrastructure construction consistently grew, and urban construction was successful. Nonetheless, the area of ecological land, such as cultivated land, grassland, and water, has continuously decreased, and ecological environmental protection is critical.

3.2. Scenario 1: Natural Development

The natural development scenario refers to unconstrained land-use changes, wherein land-use changes are primarily influenced by the natural environment and social and economic development of the study area, without any constraints from land development policies. Figure 8 shows the simulation results of land use in 2035 in the natural development scenario. Figure 9 illustrates the changes in land use type areas from 2020 to 2035 in this scenario. Compared with 2020, the areas of cultivated land, forestland, grassland, and other land use types decrease to varying degrees in 2035, with declines of −1.54%, −0.96%, −31.05%, and −21.16%, respectively. The scale of water and construction land expands, with the latter showing a relatively large increase, reaching 8529.64 km^2, which represents an increase of 33.51%. In other words, in the natural development scenario, construction land grows rapidly due to human activities to meet the needs of social and economic development, while cultivated land, forestland, grassland, and other land use types become the primary sources of land-use conversion.

In terms of spatial distribution, the expansion of construction land is based on the original distribution status and continues to extend along the riverbanks, mainly occurring in the northern (Shiyan), southern (Xiangyang), and central (Wuhan) regions, with a relatively concentrated distribution. The main reason for the expansion of urban areas is the continuous and rapid pace of overall urbanization. The results of this scenario indicate that the rapid development of social and economic conditions in Hubei Province in the future is expected to lead to the further expansion of construction land due to urbanization. However, in sharp contrast with this trend, there will be a substantial reduction in the areas of cultivated land and forestland. The phenomenon of urban development occupying arable land resources is severe, and the reduction in forestland and other ecological spaces due to urban expansion has exerted substantial pressure on regional ecological health.

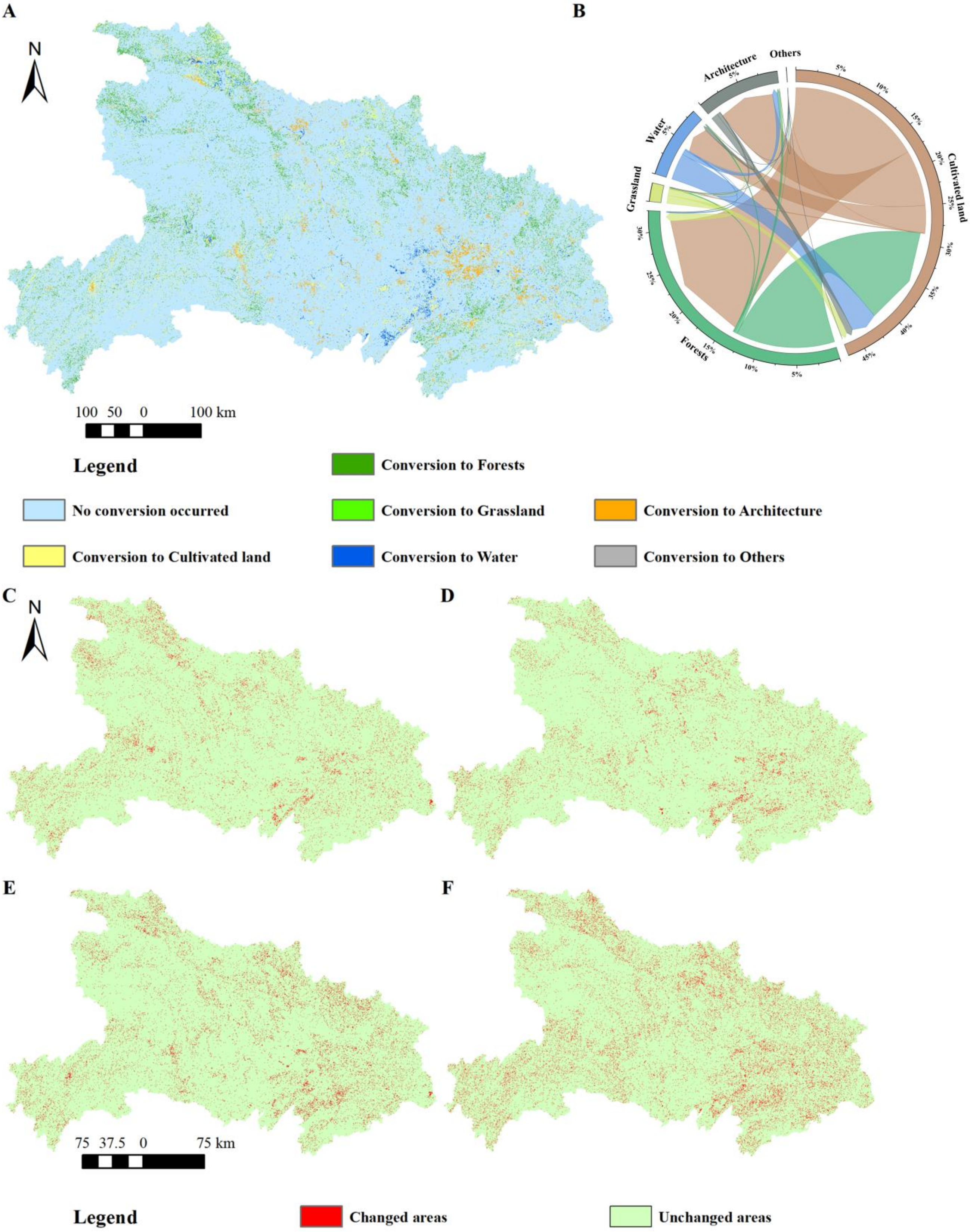

Figure 7. The (**A**) land-use change and (**B**) transitions between different land use types in Hubei Province from 2000 to 2020, the areas where land use has changed during different time periods: (**C**) period 2000–2005, (**D**) period 2005–2010, (**E**) period 2010–2015, and (**F**) period 2015–2020.

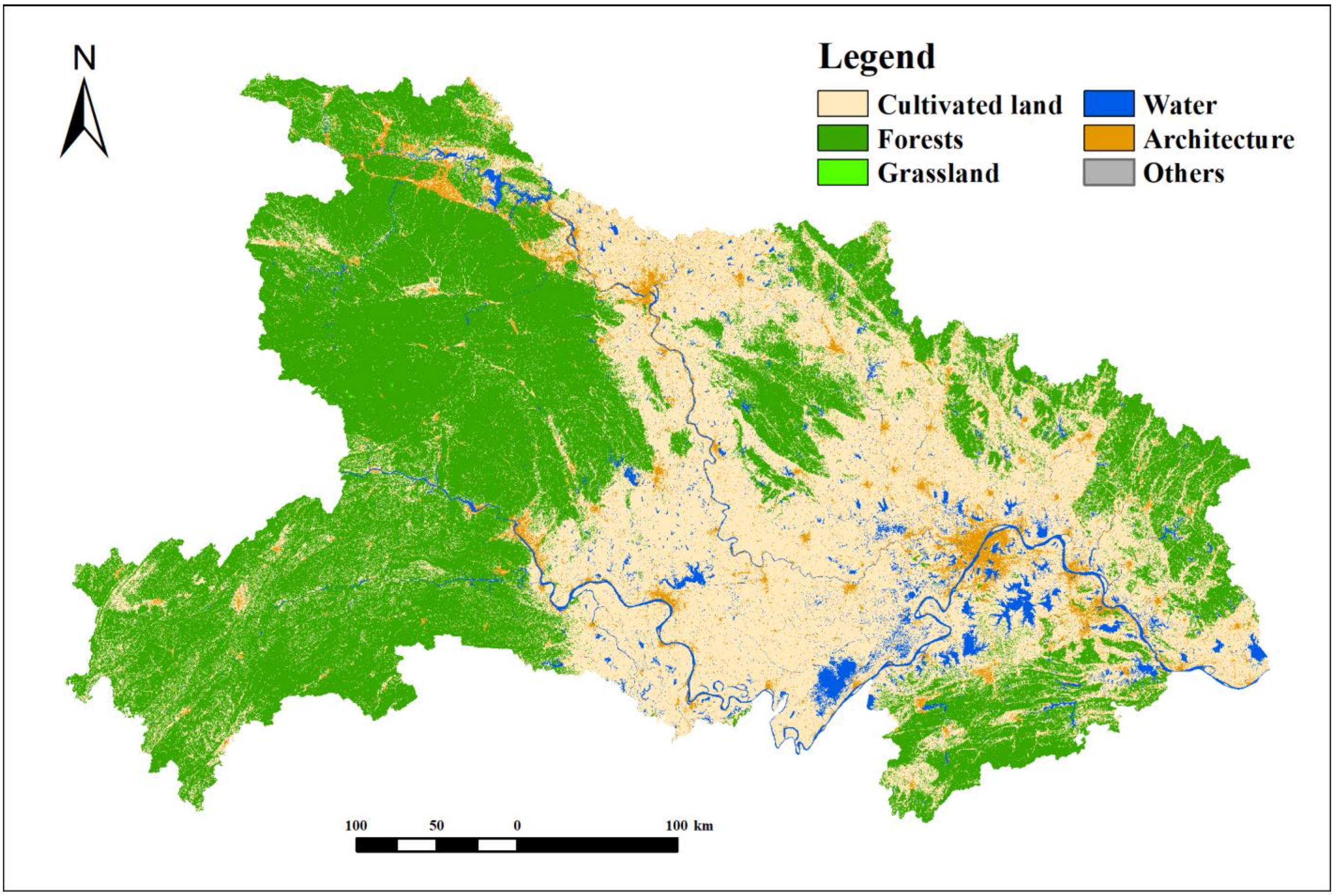

Figure 8. Simulation results for land use in 2035 in the natural development scenario.

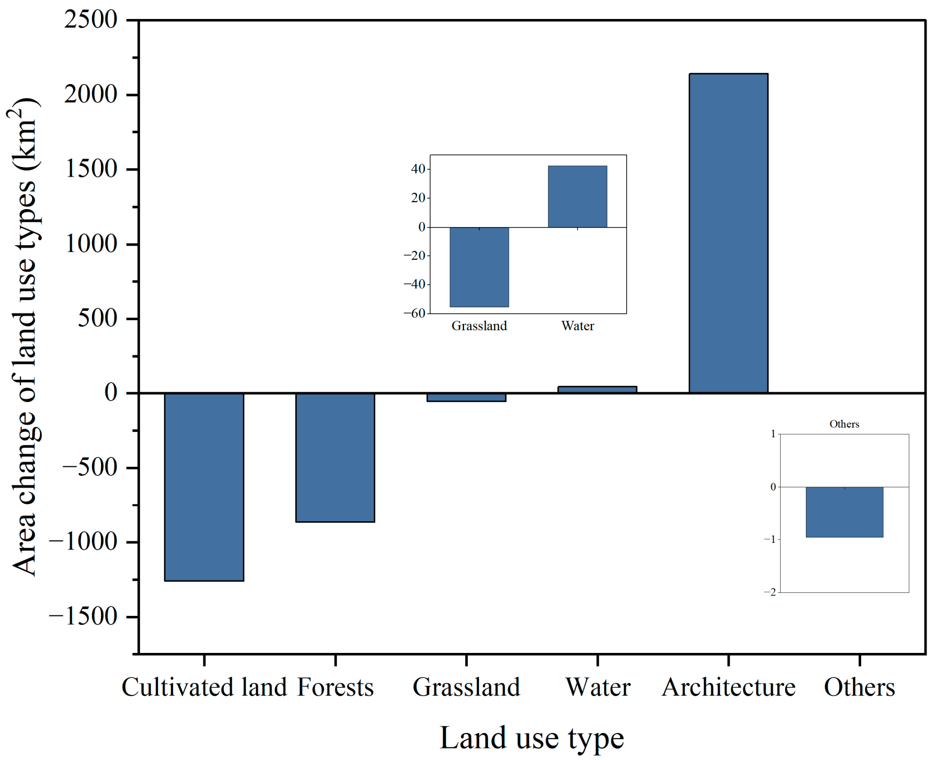

Figure 9. Area changes in land use types in the natural development scenario from 2020 to 2035.

In summary, in the scenario of inertia development, unconstrained development will cause a rapid expansion of regional construction land and a marked reduction in production and ecological lands such as cultivated land, forestland, and grassland. This will result in an inability to maintain the coordinated development of the regional ecology, society, and economy. If this trend is not restricted, food and ecological security will be at risk.

3.3. Scenario 2: Economic Priority

The economic priority scenario is primarily based on the natural development scenario and incorporates the actual situation in Hubei Province, which is undergoing a phase of rapid economic development, as well as regional land use development plans. In this scenario, the urban construction area is designated as a restricted conversion area, and the transfer probability of construction land to cultivated land, forestland, grassland, water bodies, and other land use types is reduced based on the land use transfer probability from 2000 to 2020. Figure 10 shows the simulation results of land use in 2035 in the economic priority scenario, while Figure 11 illustrates the changes in land use type areas from 2020 to 2035 in this scenario.

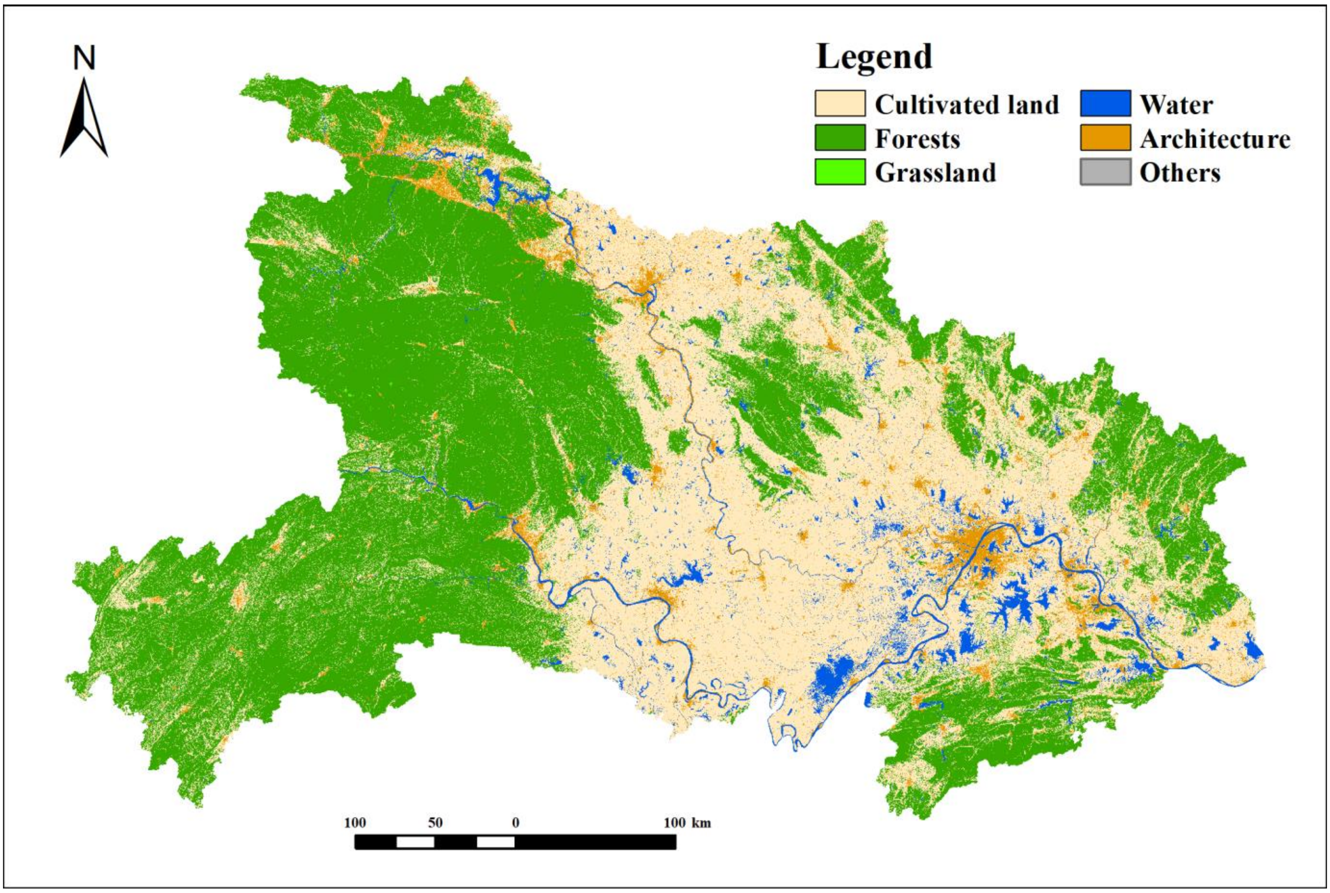

Figure 10. Simulation results for land use in 2035 in the economic priority scenario.

The trends and spatial differences in the changes in different land use types are generally similar to those in the natural development scenario. Cultivated land, forestland, grassland, water bodies, and other land use types decrease in area, while the area of construction land increases dramatically. However, the growth rate of construction land in the economic priority scenario is clearly higher than that in the natural development scenario, increasing from 6388.62 km^2 in 2020 to 9164.25 km^2 in 2035, with the growth rate increasing from 33.51% (in the natural development scenario) to 43.45%. Correspondingly, the trend of decreasing cultivated land is even more severe, decreasing from 81,610.09 km^2

in 2020 to 79,825.25 km^2 in 2035. In addition, all ecological land use types, including water bodies, show a decreasing trend, indicating that under the economic priority scenario, the expansion of urban areas leads to a reduction in the size of ecological land use types, resulting in a decline in regional ecological sustainability.

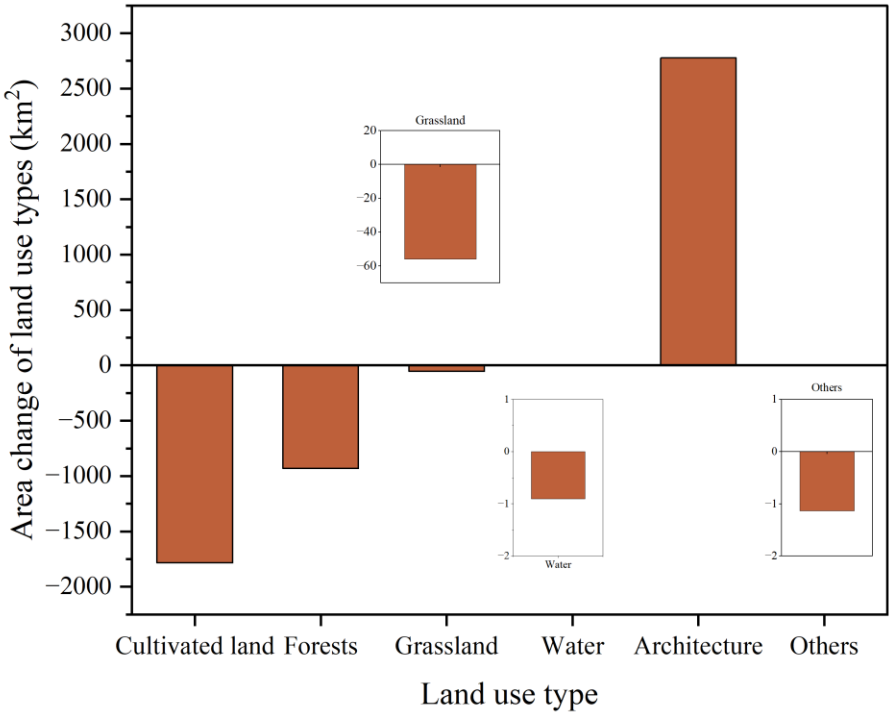

Figure 11. Area changes in land use types in the economic priority scenario from 2020 to 2035.

3.4. Scenario 3: Ecological Protection

In response to the Chinese government's "no large-scale development, joint protection" strategy [80], this study establishes an ecological conservation scenario. To maintain regional ecological security, areas that have an important impact on the ecological environment, such as forests, grasslands, and water bodies, must be strictly protected, and large-scale development and utilization should be prohibited, as outlined in Hubei Province's land development policy. Accordingly, the ecological conservation area is designated as a restricted conversion zone in this scenario. Figure 12 shows the simulated results for land use in 2035 in the ecological conservation scenario, and Figure 13 illustrates the changes in land use types from 2020 to 2035 in this scenario.

Compared with 2020, the forest and water areas in 2035 show a slight increase, with growth rates of 0.05% and 1.22%, respectively. However, the changes in land use types in this scenario still primarily focus on cultivated land and construction land. Cultivated land continues to decrease, with its area further compressed by −1.52% to only 80,367.79 km^2. The expansion of construction land is evident, but its expansion rate is effectively controlled, decreasing from 33.51% in the natural development scenario and 43.45% in the economic priority scenario to 18.19%. This development satisfies the needs for urban economic and social growth to some extent. Nonetheless, given Hubei Province's current land use efficiency, the total amount of construction land is insufficient, which is not conducive to economic development. Consequently, in the future, there will be higher requirements for intensive and efficient land use in Hubei Province.

Overall, to ensure ecological land use and meet the needs of socioeconomic activities, the primary direction of cultivated land conversion remains toward construction land. In other words, in the ecological conservation scenario, ecological land such as forests and water bodies exhibit a growth trend, prompting cultivated land to become the primary type of land conversion. The reduction in construction land encroachment on ecological land contributes to maintaining regional ecological security.

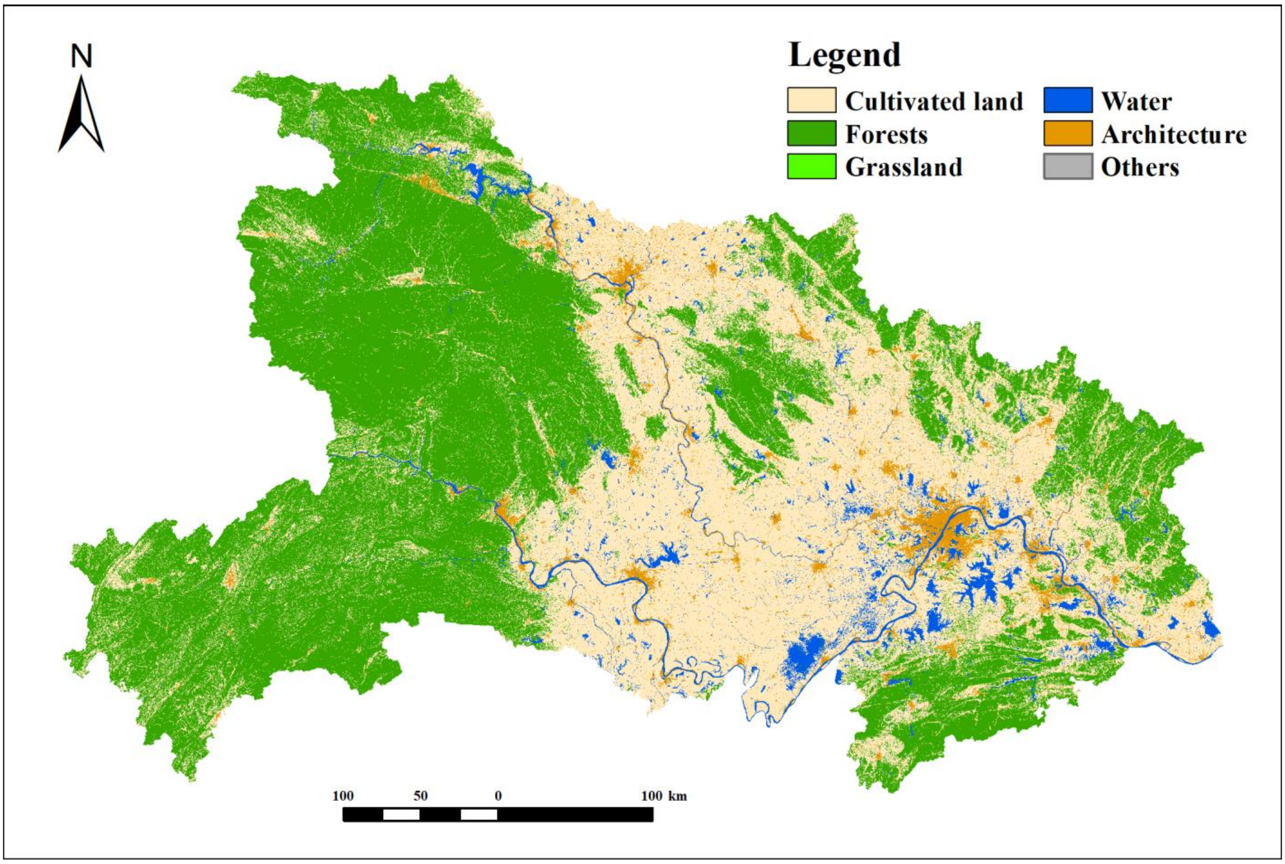

Figure 12. Simulation results for land use in 2035 in the ecological protection scenario.

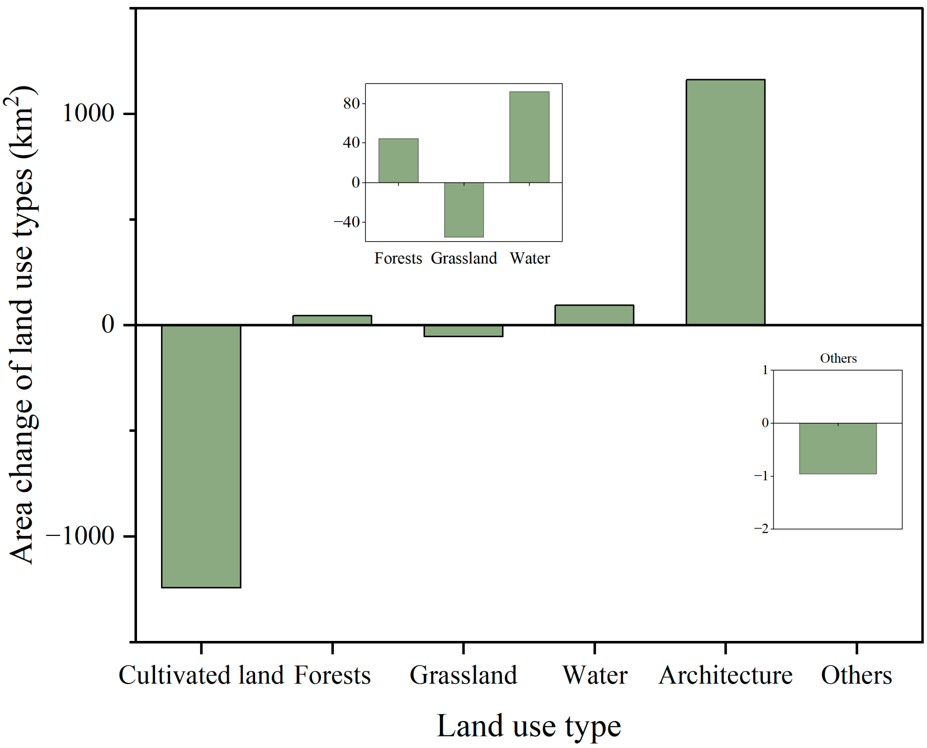

Figure 13. Area changes in land use types in the ecological protection scenario from 2020 to 2035.

3.5. Scenario 4: Cultivated Land Protection

Cultivated land protection is essential for the effective conservation of farmland resources. To achieve this, a basic cultivated land protection zone has been established, and the cost of cultivated land conversion has been increased to restrict the transfer and change of cultivated land to other land types. Additionally, the occupation of cultivated land resources by economic and social development has been strictly controlled. The simulation results for land use in 2035 in the cultivated land protection scenario are shown in Figure 14, while Figure 15 shows the changes in land use types from 2020 to 2035 in this scenario.

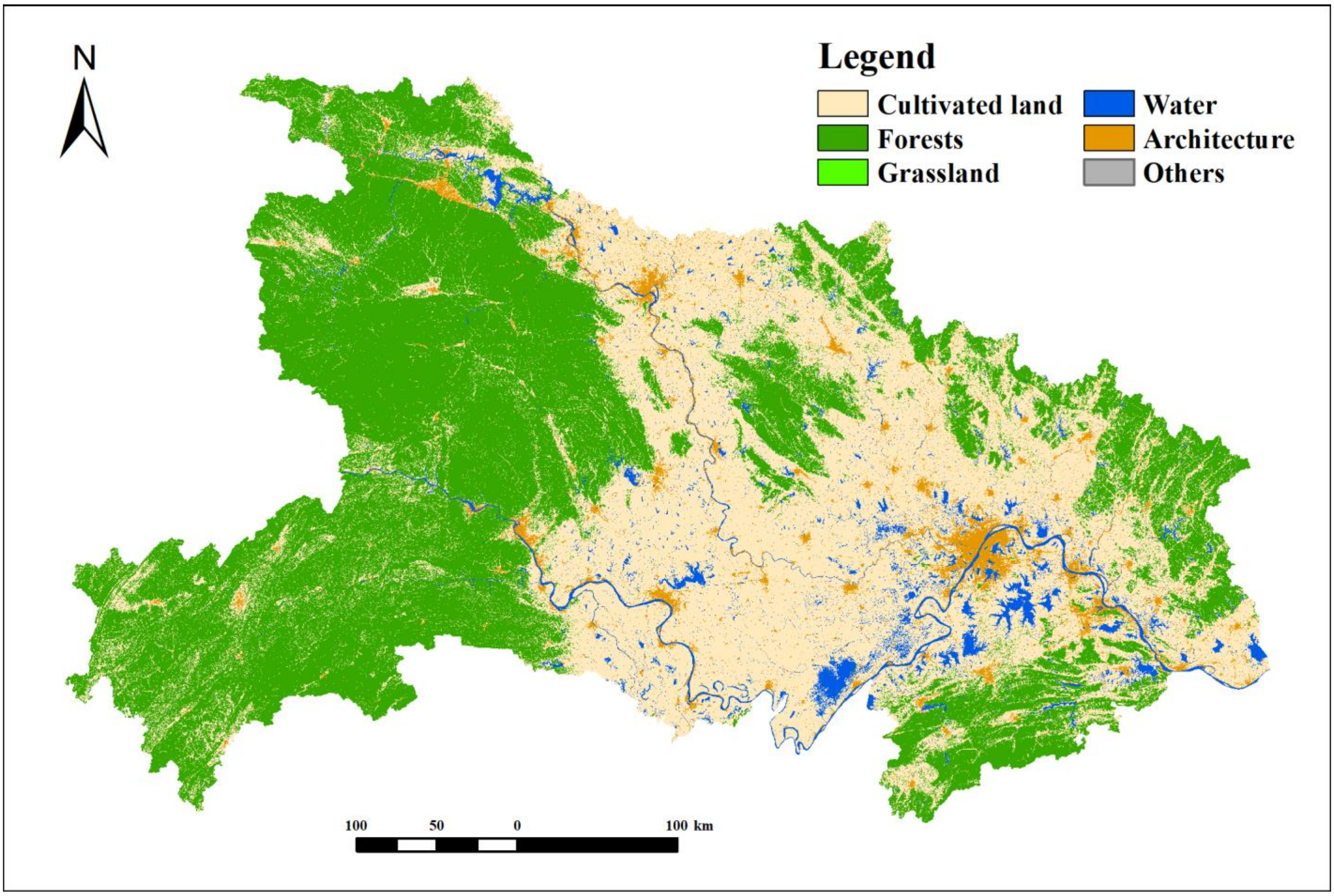

Figure 14. Simulation results for land use in 2035 in the cultivated land protection scenario.

According to this scenario, the cultivated land area is 82,876.46 km^2, which makes it the largest and only scenario with a growth trend among the 4 scenarios, with an increase of 1.55% compared with 2020. The increased area of cultivated land is mainly concentrated in the central Jianghan Plain area, where the terrain is flat and the water system is developed. This trend is in line with the planning projects for high-standard farmland construction in central Hubei cities such as Xiangyang, Xiantao, and Ezhou. The results indicate that the strict implementation of basic cultivated land protection policies and the prohibition of construction land occupying basic cultivated land can effectively protect farmland and ensure food security.

The areas of forestland, grassland, and water have shown varying degrees of reduction, with forestland experiencing the most dramatic downward trend among the four scenarios, decreasing by 1974.86 km^2 (2.19%). It is worth noting that the expansion rate of construction land clearly slows compared with the other scenarios. Its expansion direction is similar to the natural development scenario, mainly concentrated in the central region, but it still increased by 15.87% compared with 2020. This indicates that the speed of urban expansion will be somewhat controlled when implementing cultivated land protection.

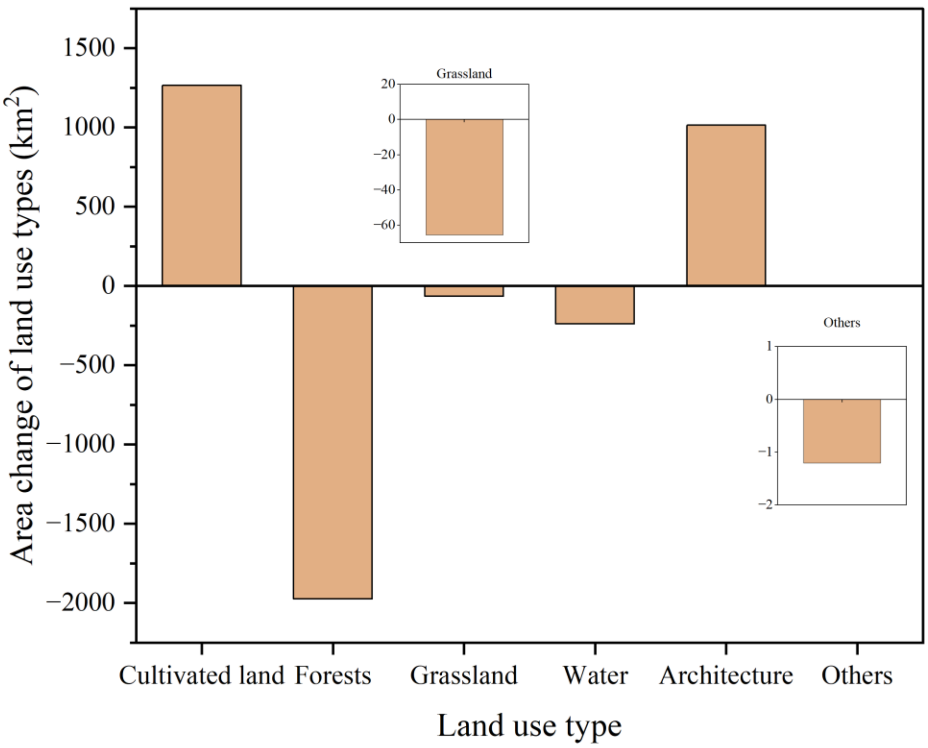

Figure 15. Area changes in land use types in the cultivated land protection scenario from 2020 to 2035.

In summary, this scenario has effectively slowed the rate of cultivated land conversion by implementing limiting factors in the basic cultivated land protection zone and increasing the conversion cost. This has ensured the quantity of cultivated land and implemented protection policies. However, despite these measures, the rapid economic development of various cities will inevitably lead to the expansion of construction land, which, coupled with the compression of forestland, grassland, and water, poses a threat to cultivated land protection and food security.

4. Limitations and Future Work

Despite the progress made in this study, it is essential to acknowledge its limitations. One of the main limitations of this study is the exclusive use of the classic FLUS model, as opposed to more advanced landscape-driven patch-based cellular automaton (LP-CA) and land use scenario dynamics (LUSD) models in recent years. These updated models incorporate more complex spatial and temporal dynamics and are known to produce more accurate and precise results in capturing the complexities of land-use changes in a given area [81–84]. Therefore, our study may have missed some crucial dynamics of the study area, resulting in less accurate results.

To address this limitation, we suggest that future research could incorporate the LP-CA and LUSD models to improve the accuracy of the findings. These models can capture the heterogeneity of the landscape and the interactions between land-use changes and driving factors, such as urban expansion and population growth [85–87]. Furthermore, these models allow for the integration of multiple factors, such as land use policies and economic development, into the simulation process [66,88]. By incorporating these models, future studies can provide more comprehensive and accurate insights into land-use change dynamics.

Another limitation of this study is the subjective nature of the scenario-setting methods. While different scenarios can indicate the likelihood of associated land-use changes, they do not necessarily reflect the actual future land-use patterns. To overcome this limitation, we plan to select additional driving factors and employ multiple scenario-setting methods to conduct multifactorial and multiscenario land-use change simulations. This approach will provide a more comprehensive understanding of the potential land-use changes in different scenarios and help decision-makers to formulate more effective land-use policies.

Overall, this study has significant contributions to the field of land-use change modeling. However, acknowledging and addressing its limitations is crucial to ensure the accuracy and reliability of the findings. By incorporating advanced models and employing multiple scenario-setting methods, future studies can provide more comprehensive and accurate insights into land-use change dynamics and help to facilitate sustainable land-use planning and management.

5. Conclusions

The Markov-FLUS model predicts future land-use quantity changes using system dynamics, relying on past land-use quantity changes [61,68]. This study employed the Markov-FLUS model to simulate potential land-use changes in Hubei Province in various scenarios for 2035. This study aimed to explore the potential outcomes in different scenarios rather than evaluating the effectiveness of existing policies. The simulation results indicate large variations in land-use patterns across the different scenarios tested.

The findings suggest that cultivated land is the predominant land use type in Hubei Province, occupying 43.90% of the total area. Nevertheless, cultivated land decreased by 1260.50 km^2 (−1.54%), 1784.83 km^2 (−2.19%), and 1242.30 km^2 (−1.52%) in the natural development, economic priority, and ecological protection scenarios, respectively, while it increased by 1266.37 km^2 (1.55%) in the cultivated land protection scenario. In the ecological protection scenario, forestland was effectively safeguarded, increasing by 44.17 km^2 (0.05%), while it decreased in the other 3 scenarios. Grassland and other land uses showed a decreasing trend across all four scenarios. The expansion of construction land was the most dramatic, exhibiting outward and infill expansion. The area of construction land increased in all scenarios, but the cultivated land protection (15.87%) and ecological protection (18.19%) scenarios had much smaller increases than the natural development (33.51%) and economic priority (43.45%) scenarios.

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Predictive Scenarios of LULC Changes Supporting Public Policies: The Case of Chapecó River Ecological Corridor, Santa Catarina/Brazil

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Abstract: The studies of spatial-temporal land use and land cover (LULC) change patterns, supported by future scenarios and simulation methods based on the assumption of natural socio-economic and territorial driving forces, allow us to go beyond an accurate diagnosis of the dynamics that have occurred so far, providing a picture of possible alternative futures, and are fundamental in assisting with the planning and policy-making in the territory. In this paper, we use LULC maps and explanatory variables aggregated in five dimensions (physical/natural, economic, sociocultural, technological, and demographic) to identify which are the main drinving forces in the evolution process and the simulation of LULC dynamics for 2036, using as a case study the Chapecó River ecological corridor (Chapecó EC) area. The Chapecó EC was created by the state government in 2010 with the goal of combining nature conservation with local and regional development. In this region, in the last two decades, the loss of areas of natural grassland and forest was on average five times higher than the average recorded in the state. Based on scenario-building methods using artificial neural networks, six predictive scenarios were elaborated, based on three socioeconomic scenarios (current conditions, growth, and socioeconomic recession) and two territorial intervention options (actions). This includes an action based on maintaining the current LULC, and another action of a conservationist nature with the recovery of forest and natural grassland areas to the proportions of areas found in 1990. The results indicate that if the current LULC is maintained, forest, pasture and agriculture areas tend to increase, while silviculture and natural grassland areas decrease, driven by economic and physical/natural driving forces. If there is a conservationist action, natural grassland and pasture areas tend to increase and silviculture and agriculture tend to lose area due to economic, technological, and physical/natural driving forces. These trends have revealed that the natural grassland preservation/restoration, the encouragement of conservationist agricultural practices combined with economic strategies, and the technological development of the rural sector seem to form the basis of economic development combined with biodiversity conservation.

Keywords: spatial modelling; predictive scenarios; artificial neural networks; good farming practices; agricultural technological development; spatial planning

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1. Introduction

The term land use and land cover (LULC) refers to the different categories of land use and land cover. Land use relates to human manipulation to meet certain needs, while land cover refers to the physical condition of the surface [1–3]. Land use impacts the environment mainly through its coverage, which may change as a result of a change in its use [4].

Historically, human populations have been modifying the landscape, and currently this process is occurring in a more accelerated way due to the extraction and appropriation of natural resources as well as the expansion of territories. Negative effects on the environment and social disturbances associated with the intensification of land use are documented in a number of studies that point to agriculture as the main force of land cover transformation on the planet [5–8]. It is estimated that one third of the surface of the earth is used for crops or livestock, and such lands are converted from natural forests, grasslands, and swamps [8].

The study of land use and land-cover (LULC) dynamics stands out as a fundamental topic in the context of the challenges that humanity is facing—e.g., global urbanisation, climate change, food security, global health, and pandemics—since they influence and are influenced by various systems, namely environmental, social, and economic. Therefore, knowledge about these processes and their impacts is crucial in various fields, namely environmental monitoring, land use development and planning, and political and economic evolution trends [9].

Studies on LULC dynamics involve two key steps: identifying changes in the landscape and assigning to those changes a set of causal factors [10] or driving forces. The driving forces are forces that provoke changes and create dynamics in the territory [8,11–13]. They are usually represented by a set of variables [14] classified in different dimensions of analysis, i.e., physical/natural, demographic, economic, technological, social, cultural, and political [15].

In Brazil, the expansion of urban areas (including roads/highways) and areas dedicated to agriculture, cattle raising, and forestry (silviculture) are important driving forces of natural vegetation suppression [7,16–20]. As with urban population growth, the expansion of urban areas and the export of agricultural products are cited as the leading causes of rainforest loss in 41 countries [7].

In that context, it becomes relevant to analyse these processes of change and to explain that LULC dynamics analysis models are tools to support planning and policy decisions in the territory [18–20]. They can include the dynamic simulation of natural and socioeconomic processes and the identification of indicators and predictors [21]. The integration of environmental and human sciences, geographic information systems, and remote sensing has enabled the improvement of techniques for measuring LULC changes and the development of predictive models [22].

The literature presents a set of models that have been widely used in simulation studies of LULC dynamics relating it with their driving forces. There are a variety of models based on different empirical techniques. One of the most used approaches is CA, ANN and ABM [23]. Examples include MOLAND, SLEUTH, FLUS, SECOA, Dynamic EGO, CLUE-S, and the Desakota models [24–30]. Since the decisions and choices made in the scope of land use development and planning processes always address issues related to the future, the construction of scenarios represents an essential tool. Uncertainties about that future increase [31,32], and scenarios provide alternative visions of possible futures, providing insights into the creation of risk management plans, and anticipate action measures that can avoid the potential problem and/or mitigate it, within a cost-effectiveness rationale.

The term 'scenario' adopted in this paper denotes a coherent story or narrative of what might happen in the future [31]. The scenarios resulting from the models illustrate potential and plausible descriptions of the future based on 'if/then' assumptions [33]. The independent variables in the model are altered to compose the desired scenario. The scenarios allow us to measure and evaluate what is more likely to occur, allow for the identification of the driving forces that can influence the results, and offer support to the formulation of public policies [11,32,34–37].

From the model's point of view, the driving forces are the main uncertainties and trends that will influence changes in the baseline scenarios (i.e., business as usual) and allow us to explore plausible futures (scenarios) under a 'what if' approach by changing the values of the main uncertainties. This type of scenario is called a probabilistic predictive scenario and addresses the question, 'What will happen?' [33].

Predictive scenarios are composed of scenarios that represent plausible futures—where the values of one or more independent variables are deliberately changed to compose the future narrative to be considered—and actions, i.e., any policies, projects and territorial restrictions considered to be implemented in the study area. To this end, the actions are carried out in the dependent variable [11,31,33].

The literature highlights some scenario-building methods, e.g., cellular automata (CA), CA and fuzzy analysis, artificial neural networks (ANN), and multicriteria decision analysis (MCDA) [11,32–34,38–40]. In this research, we adopted an artificial neural network modelling approach for its flexibility, which permits the inclusion of express rules that incorporate specialised knowledge, operator experience, and the participation of different interests in addressing 'what if' questions [11,17,32,35,41–43].

In the last two decades, the state of Santa Catarina registered a loss of 15% of grassland and approximately 2% of forest [44]. While our study area, located in the Western region of the state, the Chapecó EC, registered for the same period, includes losses of these areas considerably higher than the state average. Natural grassland lost 55% of its cover to the expansion of agriculture, and forest lost 13% of its area to forestry (silviculture) [17].

The region is seen as an economic influence area and a tug of war between family farming and the agro-industrial complex. This territory is a bone of contention since the situation has not been defined either in terms of a hegemonised production pattern favoured by the agro-industrial complex or the capacity of family farmers to resist or adapt to new scenarios [45].

In 2010, the government of the state of Santa Catarina enacted by State Decree No. 2957 of 20 January [46] the creation of the Chapecó River EC (Chapecó EC), whose principal objective is: *'Developing and implementing a model for the promotion, marketing and leveraging of native forests (and other natural environments) as environmental assets, promoting the maintenance and improvement of the permeability of the landscape'* [47].

Currently, another important territorial policy operates in the region. The Development Plan of the State of Santa Catarina 2018–2030, called the SC2030 Plan, aims to reduce inequalities and promote social equity, seek sustainable regional development, and boost innovative development and the entrepreneurial capacity of Santa Catarina [48].

Furthermore, we identified a lack of information about the LULC change, its drivers and possible future implications in the region of the Chapecó CE, in a way that can subsidize, guide and support territorial and environmental policies.

Thus, this study was aimed at counterposing different predictive scenarios of changes in LULC, taking into account the guidelines of both public policies. Specifically we sought to: (i) build six predictive scenarios of LULC for 2036 from the guidelines of two public policies; (ii) identify the main LULC change between the predictive scenarios and the reference year (2018); (iii) discuss the influence of the main driving forces in each predictive scenario; and (iv) understand the importance of adopting these policies in the region.

This paper is organized as follows: Section 2 describes the study area, data, and methods used for this purpose. Section 3 introduces the main results of LULC changes expected for 2036 and the main driving forces. Section 4 approaches the discussion on the main LULC changes related to the driving forces and the effects of public policies on LULC dynamics. Finally, Section 5 introduces the main conclusions, implications, and limitations of the research.

2. Materials and Methods

2.1. Study Area

The study area is 7242.33 km^2 and is located between the geographical coordinates 27°5′0″ and 26°20′0″ South latitude and 53°0′0″ and 51°10′0″ West longitude. It is located Northwest of the state of Santa Catarina in the Southern region of Brazil (Figure 1). It shelters a preservation area called Chapecó EC, created in 2010 by the Government of the State of Santa Catarina/Brazil [46].

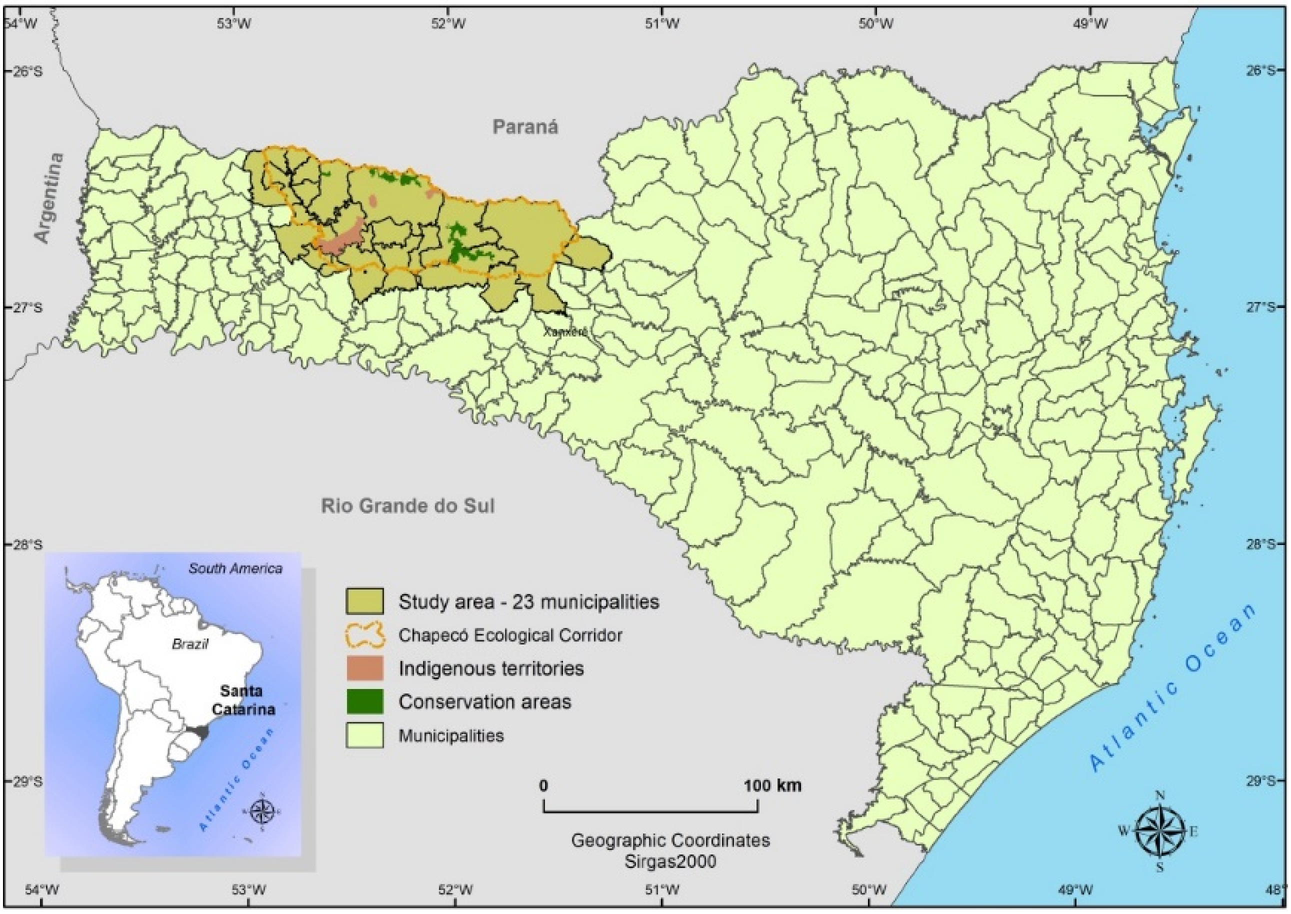

Figure 1. Location of the study area.

This area has different social arrangements with four main segments: indigenous populations, family farmers (plus settlers), employing farmers (grain and cattle ranchers), and foresters. It stands out with the economic activities of soybean cultivation, beef and dairy cattle raising, and wood production [47]. This complex social arrangement, together with land use and land cover changes [16] and territorial conflicts [45], makes this region of great environmental, social, and economic appeal for the state of Santa Catarina.

The Chapecó EC is formed by 23 municipalities, occupying approximately 7.6% of the total area of the state of Santa Catarina. It had an estimated population of 185,000 inhabitants in 2018, in addition to a demographic density and urbanization rate lower than the state average. The municipalities are small, with agricultural and cattle raising traditions. The area dedicated to agriculture and cattle-raising in the region, as well as the Gross value added of agriculture and cattle-raising (GVA) are expressive, which reveals the agricultural aptitude of the region. It exhibits twice as much area dedicated to agriculture and cattle-raising compared to Brazil and participates with 2.2% of the Gross Domestic Product (GDP) of the state (Table 1).

Table 1. Socioeconomic indicators.

Indicators	Chapecó EC	Santa Catarina	Brazil
Area (km^2)	7242 *	95,346	8,516,000
Estimated population (2018)	185,300 *	7,075,500	211,755,692
Demographic density (2018) (inhab./km^2)	25.6	74.2	24.9
Urban population (2010) %	64.6 *	84.0	84.3
Agricultural area (2018) %	67.6 *	48.9	30.6
GVA of agriculture and cattle-raising (2018) %	31.3 **	5.51	5.15
GDP (2018) BRL 1000	6,603,755 *	298,227,090	7,004,141,000

Source: IBGE/SIDRA [49]. Values referring to the sum (*) and average (**) of the 23 municipalities that are part of the Chapecó EC.

The Chapecó EC area is located in the Atlantic Forest biome composed of mixed ombrophilous forest (Araucaria forest), deciduous seasonal forest, and gramineous steppe (natural grassland) [47,50]. Figure 2 shows the phytogeographic composition of the region.

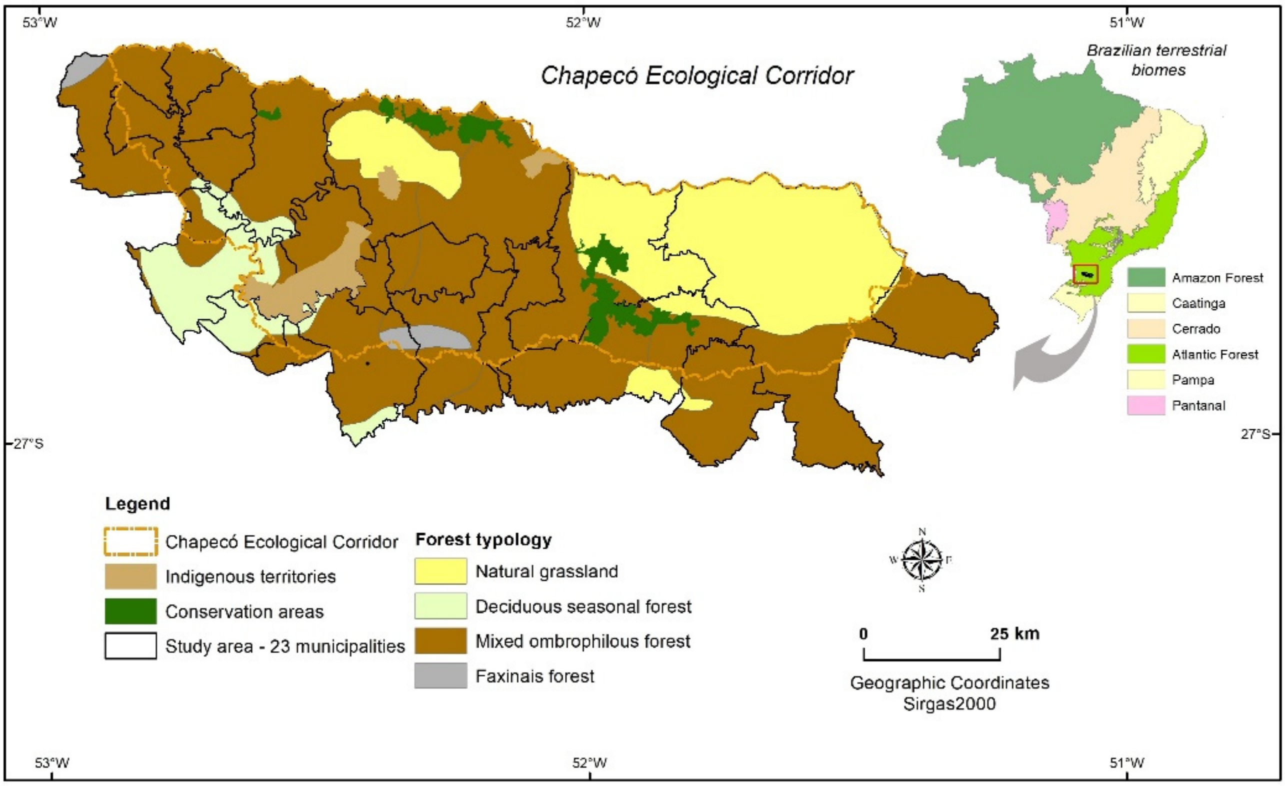

Figure 2. Forest tipology (Atlantic Forest biome) in CHapecó CE.

Geomorphologically, it is formed by the Campos Gerais Plateau and the Dissected Plateau. In the Campos Gerais Plateau, the altitude varies between 800 m and 1200 m, and the area is higher than the surrounding areas, which belong to the Dissected Plateau. The latter has a great topographic contrast with the Campos Gerais Plateau area, with a strongly dissected relief of deep valleys and terraced hillsides. The main types of soil found in the Chapecó EC are latosoil, nitosoil, cambisoil, and litholic soil, where cambisoil is the predominant soil type [45,51,52].

Regarding the climate, in areas below 800 m, the climate is of the humid mesothermal type with hot summers (Cfa), and in areas above that altitude, the climate is of the humid mesothermal type with cool summers (Cfb). The average annual temperature ranges from 15 °C to 18 °C [53], with well-distributed rainfall throughout the year, varying between 1640 and 2035 mm [52,53].

2.2. Methodological Framework

Figure 3 illustrates the methodological framework used to simulate future LULC changes and identify the main driving forces acting under different predictive scenarios [11,32]. The development of the work can be divided into four steps.

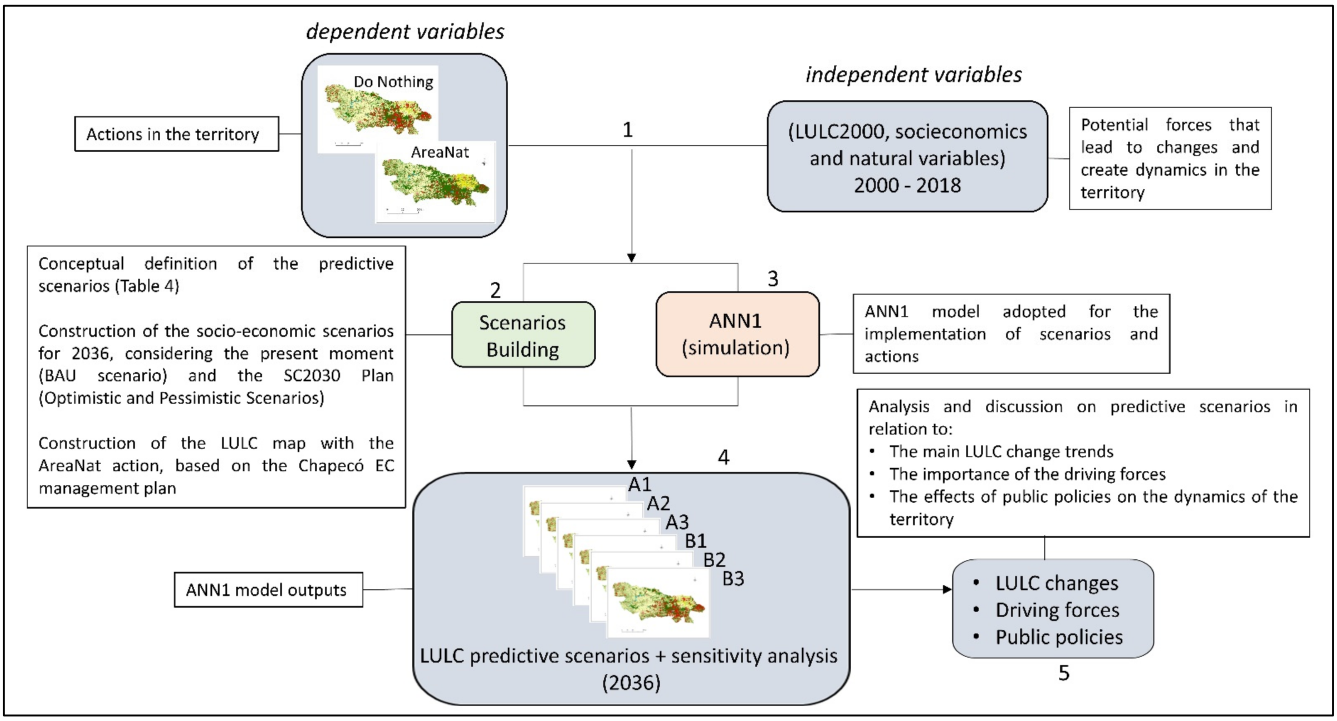

Figure 3. Methodological framework. Step 1—variable selection and systematisation; Step 2—predictive scenario-building; Step 3—LULC dynamics simulation based on artificial neural networks for 2036; Step 4—ANN1 model outputs, and Step 5—analysis and discussion.

In the first step, the representative variables of the scenarios and actions were selected, and the database used in the model was structured. In the second step, the predictive scenarios were conceptually defined based on the combinations between scenarios and possible actions. In the third step, scenarios and actions were implemented, and the model was run. The fourth and fifth steps introduce the results of the predictive model and the analysis and discussion on the trends of LULC dynamics, the main driving forces identified, and the effects of the selected public policies [11,32,41].

2.3. Database

The data used in this work include land use and land cover, physical, social, and economic data; they were selected from available online databases [44,49,53–57].

The whole database was organised in a GIS (Geographic Information System) environment, stored in raster format with 100 m of spatial resolution, and referenced to the SIRGAS UTM 22S system. For the simulation of LULC changes and the sensitivity analysis based on artificial neural networks, the software SPSS 24 [58] was used, and the software ArcGis 10.7 [59] was used for specialisation and LULC change analysis in the different scenarios.

2.3.1. Land Use and Land-Cover Data

The LULC data used in this research comprise maps from 2000 and 2018 from the MapBiomas Project, collection 4.1 [44]. The LULC classes are: forest, silviculture, grassland, pasture, agriculture, mosaic, artificial area, and water bodies. The description of the LULC classes can be seen in Table 1, in the classification key adopted in the Mapbiomas Project [44] and in the phytogeographic typologies of Santa Catarina [50] (Table 2).

Table 2. Land use and land cover description.

LULC Class	Description
Forest (forest formation)	Dense, open and mixed ombrophilous forest, semi-deciduous and deciduous seasonal forest, and pioneer formation.
Silviculture (forest plantation)	Planted tree species for commercial use (e.g., Eucalyptus, Pinus and Araucaria).
Natural grassland	Savannas, park and grassland steppe savannas, steppe and shrub and herbaceous pioneers.
Pasture	Pasture areas, natural or planted, related with farming activity.
Agriculture (annual and perennial crop)	Areas predominantly occupied with annual crop (short to medium-term crops, usually with a vegetative cycle of less than one year, which after harvest needs to be re-planted) and in some regions with perennial crops (Areas occupied with crops with a long cycle (more than one year), which allow successive harvests without the need for new crop).
Mosaic (mosaic of agriculture and pasture)	Farming areas where it was not possible to distinguish between pasture and agriculture.
Artificial Area (urban infrastructure + other non vegeteded area)	Urban infrastructure: urban areas with predominance of non-vegetated surfaces, including roads, highways and constructions and other non vegetated areas Non-permeable surface areas (infrastructure, urban expansion or mining) not mapped into their classes and regions of exposed soil in natural or crop areas.
Water bodies (river, lake and ocean)	Rivers, lakes, dams, reservoir and other water bodies.

2.3.2. Variable Selection

In this paper, the selection of variables was based on the literature review, the historical context of territorial, demographic, socioeconomic, and environmental dynamics in the region [45], as well as the availability of information, both concerning the period of analysis (2000–2018) and its spatial representativeness [16,17,39].

The physical/natural (biophysical) dimension consists of the biotic and abiotic variables which define the natural capacity and/or environmental conditions for land use changes. The economic and technological dimensions can be represented by variables that directly affect the land managers's decision-making process [12,60].

The Chapecó EC region is part of the economic influence zone and region of family farming and agro industrial complex [45]. Therefore, the variables of the economic and technological dimension were selected in order to measure the evolution of the main productive sectors in the region, the participation of family agriculture in the state economy, the rural agro-industries and the technological development in the rural sector.

The analysis of the region's economic structure shows a tendency towards the growth of agribusiness, aimed at the external market. The rate of employment in the industrial sector shows growth in the sector and retraction in the agriculture and cattle raising and forestry production activities. Formal employment in the transformation industry grew 35%, almost twice as much as the state average (19%). Employment in the farming, livestock, and forestry sectors fell 24% in the period [57].

Among the industrial sectors, the slaughtering and meat products sector stands out, measured by the herd size variables. The region presented an increase in the chicken herd (4%) [49]. Chicken meat participates with 36% of the total export of agribusiness in Santa

Catarina, ranking first, followed by wood, swine, soybeans, and tobacco (2019) [61]. The increase in the use of pesticides, the production yield of the main crops in the region and mechanization point to an intensification of agricultural activity, supported by technlogical development. The use of pesticides in the study area (17%) was almost twice the increase in the state (10%). The increase in the average yield of soy and corn production was 105%, while the state registered an increase of 90%, and high mechanization in the region, an increase of 165% in relation to the state, reinforcing the importance of the region in the state and national economic and agricultural context.

The demographic and sociocultural variables, rural population and age of the rural producer sought to portray the dynamics of rural exodus and the aging of the rural population and family succession, seen with concern in the public policies used [47,48]. The rural population in Santa Catarina, between 2000 and 2010, decreased by 24% and in the study area by 15%. In Santa Catarina, 33% of the rural producers in charge are 55 years old or older, and in the study area this problem is even greater than in the state, with 48% at retirement age [49].

Table 3 shows the relation of the variables, both dependent and independent, representing the set of driving forces inputted in the ANN1 model, organised into five dimensions of analysis. The full description of the variables is available in the Supplementary Material Repost S1: Variable description.

Table 3. ANN model variables.

Dimension	Dependent Variables	Unit	Format	Scala/ Spatial Resolution
Physical/natural	Land use and land cover (do nothing)	class	raster	30 m
Physical/natural	Land use and land cover (AreaNat)	class	raster	30 m
Dimension	**Independent Variables—Year**	**Unit**	**Format**	**Scala/ Spatial Resolution**
Physical/natural	Land use and land cover—2000	class	raster	30 m
	Temperature—2002	°C	vector	1:500,000
	Accumulated precipitation—2002	mm	vector	1:500,000
	Type of soil—2004	class	vector	1:250,000
	Type of relief—2000	class	raster	30 m
	Altitude—2000	m	raster	30 m
	Road network—2018	km/km^2	vector	municipality
Economic	Rural agribusiness—2006 and 2017	%	table	municipality
	Cattle herd—2000 and 2018	%	table	municipality
	Swine herd—2000 and 2018	%	table	municipality
	Chicken herd—2000 and 2018	%	table	municipality
	Formal employment (commerce/service)—2006 and 2018	nº	table	municipality
	Formal employment (industry)—2006 and 2018	nº	table	municipality
	Formal employment (agriculture)—2006 and 2018	nº	table	municipality
	Financing (Pronaf)—2006 and 2017	%	table	municipality
	Processing industries—2006 and 2018	nº	table	municipality
	Gross Domestic Product (GDP)—2002 and 2017	R$	table	municipality
	Agricultural land price—2000 and 2018	R$/ha	table	municipality
	Per capita income—2000 and 2010	R$	table	municipality
	Log Production—2000 and 2018	m^3	table	municipality
	Gross value added of agriculture and cattle-raising—2000 and 2017	%	table	municipality
	Milk production value—2002 and 2017	%	table	municipality
Sociocultural	Family agriculture—2006 and 2017	%	table	municipality
	Schooling of the head farmer—2006 and 2017	nº	table	municipality
	Age of the head farmer—2006 and 2017	nº	table	municipality
	Municipal Human Development Index (HDI)—2000 and 2010	index	table	municipality
	Rural workers—2006 and 2017	nº	table	municipality
	Land structure—2006 and 2017	ha	table	municipality
Technological	Use of agrochemicals—2006 and 2017	%	table	municipality
	Mechanization in the rural property—2006 and 2017	tractors/km^2	table	municipality
	Technical orientation—2006 and 2017	%	table	municipality
	Maize yield—2002 and 2017	kg/ha	table	municipality
	Soybean yield—2002 and 2017	kg/ha	table	municipality
	Bean yield—2002 and 2017	kg/ha	table	municipality
	Tobacco yield—2002 and 2017	kg/ha	table	municipality
Demographic	Population density—2000 and 2018	inhab/km^2	table	municipality
	Rural population—2000 and 2010	%	table	municipality

2.4. Scenario Building

The construction of the predictive scenarios for the year 2036 for the Chapecó EC region was based on the method presented by the European Environment Agency (EEA) report [31] and applied by Morgado et al. [11,33].

Table 4 summarises how the six predictive scenarios proposed in this paper were constructed to assess LULC change trends and their main driving forces. The full table of scenario construction is available in the Supplementary Material Repost S2: Scenario building.

Table 4. Scenario building schema.

		Scenarios		
		BAU	**Optimistic**	**Pessimistic**
Action	Do Nothing	A1	A2	A3
	AreaNat	B1	B2	B3

A1—'do nothing and business as usual'—this is the predictive status quo scenario to which the others refer. It considers no action in the territory in the current social and economic condition.

A2—'do nothing and optimistic scenario'—this predictive scenario represents the socioeconomic expansion over the last analysis period (2018) and no action in the territory.

A3—'do nothing and pessimistic scenario'—this predictive scenario represents socioeconomic recession and climate change over the last analysis period (2018) and no action in the territory.

B1—'AreaNat and business as usual'—this scenario describes the counterfactual case of forest and grassland restoration. It considers the recovery of natural areas in the territory in the current social and economic conditions.

B2—'AreaNat and optimistic scenario'—this scenario reports socioeconomic expansion over the last analysis period (2018) and the recovery of natural areas in the territory.

B3—AreaNat and pessimistic scenario'—this scenario assumes socioeconomic recession, social crisis in the countryside and climate change in the last period of analysis (2018) and the recovery of natural areas in the territory.

To define the scenarios and actions, some of the agricultural and environmental guidelines were considered, according to the problematic of the study area, of two public policies, the *Development Plan of Santa Catarina State 2030—SC 2030 Plan* and the *Management Plan of the Ecological Corridor of Chapecó* [47,48], as well as state climate projections [62–65] and socio-economic indicators [49].

Table 5 presents the list of guidelines and target defined in the policies, related to the variables for the construction of the predictive scenarios.

Table 5. Summary of public policy guides used to build scenarios.

Public Policy	**General Objective**		
SC2030 Plan	*To reduce inequalities and promote social equity, seek sustainable regional development, boost innovative development and the entrepreneurial capacity of the Santa Catarina society*		
Guidelines	**Indicators**	**Targets**	**Variables**
Protect, restore, and promote the sustainable use of terrestrial ecosystems	Percentage of territory with native vegetation cover	+1%	AreaNat action
Combat climate change and its effects	Projections of increased temperature and precipitation [62–65]	+4 °C	Temperature
		+84 mm	Accumulated precipitation
Add value to family farming	Number of family farming agroindustry enterprises	+55%	Family agriculture
	Municipal GDP growth [49]	+54	GDP
Revitalize the rural world	Rural credit—participation of Pronaf in the total number of contracts	+0.3%	Financing (Pronaf)
Ensure sustainable production	Maize yield (kg/ha)	+45%	Maize yield
	Soybean yield (kg/ha)	+53%	Soybean yield
Social problems in rural areas: rural exodus, aging of head farmers and family succession	Age of the head farmer [49]	+70%	Age of the head farmer
	Rural population [49]	−20%	Rural population
Public Policy	**General Objective**		
Management Plan of the Chapecó EC	*Developing and implementing a model for the promotion, marketing and leveraging of native forests (and other natural environments) as environmental assets, promoting the maintenance and improvement of the permeability of the landscape'*		
Guideliness	**Indicators**	**Targets**	**Variables**
Combat the expansion of productive areas (pasture, agriculture and silviculture) over areas of natural vegetation Combat the loss of natural vegetation Conservation of natural grasslands	LULC map	Natural areas recovered to the conservation status of the year 1990	AreaNat action

2.4.1. Scenarios

The business as usual (BAU) scenario represents a narrative of current conditions in the study area. This scenario assumes, for the period of the analysis, that political, economic, demographic, environmental, and social conditions remain as they have been. These are represented by the independent variables observed between 2000 and 2018 and analyzed in Section 2.3.2.

To build the optimistic and pessimistic scenarios, the targets of the rural development policy indicators, historical data from official sources, and climate projections were considered. For the pessimistic scenario, the authors considered it reasonable to adopt only 1/3 of the increase applied to the optimistic scenario.

The optimistic scenario represents social and economic growth, guided by some goals and objectives of the Economic Development axis: Agriculture and Fishing, the Development Plan of the state of Santa Catarina 2030, and the SC2030 Plan [48]. The optimistic scenario foresees an increase in productivity in the agricultural sector (soybean and maize crops), the support for family agriculture with an increase in the participation of Pronaf in the total number of contracts (rural credit), and increased participation of family agriculture in the rural agribusiness. For this scenario, a GDP per capita increase was also considered, since this is a synthetic indicator of the local economy. For this scenario, five independent variables were altered.

For maize and soy yields, the increase applied was 45% and 53%, respectively, an increase of 0.3% in the number of agricultural sites with Pronaf financing and by 55% in the participation of family farming in rural agribusiness according to the SC2030 Plan [48]. The average GDP growth rate in Santa Catarina for the years 2002 to 2017 was 2.5% per annum [49]. Thus, an increase of 54% in the GDP per capita was considered, referring to an increase of 3% per annum multiplied by the number of years of the scenario period (18 years).

The pessimistic scenario, as opposed to the optimistic scenario, reflects conditions of economic recession, social crisis in the rural sector, and climate change. A total of eight independent variables were altered: maize and soybean yields, participation of family farming in the rural agribusiness, GDP, rural population, producer age, temperature, and accumulated precipitation.

The variables 'maize and soybean yields' and 'participation of family farming in rural agribusiness' were considered to grow by only one-third of the target projected in the SC2030 Plan. An increase of only 0.75% per annum was considered for the GDP. Thus, the correction was increased by 15%, 17.5%, 18%, and 13.5%, respectively.

Additionally, in this scenario, we considered a climate of social crisis in the rural sector, where according to the latest censuses and the Management Plan of the Ecological Corridor of the Chapecó River [47,49,66], there is a tendency for the rural population to decrease and age. Thus, a negative variation of 20% was considered for the rural population variable, based on the trend calculated by the variation rate for the 2000 to 2010 period [49]. To characterise the problem regarding the lack of succession in the command of rural property and the ageing of the leading producers [47,48,67] a 70% increase in the number of farmers over 55 was projected.

In the pessimistic scenario, we introduced changes to the variables temperature and precipitation based on different global and regional climate change studies [62–65,68]. To this end, we considered an increase in the average air temperature of 4 °C and an increase in the accumulated precipitation of 84 mm in the study region and the period under analysis.

Table 6 shows the increased values of the independent variables used to prepare optimistic and pessimistic scenarios.

Table 6. Increase in the independent variables used for the construction of optimistic and pessimistic scenarios.

Scenarios			
Optimistic		Pessimistic	
Independent Variable	**Increase**	**Independent Variable**	**Increase**
Family agriculture—2017	+55%	Family agriculture—2017	+18%
Financing (Pronaf)—2017	+0.3%	GDP—2017	+13.5%
GDP—2017	+54%	Maize yield—2017	+15%
Maize yield—2017	+45%	Soybean yield—2017	+17.5%
Soybean yield	+53%	Temperature—2002	+4 °C
		Accumulated precipitation—2002	+84 mm
		Age of the head farmer—2017	+70%
		Rural population—2010	−20%

2.4.2. Actions

For the case study of this research, two actions were considered of relevance since they are pervasive in the discussions of territorial changes due to the implementation of the Chapecó EC, namely, (i) the lack of any forecast action in the territory (do nothing); and (ii) the action of recovery of natural areas (AreaNat).

As the 'do nothing' action does not provide for intervention in the territory, the 2018 land use and land-cover map was used as the dependent variable in the model.

The AreaNat action was elaborated based on the guidelines of the Ecological Corridor Zoning, which defined priority areas for the recovery of permanent preservation areas according to their vocation for conservation and/or direct or indirect use [47]. In addition, another management instrument used as a reference was the SC2030 Plan, which stipulated an increase by 1% of the area with native vegetation cover in the state of Santa Catarina as a goal for 2030 [48]. The details of the guidelines for this action in the territory can be seen in Table 5 (synthesis of public policies). The AreaNat action was considered in the predictive scenarios in order to evaluate the likely effects on future LULC dynamics when a public conservation policy is adopted.

However, due to a spatial scale limitation of the LULC maps, the action was generalised by cross-referencing the 1990 and 2018 LULC maps, restoring the natural areas (forest and natural grassland) that existed in 1990, and conserving those that existed in 2018.

In the study area between the years 2000 and 2018 there was a growth of 190% in areas dedicated to silviculture (forestry) [17] and 79% for soybean [69]. Thus, we adopted as a reference the year 1990, because it represents a reality of LULC dynamics prior to this growth. Government incentives and policies, due to market demands, boosted silviculture activity in the region [70] and the expansion of agricultural commodities [71].

2.5. Simulation Model Based on Artificial Neural Networks

For the simulation of predictive LULC change scenarios for 2036, the type of machine learning adopted was artificial neural networks (ANN), the multilayer perceptron (MLP) method, and the backpropagation algorithm. This is the type of model most widely used in works of this nature [11,17,32,35,41–43].

The simulation is done for the year 2036, because the literature recommends that the predictive scenarios should follow the same time interval as the model input data [11]. In this case, it was from 2000 to 2018, totaling 18 years.

In this study, we used the ANN1 model [17] to simulate the six predictive scenarios (Table 7). Predictive scenario A1 represents the baseline scenario, which is based on extrapolating the trends in LULC dynamics and the current socio-economic scenario between the years 2000 and 2018. The others consider different predictive scenario assumptions (A2, A3, B1, B2 and B3).

Table 7. ANN1 model parameters used to simulate the predictive scenarios.

Parameter	Parameterisation Object	Parameterisation Adopted
Input layer	Independent variables Rescaling method	67 Normalised
Sample	Training Testing Holdout Iterations	70% 20% 10% 500
Hidden layer	Number of hidden layers Number of units (neurons) Activation function	1 56 Hyperbolic tangent
Output layer	Dependent variable Activation function Error function	LULC map* Softmax Cross-entropy

LULC map*: LULC 2018 for scenarios A and AreaNat for scenarios B.

According to the ANN1 model, the classification matrix showed approximately 70% overall accuracy. Individually, the forest class represented 89.5% of the validation sample correctly classified, silviculture represented 38.0%, natural grassland represented 9.5%, pasture represented 57.0%, agriculture represented 79.6%, mosaic represented 20.0%, articicial area represented 56.1%, and water bodies represented 42.6% [17].

Model validation was supported by the area under the curve (AUC) measure derived from the relative operating characteristic (ROC) [72]. The AUC value informs how well the model can distinguish between the classes [42,73–75].

Based on the classification of AUC, the model has excellent accuracy capacity in the following classes: forest, natural grassland, agriculture, artificial area, and water bodies (>90%). The classes silviculture and pasture, with values between 80 and 90%, are classified as having 'very good' quality, and the mosaic class was classified as 'acceptable' (79.4%) [17].

2.6. LULC Dynamics and Sensitivity Analysis

From the transition matrix between the LULC maps of the year 2018 and the LULC maps of the predictive scenarios for 2036 (A1, A2 A3, B1, B2, and B3), the LULC dynamics were verified [76–78].

The transition matrix presents, diagonally, the persistence of each LULC class from the beginning to the end of the period. The column total denotes the proportion of the landscape occupied by each LULC class at the end of the period, and the row total is the proportion occupied by each LULC class at the beginning of the period. The values outside the diagonal represent the transitions between classes from the beginning of the period to its end [76].

The sensitivity analysis presented the relationship between the input variables of the model in a rank format [79]. It allowed us to observe which variables (driving forces) are relatively more influential in the changes seen in the territory [32].

To this effect, first, the contribution of each dimension to the composition of scenarios was verified by considering the sum of the importance of each driving force inputted into the model. Subsequently, the driving forces' influence was analysed based on the average of the normalised importance of the first ten driving forces.

3. Results

In this section we present the six predictive scenarios, considering first the 'no action' in the territory (do nothing—A) and following the conservation action (AreaNat—B), associated with three socioeconomic scenarios (BAU—1, optimistic—2, pessimistic—3). The six predictive scenarios (A1, A2, A3, B1, B2, B3) provide the main LULC changes predicted for 2036, compared to the LULC reference year 2018. For each scenario, according to the sensitivity analysis, we present the list of the ten most important driving forces with an average of the normalized importance of these 10 driving forces organized by dimension.

3.1. Predictive Scenario A ('Do Nothing')—LULC Changes and Key Driving Forces

LULC trends for the different predictive scenarios A1, A2, and A3 for the year 2036 obtained by the ANN1 model can be seen in Figure 4 and Table 8.

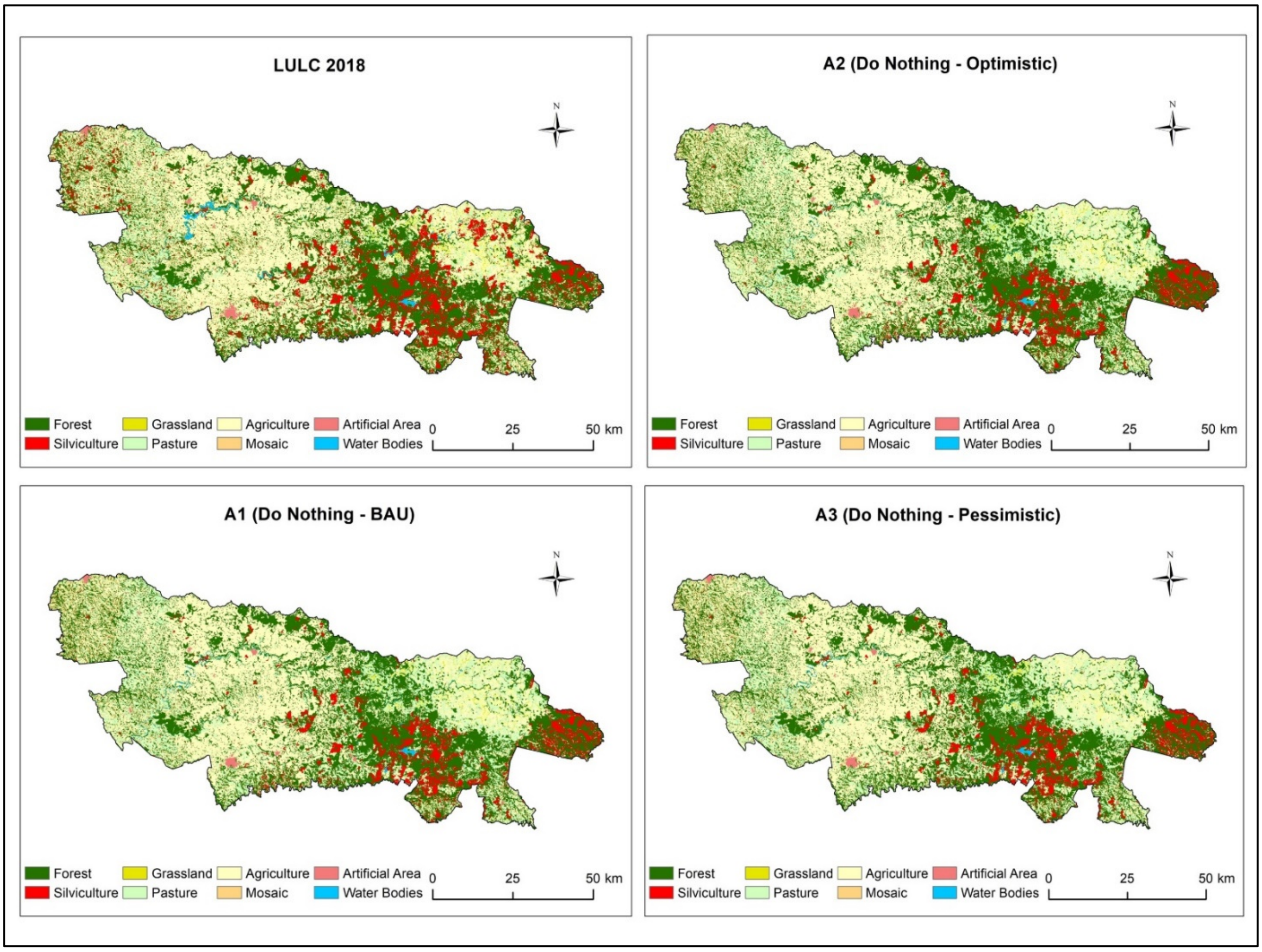

Figure 4. Scenario A—LULC evolution trends of the predictive scenarios for 2036—Chapecó River EC/SC—Brazil.

Table 8. LULC evolution trends of the predictive scenarios A.

LULC	Area (km^2)	Predictive Scenarios (2036)		
	Base Year (LULC2018) (Do Nothing)	A1	A2	A3
Forest	2097.6	2418.2	2418.4	2418.6
Silviculture	914.0	422.9	418.8	409.1
Natural grassland	149.0	34,2	36.5	18.3
Pasture	886.3	1306.1	1322.2	1324.3
Agriculture	2416.3	2637,9	2661.8	2670.0
Mosaic	677.7	363.7	327.2	340.7
Artificial Area	50.1	31.6	31.9	31.9
Water bodies	51.2	27.7	25.4	28.7
Total	7242.3	7242.3	7242.3	7242.3

Table 9 presents, for each scenario, the top ten driving forces responsible for the LULC changes presented in Table 8. The arrows indicate whether the driving force represents a positive (↑) or negative (↓) variation over the period. In Supplementary Material Repost S3: Sensitivity Analysis, one can observe the complete ranking of the driving forces for each scenario.

Table 9. The ten most important driving forces in predictive scenarios A.

Predictive Scenarios	Driving Force	Normalized Importance (%)
A1	Land use and land cover—2000	100.0
	Type of soil—2004	44.8
	Road network—2018	31.6
	Type of relief—2000	30.1
	Per capita income—2010 ↑	21.9
	Agricultural land price—2000 ↓	20.8
	Cattle herd—2018 ↑	20.3
	Processing industries—2006 ↓	19.8
	Rural population—2000 ↑	19.0
	Chicken herd—2000 ↑	18.7
A2	Land use and land cover—2000	100.0
	Type of soil—2004	38.5
	Road network—2018	38.2
	Type of relief—2000	26.1
	Processing industries—2006 ↓	19.3
	Use of agrochemicals—2017 ↑	18.7
	Agricultural land price—2000 ↓	18.7
	Cattle herd—2018 ↑	16.3
	Per capita income—2010 ↑	15.5
	Maize yield—2017 ↑	15.3
A3	Land use and land cover—2000	100.0
	Type of soil—2004	44.8
	Road network—2018	43.5
	Type of relief—2000	24.9
	Financing (Pronaf)—2017 ↓	21.3
	Gross value added of agriculture and cattle-raising—2002 ↑	21.2
	Gross Domestic Product (GDP) –(pessimistic) ↑	20.2
	Agricultural land price—2018 ↑	19.2
	Land structure—2017↑	18.0
	Swine herd—2018 ↓	17.9

Table 10 introduces the normalized importance average per analysis dimension of the ten first driving forces for each scenario.

Table 10. Statistics per analysis dimension of normalized importance of the ten first driving forces in LULC dynamics for the predictive scenarios A.

Predictive Scenario	Dimension	Average Normalized Importance (%)	N° of Driving Forces
A1	Physical/natural	51.6	4
	Economic	20.3	5
	Demographic	19.0	1
	Total		10

Table 10. *Cont.*

Predictive Scenario	Dimension	Average Normalized Importance (%)	N° of Driving Forces
A2	Physical/natural	50.7	4
	Economic	17.4	4
	Technological	17.0	2
	Total		10
A3	Physical/natural	53.3	4
	Economic	19.9	5
	Sociocultural	18.0	1
	Total		10

3.2. Predictive Scenario B ('AreaNat')—LULC Changes and Key Driving Forces

LULC trends for the different predictive scenarios B1, B2, and B3 for the year 2036 can be seen in Figure 5 and Table 11.

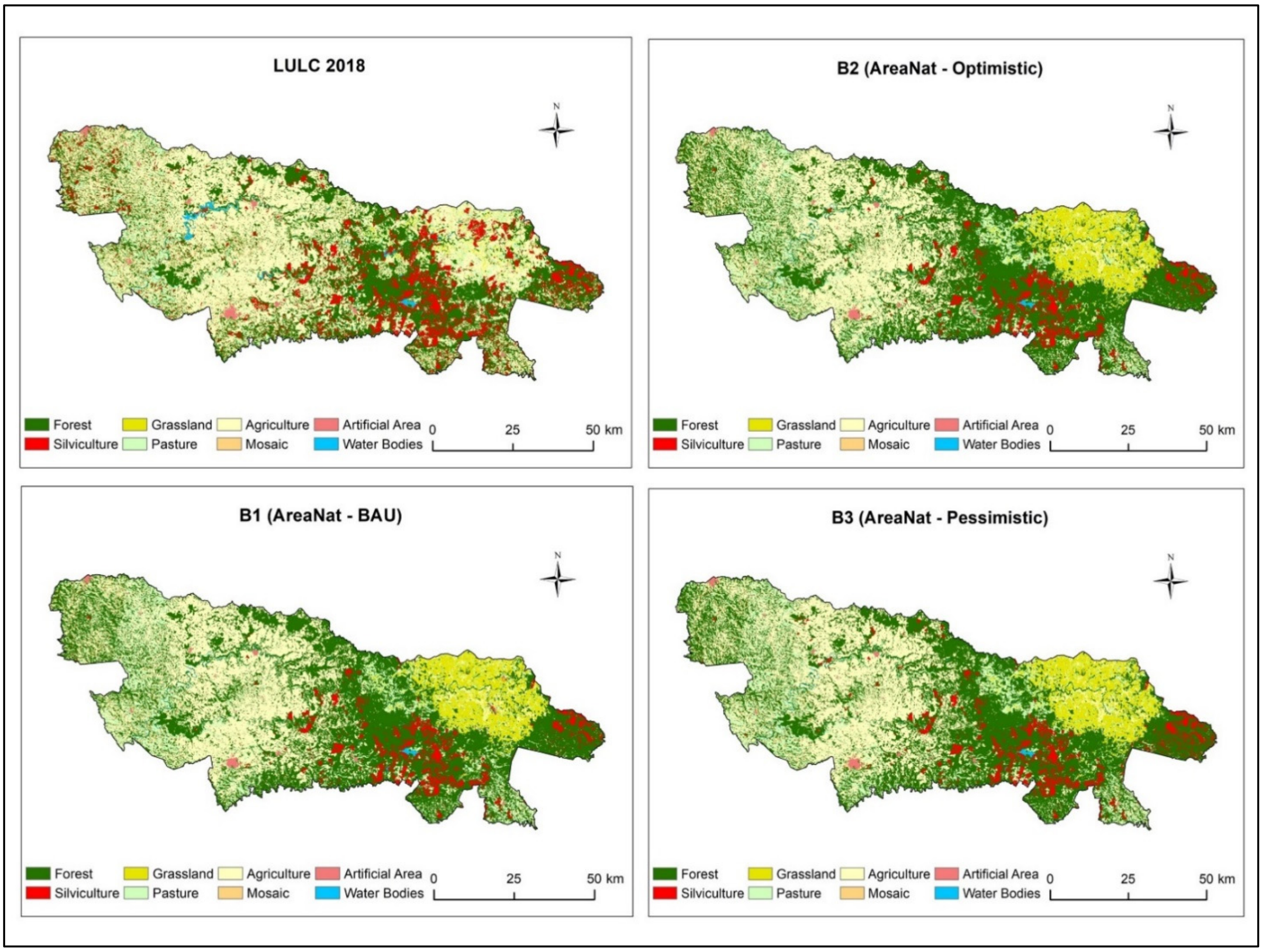

Figure 5. Scenario B—LULC evolution trends of the predictive scenarios for 2036—Chapecó River EC/SC, Brazil.

Table 11. LULC evolution trends of the predictive scenarios B.

LULC	Area (km^2)	Predictive Scenarios (2036)		
	Base Year (LULC2018) (Do Nothing)	B1	B2	B3
Forest	2097.6	3129.2	3151.8	3116.5
Silviculture	914.0	304.8	314.8	338.8
Natural grassland	149.0	624.0	628.3	622.2
Pasture	886.3	944.0	930.8	916.1
Agriculture	2416.3	2052.7	2033.8	2080.6
Mosaic	677.7	135	130.9	113.4
Artificial Area	50.1	31.4	32.9	34.1
Water bodies	51.2	21.2	19.1	20.6
Total	7242.3	7242.3	7242.3	7242.3

Table 12 presents, for each scenario, the top ten driving forces ranked according to their importance. The arrows indicate whether the driving force represents a positive (↑) or negative (↓) variation over the period. In Supplementary Material Repost S3: Sensitivity Analysis, one can observe the complete ranking of the driving forces.

Table 12. The ten most important driving forces in predictive scenarios B.

Predictive Scenarios	Driving Force	Normalized Importance (%)
B1	Land use and land cover—2000	100.0
	Type of soil—2004	43.8
	Road network—2018	30.2
	Type of relief—2000	23.6
	Use of agrochemicals—2017 ↑	20.8
	Technical orientation—2017 ↓	20.4
	Agricultural land price—2000 ↓	19.4
	Gross Domestic Product (GDP)—2017 ↑	18.6
	Tobacco yield—2002 ↑	18.3
	Formal employment (agriculture)—2006 ↑	18.1
B2	Land use and land cover—2000	100.0
	Road network—2018	51.1
	Type of soil—2004	38.6
	Type of relief—2000	23.8
	Formal employment (commerce/service)—2006 ↓	21.4
	Altimetry—2000	20.9
	Agricultural land price—2000 ↓	19.9
	Swine Herd—2018 ↓	17.2
	Gross value added of agriculture and cattle-raising—2017 ↓	17.0
	Tobacco yield—2017 ↓	16.8
B3	Land use and land cover—2000	100.0
	Road network—2018	49.5
	Type of soil—2004	40.3
	Type of relief—2000	26.9
	Altimetry—2000	22.6
	Agricultural land price—2000 ↓	21.8
	Cattle herd—2018 ↑	17.4
	Use of agrochemicals—2017 ↑	16.6
	Maize yield—2017 ↑	16.6
	Rural population—2010 ↓	15.4

Table 13 introduces the normalized importance average per analysis dimension of the ten first driving forces for each scenario.

Table 13. Statistics per analysis dimension of normalized importance of the ten first driving forces in LULC dynamics for the predictive scenarios B.

Predictive Scenario	Dimension	Average Normalized Importance (%)	N° of Driving Forces
B1	Physical/natural	49.4	4
	Technological	19.8	3
	Economic	18.7	3
	Total		10
B2	Physical/natural	46.9	5
	Economic	18.9	4
	Technological	16.8	1
	Total		10
B3	Physical/natural	47.9	5
	Economic	19.6	2
	Technological	16.6	2
	Demographic	15.4	1
	Total		10

4. Discussion

The main guidelines of public policies for rural development and management of the Chapecó ecological corridor (Table 5) point to objectives that must be achieved in an integrated manner through actions that favor socioeconomic advances, maintenance of native vegetation, and rehabilitation of degraded natural areas. An artificial neural network-based LULC dynamics model was used to simulate different socioeconomic scenarios and create predictive scenarios with a desired level of recovery and maintenance of natural areas.

Three possible socioeconomic scenarios were simulated through the manipulation of nine independent variables (Table 6). The first scenario considered that the model would not suffer any interference from the independent variables (BAU). Following some achievements theorized in public policies (Table 5), the optimistic scenario included potentially realistic increments to family farming, Pronaf, GDP, and productivity gains for soybean and maize. In the pessimistic scenario, the values of these variables were changed to lower gains, and an aging population and a rural exodus were simulated. Also, the climate scenarios of increase in average temperature and precipitation were simulated in the pessimistic scenario.

Three predictive scenarios (A1, A2, and A3) (Figure 3, Table 8) were obtained as a first result. Comparing them to the 2018 LULC map, regardless of the socioeconomic gains achieved, a recovery trend was observed in relation to forest areas until 2036, mainly through the reduction of silviculture areas. On the other hand, natural grasslands tend to continue suffering significant losses of areas due to the expansion of pasture areas for livestock activities, which presents the higher expansion rate (48%) in the region. Although at a lower rate (10%), the expansion of agriculture may also be responsible for advances over native grassland areas (Table 8).

In socioeconomic terms, the first two predictive scenarios (A1 and A2) suggest favoring rural development as the driving forces that most influence LULC dynamics indicate economic gains, productivity gains, and the expansion of agricultural activities. On the other hand, the expressive trend of loss of natural grasslands is even more visible in case of economic recession, social crisis involving the rural sector, and climate changes (scenario A3). In this pessimistic scenario, the trend of area loss is twice as high as in the other scenarios, indicating a trend of loss of 87% of natural grassland areas for 2036 compared to 2018 (Table 8). The predictive scenario A3 is the least favorable to the recovery and conservation of natural grasslands, which is one of the main guidelines of the Management Plan of the Chapecó EC (Table 5).

The most active forces that cause this even greater loss of natural grasslands are related to a greater concentration of land, represented by the driving force land structure; the weakening of public policies to support rural producers, indicated by Financing (Pronaf); low economic growth, represented by the GDP; and the expansion of agricultural activities, represented by the driving force gross value added of agriculture and cattle-raising (Table 9). In addition to reflecting that low socioeconomic development has a negative impact on the conservation of natural resources, this result corroborates the importance of the social aspect represented by the mischaracterization of a land structure, represented by small rural properties. The average size of rural properties in the EC area between 2003 and 2017 presented an increase of 22%, while in the state of Santa Catarina this increase reached 12.5% [61].

The promotion of agriculture and preservation of natural resources combined with economic mechanisms aimed at promoting social equity and sustainable regional development (SC2030 Plan) is not sufficient to meet the guidelines for the conservation and recovery of natural areas. The trend towards a growing demand for agricultural and pasture areas demonstrates the importance of agrobusiness for the economy of the state. It reflects a rural development policy that is still ineffective in terms of sustainability, tending to favor large agro-industrial complexes (soybean and animal production complexes), as agrobusiness accounts for more than 70% of the exports of the state [61].

It is necessary to move forward and guarantee continuity in the materialization of the different economic mechanisms aimed at the conservation of natural resources proposed in the ecological corridor management plan, including conservation credits, financial support, and integration systems for agro-industry and local productive arrangements. In addition, it is necessary to engage local agents, investors, public and private institutions, and partners in the implementation of the action mechanisms specified in the plan [47].

Given the environmental inefficiency of the predictive scenarios generated from the simulations of socioeconomic variables, a simulation of the return to the vegetation cover similar to that observed in 1990, prior to the period of promotion of silviculture and agricultural commodities was presented [70,71].

Considering the same socioeconomic conditions of the three first scenarios, with this action in the territory three predictive scenarios were simulated (B1, B2, and B3), in which an environmental variable (AreaNat) was incorporated into the model with the aim of determining the preservation and recovery of natural areas.

As a result, significant gains of natural grassland areas were obtained, as well as a recovery in forest areas and gains of pasture areas. In predictive scenarios B (1, 2, and 3), agriculture tends to suffer a loss of approximately 15% of area compared to the 2018 LULC reality (Table 11). This simulation demonstrated the importance of territorial action policies for the preservation and recovery of natural areas. The advance of human activities on the natural environment, especially in areas of natural grasslands, can only be suppressed by means of actions such as the definition of areas of environmental preservation and legal reserves, the definition of conservation units or creation of ecological corridors [80,81].

The territorial intervention promotes direct actions in the landscapes, whose elements are represented in the model by the four first driving forces of greater importance in the LULC dynamics. These driving forces belong to the physical/natural dimension (Tables 9 and 12), presenting the greatest influence among the main driving forces in LULC dynamics. The greatest influence associated with physical-natural driving forces is present in most articles with similar approaches [13,27,38,82–85].

Thus, the adoption of actions that favor the desired changes in the driving forces of the physical/natural dimension is essential to achieve preservation and recovery objectives.

The significant influence of the driving forces of the technological dimension was also observed for predictive scenarios B (1, 2, and 3) (Table 12), indicating the importance of investing in technology and innovations in order to create a dynamic balance between the socioeconomic needs of rural areas and environmental preservation. Agricultural research in Brazil has always been synonymous with technology and innovation [86–88].

However, precisely due to the search for this dynamic balance between production, revenue, and environmental preservation, there is currently a trend towards a paradigm shift.

This change has been taking place in the state of Santa Catarina. In the 1970s and 1980s, research and technological developments in rural areas were focused on productivist models that emerged from the "green miracle" (genetic research, development and massive use of chemical fertilizers and pesticides, and a focus on increasing productivity). Currently, the new paradigm seeks to maintain the productive capacity of food for a still growing population, but with greater integration with ecosystems and natural dynamics (agroecology, agroforestry systems, organic agriculture, and direct sowing) [89].

Thus, the technological innovation necessary to achieve sustainable agriculture must undergo a process of adaptation and change.

The area of the Chapecó River Ecological Corridor is part of a region pointed out as an economic influence zone and force field for family farming and the agro-industrial complex. It is a territory of multiple interests to the extent that things are not defined either in terms of hegemonization of the productive pattern favored by the agro-industrial complex or in terms of resistance or adaptability to new scenarios by family farmers [45].

If, on the one hand, there is an area of importance for agroindustry and agrobusiness of the state of Santa Catarina, on the other hand there is an area of important biological diversity, with substantial diversity of social agents, such as cattle farmers, soybean producers, silviculturists, small family farmers descended from immigrants, small resettled family farmers, and indigenous peoples from the Guarani and Xokleng ethnic groups, defending different interests related to land ownership and use [47].

The territorial actions established by the ecological corridor management plan, such as the recovery of permanent preservation areas and the environmental suitability of rural properties proposed by the Management Plan of the Chapecó EC [47] should be strengthened.

In addition, new ways of doing agriculture should be encouraged, such as agroforestry systems, which are essential to ensuring economic development combined with environmental sustainability [90,91].

High levels of productivity in a smaller proportion of area and maximum environmental preservation may be achieved through the integration of modern techniques and knowledge from forestry, agricultural, and environmental sciences, such as agroforestry systems [91]. In the search for alternatives in response to the technical, globalized agriculture [92], the reconciliation of the development of rural environment (economic and social) with the conservation of biodiversity requires a broader participation of the government in the elaboration and implementation of public policies, offering greater prominence to local agents.

5. Conclusions

The adoption of LULC dynamics modelling through artificial neural networks proved to be a very useful tool to build predictive scenarios based on public policy guidelines that integrate rural development and environmental preservation and recovery.

Driving forces of a physical/natural are those with the greatest influence on LULC dynamics, regardless of the proposed socioeconomic scenarios.

For predictive scenarios generated from actions in the territory, technological driving forces are identified as the most important following the physical/natural ones.

One of the paths pointed out by these driving forces consists of investing in new agricultural technologies generated from productive systems integrated to nature.

Depending on the scope of the guidelines adopted in public policies, different predictive scenarios of land use and land cover may be expected. Public policies for social and economic development applied in isolation tend to generate future scenarios of low effectiveness in preserving and restoring natural environments.

Public policies for territorial intervention are required so that preservationist objectives are achieved in parallel with social and economic objectives.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12010181/s1, Report S1: Variable description. A summary table of the construction of the predictive scenarios is available online, Report S2: scenario building. Sensitivity analysis results are available online, Report S3: Sensitivity analysis.

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Article

Optimization of Land Use Based on the Source and Sink Landscape of Ecosystem Services: A Case Study of Fengdu County in the Three Gorges Reservoir Area, China

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Abstract: Promoting the preservation and appreciation of ecosystem services is an important value guide for land use optimization. In this research, Fengdu County in the Three Gorges Reservoir Area was selected as the focus of a case study. From the perspective of the source and sink landscape of ecosystem services, a MOP model and FLUS model were used to optimize the areas of various land use types and the spatial configurations of those land use types in the study area in 2035 under a strict ecological constraint (SEC) scenario, a moderate ecological constraint (MEC) scenario, and a relaxed ecological constraint (REC) scenario. We also superimposed and adjusted the results of land use optimization under the three ecological constraint scenarios, and obtained land use regionalization results that integrated multiple scenarios. The results indicated that (1) there were large differences in the areas and spatial distributions of the source and sink landscapes under the three scenarios. Under the SEC scenario, the important source landscapes (ISLs), common source landscapes (CSLs), and sink landscapes (SLs) areas covered 1676.62 km^2, 1190.43 km^2, and 33.81 km^2, respectively. A large area of the CSLs and a small area of the SLs were transformed into ISLs area, and the degree of fragmentation of the landscape was low. Under the MEC scenario, the ISLs, CSLs, and SLs areas covered 1609.22 km^2, 1241.60 km^2, and 49.74 km^2, respectively. The development of the source landscapes and sink landscapes was similar, and the degree of fragmentation was moderate. Under the REC scenario, the ISLs, CSLs, and SLs areas covered 1603.96 km^2, 1243.32 km^2, and 53.58 km^2, respectively. A large area of CSLs was transformed into SLs area, and the degree of fragmentation was high. (2) Fengdu County was divided into seven types of areas: ecological conservation area; agricultural production area; construction optimization area; construction-ecological area; ecological-agricultural area; agricultural-construction area; and integrated development area. The results of this study can provide references for the territorial spatial planning and management of ecological barrier zones.

Keywords: ecosystem services; source and sink landscape; land use optimization; MOP model; FLUS model; Fengdu County

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1. Introduction

Ecosystem services (ESs) are the sum of life-sustaining products and services that humans acquire from ecosystems—these products and services are closely related to human well-being and sustainable development [1]. Ecosystems support and maintain balance in areas occupied by humans by regulating the air and water quality, and maintaining biodiversity [2]. Ecosystems also provide the food and raw materials needed to sustain life and the production of goods, and provide entertainment and aesthetic enjoyment to humans [3]. Terrestrial and aquatic environments provide the materials needed to support ESs. Land use change is considered one of the main driving forces of changes in Ess at regional and global levels because it reflects the coupling relationship between natural systems and human systems, and profoundly affects the structures, functions, and processes of ecosystems. Therefore, land use change plays an important role in ES functions [4]. At present, due to an increasing economic downturn and pressure for structural adjustment, China is in a period of economic and social transformation. The country faces the challenges of tightening resource constraints, insufficient ecological environment carrying capacity, and inadequate institutional systems; therefore, the Chinese government has proposed creating a spatial planning system based on the core value of advancing the development of an ecological civilization [5]. Optimizing the areas and spatial configurations of land use types and zone-based land management are among the main elements of territorial spatial planning. ESs are closely related to environmental quality and human well-being, and form an important basis for testing whether the development pattern of an area conforms to the concept of ecological civilization [6,7]. Scientific analysis of ESs can help to identify costs and benefits in territorial space management and decision-making [8–10]. At present, the importance of applying ESs to the land use optimization process has been widely recognized [11,12]. However, the lack of theories and methods for integrating ESs into land use planning impedes the development of guidance for policy-makers [13–15].

The "source-sink" theory originated from the field of environmental science, and proposes that there are "sources" and "sinks" in the process of temporal and spatial changes in matter across landscapes. In this context, "source" refers to the starting point of a process, and "sink" refers to the place where a process disappears. In 1988, Pulliam [16] first used the source-sink concept in the research of wildlife population ecology. In 2003, Chen et al. [17,18] introduced the source-sink theory into landscape ecology, constructed the source-sink landscape theory, and integrated landscape pattern research and ecological process research. Since then, the source-sink landscape theory has been applied to nonpoint source pollution control [19], ecological risk assessment [20], soil erosion control [21], ecological security network construction [22], functional regionalization of nature reserves [23], suitability evaluation of land use [24], etc. The source-sink landscape theory integrates landscape type, area, and spatial location and the impact of the landscape on ecological processes better than other theories. According to source-sink landscape theory, in the process of ES supply, source landscapes can promote the supply of ESs, and sink landscapes can hinder the supply of ESs. The encroachment and contraction of source and sink landscapes profoundly affects the current status and trend of ES supply. Using the source-sink landscape theory to examine the impacts of land use changes on ESs is conducive to a deeper understanding of the important issues associated with land use under the influence of multiple factors, and can provide a basis for territorial spatial planning. Moreover, the source-sink landscape theory pays more attention than other theories to the spatial heterogeneity of ecological processes—the information derived from this approach is conducive to integrating ESs into the spatial optimization of land use, and can provide scientific support for comprehensively improving the ecological functions of ESs. Therefore, conducting land use optimization research from the perspective of the source-sink landscape theory is not only feasible, but also practical.

With the increasingly prominent conflict between humans and land, land use optimization has gradually become a hot topic of research [25]. At present, scholars mainly follow specific optimization objectives, and realize the optimal allocation of land resources through model simulation [26]. The objectives of land use optimization include mainly economic benefits and ecological benefits: economic benefits are measured by the economic output of different land use types, whereas ecological benefits are measured by the ecosystem service value (ESV) [27], ecological green equivalent [28], carbon storage [29], and other indicators associated with different land use types. For smaller research areas, the optimization objectives are more specific, such as reducing soil erosion [30] and nonpoint source pollution [31], and improving water resource utilization efficiency and economic income [32]. Land use optimization models include quantity optimization models and spatial configuration optimization models. At present, there are three main types of quantity optimization models. The first category is traditional mathematical optimization models, such as gray linear programming models [33] and multiobjective programming (MOP) models [25,34]. The second category is heuristic algorithms, such as genetic algorithms [35], simulated annealing algorithms [36], ant colony algorithms [37], and particle swarm algorithms [38]. The third category includes other methods, such as Markov chains [39], system dynamics models [40], and neural network models [41]. Among these models, the MOP model has the advantages of flexibility, practicability, and high credibility, and can address problems associated with land use quantity optimization in dynamic situations and for multiple objectives and plans. Spatial configuration optimization models include the cellular automata (CA) model [42], multiagent model [43], conversion of land use and its effects at small regional extents (CLUE-S) model [27], future land use simulation (FLUS) model [44], and so on. Moreover, heuristic algorithms, such as the simulated annealing algorithm [45], particle swarm algorithm [46], and ant colony algorithm [47], are commonly used. The FLUS model adopts an adaptive inertial competition mechanism based on roulette selection: this mechanism can effectively cope with the uncertainty and complexity of land use change under the interaction of the natural environment and human activities, and the simulation accuracy achieved with this model is high [44]. Generally, although the existing research methods have gradually matured, leading to more robust results, the following shortcomings still exist: (1) Scholars mainly focus on the application of source-sink landscape theory in the research of specific ecological processes, but no scholars have applied this theory to the research of land use optimization. (2) Existing research has mainly focused on technical methods and optimization goals, and insufficient attention has been given to the guiding theory of land use optimization. Moreover, the constraint conditions and optimization rules considered in previous land use optimization studies have been focused on mostly macro constraints, such as the numerical values associated with land use planning, whereas policy-oriented constraint conditions, such as those associated with ecological civilization construction and high-quality development, have not been considered frequently enough. (3) Existing research often regards improvements in the functions of ESs as the objective of land use quantity optimization, and there is a lack of research on how to promote the preservation and appreciation of ESs through the spatial optimization of land use.

In this research, we selected Fengdu County as a study area, and combined the source-sink landscape theory with ES theory to construct a land use optimization framework. Moreover, we comprehensively considered the constraints imposed by the ecological environment and intensive development in the region. A MOP-FLUS coupling model, which combined the MOP model and FLUS model, was used to optimize the areas and configurations of land use types in 2035 under a strict ecological constraint (SEC) scenario, a moderate ecological constraint (MEC) scenario, and a relaxed ecological constraint (REC) scenario. We also superimposed and adjusted the land use optimization results for these three ecological constraint scenarios, and developed a land use regionalization plan that integrated multiple scenarios. Finally, we explored the role of the results in the functional optimization of ESs and space governance. The key scientific question of this research was how to scientifically and reasonably optimize the county-level land use pattern through the combination of ESs and source-sink landscape theory. The results of this research enrich the theory, perspective, and model of land use optimization research. At the same time, it also provides references for future territorial spatial planning in ecological barrier zones.

2. Study Area and Data Sources

The Three Gorges Reservoir Area (TGRA) is an important ecological barrier in the Yangtze River Basin (Figure 1). Its ecological environment is directly related not only to the long-term safe operation of the Three Gorges Dam and the provision of stable support for millions of immigrants, but also to the ecological security and sustainable development of the whole Yangtze River Basin [48]. Fengdu County, ranging from 107°28′–108°12′ E and 29°33′–30°16′ N, is a typical mountainous county in the ecological barrier zone of the TGRA, Southwest China. The predominant landform in this region is mountains, followed by hills, and only a few flat mountain and river valleys—generally, the terrain is high in the southern parts of the county and low in the northern parts. The main types of land use are cultivated land and forest, with abundant forest resources and diverse ecosystems. The county covers an area of 2900.86 km^2, with 2 subdistricts, 23 towns, and 5 townships. In 2018, the per capita GDP of Fengdu County was CNY 40,400, and the population urbanization rate was 46.48%. Since the start of the 21st century, the immigrant population in Fengdu County has become larger than the nonimmigrant population, and the total permanent population decreased from 671,100 in 2000 to 585,200 in 2018. The departing population mainly originates from rural areas. Between 2000 and 2018, the rural population decreased by 210,600. Fengdu County is faced with multiple problems, such as immigration relocation, degradation of the countryside, rapid urban expansion, and deterioration of the ecological environment. Therefore, there is an urgent need to allocate and optimize the land resources of Fengdu County according to scientific rationale.

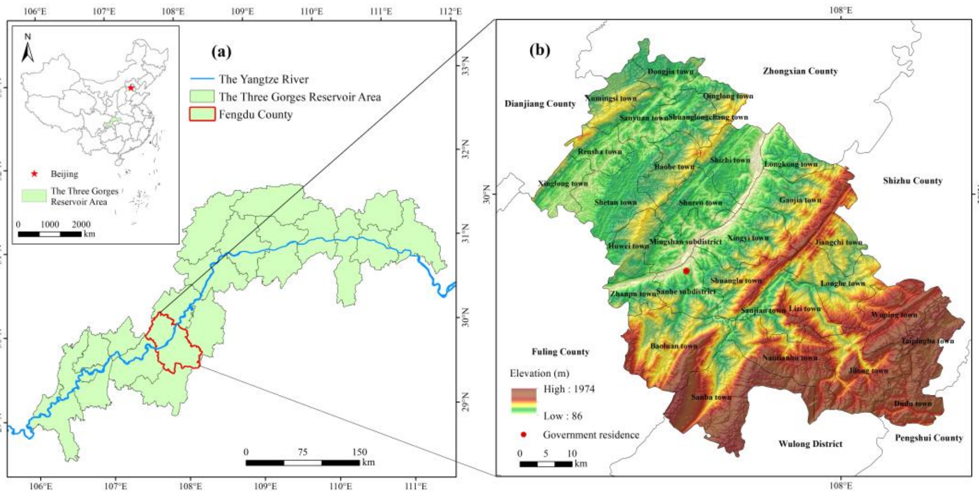

Figure 1. The study area: (**a**) the location of Fengdu County in the Three Gorges Reservoir Area; (**b**) the administrative divisions and elevation distribution of Fengdu County.

In this study, the data needed to optimize the land use in Fengdu County included spatial data and statistical data. The data sources are listed in Table 1.

Table 1. Sources of data included in this study.

Types	Datasets	Sources	Resolution
Spatial data	Land use datasets (2010, 2018)	http://www.resdc.cn/, accessed on 2 August 2021	30 m
	Administrative boundary, river system, and roads in the study area	http://www.ngcc.cn/ngcc/, accessed on 2 August 2021	Vector
	Elevation	http://www.gscloud.cn/, accessed on 2 August 2021	30 m
	Precipitation and temperature	http://www.geodata.cn/, accessed on 5 August 2021	1 km
	Soil texture and soil organic matter content	http://westdc.westgis.ac.cn/, accessed on 6 August 2021	1 km
	Ecological conservation redlines and basic farmland conservation areas	Chongqing planning and Natural Resources Bureau	Vector
	GDP grid data and population grid data	http://www.geodata.cn/, accessed on 9 August 2021	1 km

Table 1. *Cont.*

Types	Datasets	Sources	Resolution
Statistical data	Socio-economic indicators (gross domestic product, urban resident population) and agricultural production indicators (output of farming, forestry, animal husbandry, fishery, and agricultural service industries)	"Chongqing Statistical Yearbook", and "Fengdu Yearbook"	—

3. Methodology

A flow chart of the methods applied in this study is shown in Figure 2: the approach involved three main parts. After data collection and preprocessing, the MOP-FLUS coupling model was used to optimize the areas and configurations of land use types in 2035 under the three ecological constraint scenarios. Then, we used overlay analysis to develop a land use regionalization plan that integrated the results from multiple ecological constraint scenarios.

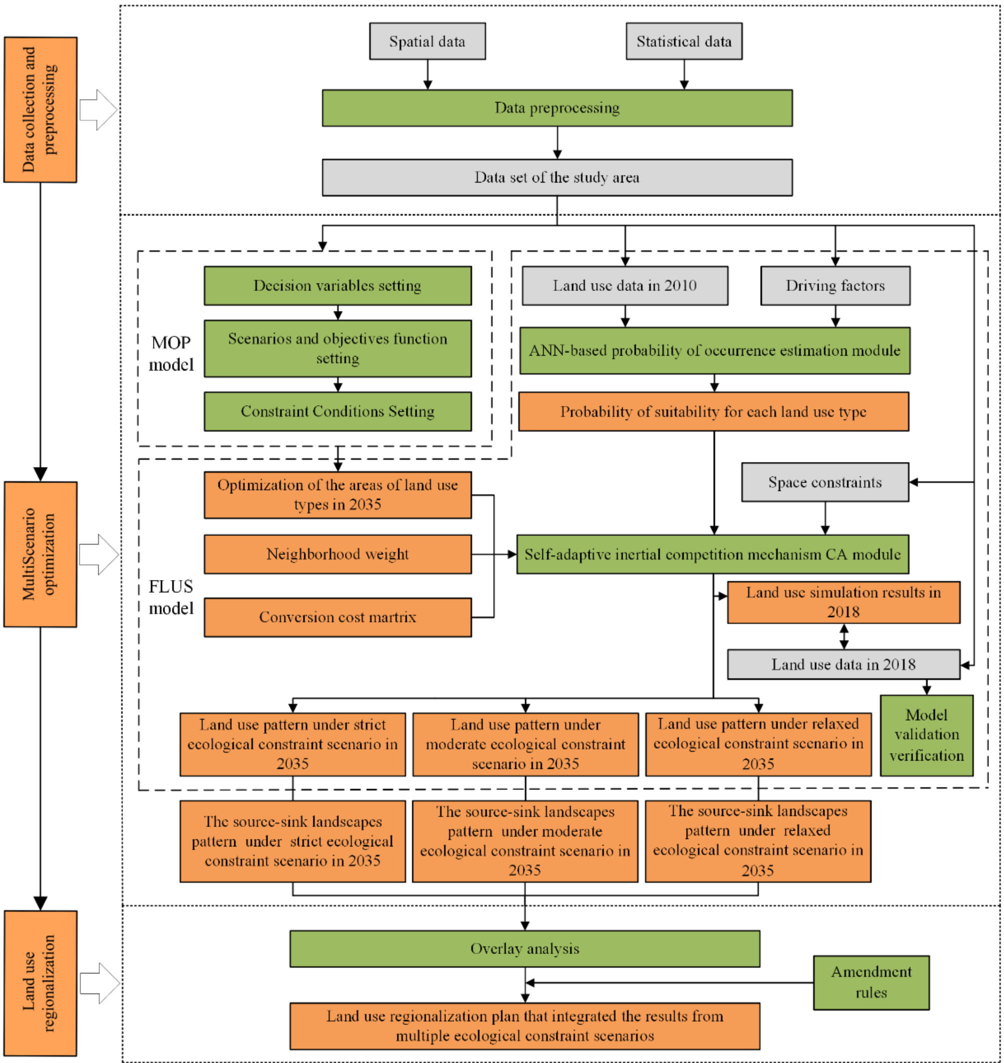

Figure 2. A flow chart of the methods applied in this study.

3.1. Land Use Optimization Framework Based on the Source-Sink Landscape of ESs

ESs are the sum of various material products and nonmaterial services provided by an ecosystem [4]. The processes by which ecosystems provide various services to human society are continually undergoing material and energy changes, and these changes can be regarded as an ecological process that includes several subprocesses [1,4]. With respect to supporting ESs, some landscapes act as "source", while others act as "sink", and the attribution of landscapes to these categories can be performed according to their roles in the ES supply process [49,50]. ESV is an important indicator to measure ES supply capacity [51]. Referring to the research of Zhang et al. [52], we investigated land use type and the ESV per unit area as the bases to identify the source and sink landscape of ESs in the study area. The results show that paddy fields, dry land, forest, grassland, water, and unused land are source landscapes, whereas urban land and rural residential areas are sink landscapes (SLs). In addition, the contribution to ES supply differs by landscape type. Forests, grasslands, and water provide the main ecological products, and their ESVs per unit area are much higher than those of dry land and paddy fields, which mainly provide agricultural products. Therefore, forests, grasslands, and water are further classified as important source landscapes (ISLs), whereas dry land and paddy fields are classified as common source landscapes (CSLs). In addition, although the ESV coefficient of unused land is low, it is also classified as a CSL.

With the rapid development of industrialization and urbanization, competition for space between sources and sink landscapes continues, promoting the change of land use patterns [53]. However, source landscapes are often at a disadvantage, which has allowed sink landscapes, such as urban land and rural residential areas, to continue to overtake other landscapes, resulting in a continuous decrease in source landscapes [54]. Therefore, it is necessary to balance the relationship between source and sink landscapes, and optimize regional land use patterns.

Land use optimization is the process of optimizing the areas and configurations of different land use types [55,56]. The optimization of land use type area allocates land resources to land use types with high efficiency under some constraint conditions to improve the overall benefits of the land [25]. Spatial land use optimization involves rearranging land resources in space, and allocating those resources to spatial units with higher suitability. This process is performed at two scales: land use spatial configurations optimization on a micro scale, and land use zoning on a macro scale [57]. The relationship between these optimization processes indicates that the optimization of the areas of land use types is determined by the spatial constraint of the spatial land use optimization, whereas the spatial land use optimization is determined by the quantity constraint imposed by the optimization of land use type area [55] (Figure 3).

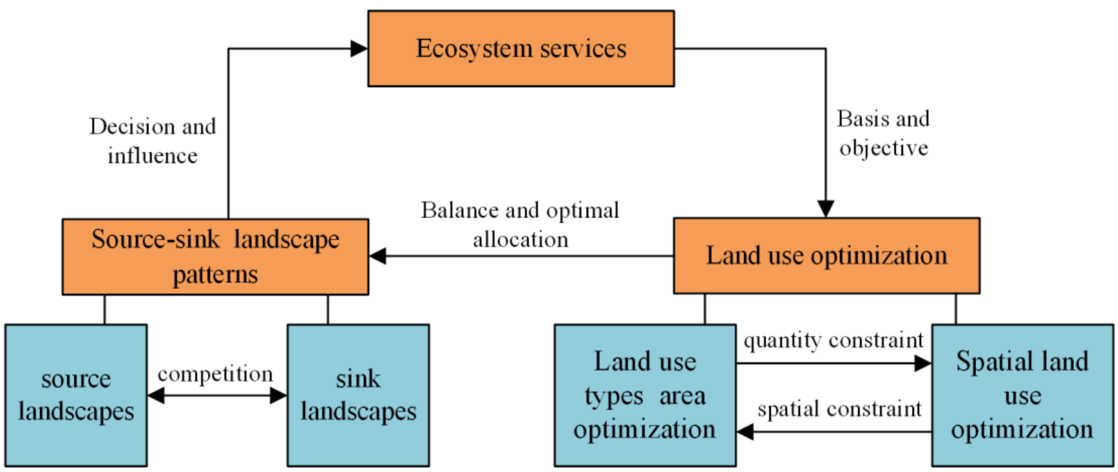

Figure 3. Relationship between land use optimization and the source-sink landscape patterns associated with ESs.

The areal proportion of various source and sink landscapes directly determines the total regional ESV [52,56]. Therefore, to optimize land use for ESs, and according to the areas of various land use types, regional land resources need to be allocated to land use types with higher ESVs per unit area under constraint conditions. Moreover, the spatial configuration of source and sink landscapes also determines the spatial characteristics of landscape connectivity and fragmentation, which have large impacts on regional ecological processes and ES functions [58,59]. For example, when a source landscape is invaded by a sink landscape, there is an increase in the resistance to the migration and flow of species and energy between landscape types—this resistance is not conducive to enhancing ecological processes, leading to a reduction in the ES supply capacity of surrounding areas. That is, the expansion of sink landscapes into source landscapes has a negative spatial effect on ESs [60–62]. This finding indicates that controlling the expansion and infiltration of sink landscapes into source landscapes, and maintaining the integrity and continuity of ecosystems are effective ways to improve regional ES functions. Therefore, land use types need to be allocated to more suitable spatial units through spatial land use optimization and land use zoning, thus, forming a spatial configuration more supportive of ESVs.

3.2. Optimization of the Areas of Land Use Types Based on the MOP Model

The MOP model is a scientific method for solving multiobjective optimization problems based on constraints and objectives [34]. The model includes three components: decision variables; objective functions; and constraint conditions. The formula of the objective function $F(x)$ is as follows:

$$F(x) = max\sum_{j=1}^{n} c_j x_j \tag{1}$$

$$s.t. = \begin{cases} \sum\limits_{j=1}^{n} a_{ij}x_j = (\geq, \leq)b_j, (j = 1, 2, \cdots, n) \\ x_j \geq 0, (j = 1, 2, \cdots, n) \end{cases} \tag{2}$$

where x_j is the decision variable j; c_j is the benefit coefficient of different land use types; $s.t.$ represents the constraint conditions; a_{ij} is the coefficient corresponding to variable j in the constraint i; b_j is the constraint value; and n is the number of decision variables. The following land use types (eight categories) are used as the decision variables: x_1, paddy field; x_2, dry land; x_3, forest; x_4, grassland; x_5, water; x_6, urban land; x_7, rural settlement; and x_8, unused land.

3.2.1. Scenarios and Objective Function Setting

The implementation period of the new territorial spatial plan is 2021–2035, so we take 2035 as the optimization year. Three development scenarios are established according to the strictness of the ecological constraints: (1) The SEC scenario represents comprehensive implementation of the following development concept: "to step up conservation of the Yangtze River and stop its over development". The goal of this scenario is to maximize ecological benefits by managing land use. (2) The MEC scenario represents coordination and unity between development and protection. In this scenario, the aim of land use is to balance ecological benefits and economic benefits. (3) The REC scenario represents the maximization of economic benefits in the context of rapid urbanization.

Ecological benefits are measured by the ESV per unit area of different land types, and the specific coefficients are determined according to the findings of Zhang et al. [52] (Table 2). Economic benefits are measured by the economic output per unit area of different land use types (Table 2). In particular, the output value of secondary and tertiary industries is used to measure the economic output of urban land; the agricultural output value after deducting the output value of mulberry, tea, and fruit is used to measure the economic output of paddy fields and dry land; and the output values of the agricultural service industries are used to measure the economic outputs of rural residential land. To determine the economic outputs of forests, grasslands, and water, we consider the output of the forestry, animal husbandry, and fishery industries. The economic benefits per unit area for these land use types are calculated as follows: We first derive the economic output data from 2000 to 2018, and then, we predict their values in 2035 by using a GM (1, 1) model. Finally, the mean value of the three predicted outputs for each land use type is divided by the corresponding area, yielding the economic benefit per unit area. However, because unused land has not yet been exploited for economic use, we assume that it does not generate any economic value, and its coefficient is set at 0.01. Based on the ecological benefit coefficients and economic benefit coefficients of each land use type, the objective functions are established as follows:

$$Z = a(\max \sum_{i=1}^{8} K_i x_i) + b(\max \sum_{i=1}^{8} P_i x_i) \quad (3)$$

where Z represents the total benefit of a land use type; x_i is the area of land use type i; K_i and P_i are the ecological benefit coefficient and economic benefit coefficient of land use type i; and a and b are the weights of the ecological benefit objective and the economic benefit objective, respectively. It was determined from related studies [63,64] that a is 0.8, 0.5, and 0.2, and b is 0.2, 0.5, and 0.8 in the SEC scenario, MEC scenario, and REC scenario, respectively.

Table 2. Economic and ecological benefit coefficients per unit area in Fengdu County (unit: 10^4 CNY/hm^2).

Land Use Type	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Ecological benefit	1.03	0.91	5.60	4.78	67.93	−0.69	−0.69	0.05
Economic benefit	11.01	11.01	7.31	25.15	9.35	80.52	19.41	0.1

3.2.2. Constraint Conditions Setting

(1) Total area constraint: The total area of each land use type is equal to the total area of the study area (Table 3). (2) Planning objective constraints: According to the study area's land use plan and related standards, the areas of cultivated land, forest, urban land, and unused land are limited in 2035. (3) Ecological environment constraints: To ensure ecological security and promote the continuous optimization of the ecosystem, constraint conditions are set for four factors (the total area of ecological land, forest area, water area, and habitat quality). Grasslands and water are important for maintaining the diversity of species in ecosystems. From 1990 to 2018, the grassland area in the study area decreased, whereas the water area increased, but the areas of these two types land cannot be reduced or expanded indefinitely. We limit the areas of grassland and water to between the value in 2018 and the predicted value in 2035. In addition, according to the method for calculating the habitat quality index E_m described in the "Technical Criterion for Eco-environmental Status Evaluation", the E_m in 2035 must be greater than the E_m in 2018. (4) Intensive development constraints: To promote the intensive use of land and improve the sustainability of social and economic development, we set constraint conditions from two factors (urban land area and rural residential area). According to the "Code for Classification of Urban Land Use and Planning Standards of Development Land", Fengdu County belongs to architectural climatic zone III, and the planned upper limit of its urban land area per capita is between 85 m^2 and 105 m^2 [65]. Therefore, the upper limit of the urban land area per capita in 2035 is set at 105 m^2. In addition, although a large number of people from rural areas have left the region for work, the rural residential area has increased rather than decreased. It is very important to promote the withdrawal of idle homesteads—however, this withdrawal is affected by policies, funds, and farmers' willingness, and is a relatively slow process. According to related research, the theoretical potential of rural residential land reclamation is approximately 40% of the actual area [66]. Therefore, we limit the area of rural settlements in 2035 to between 60% and 100% of the area of rural settlements in 2018. The predicted values of the above indicators in 2035 were calculated by the GM (1, 1) model based on data from 2000 to 2018.

Table 3. The constraint conditions of land use type area optimization.

Constraint Types.	Constraint Variables	Constraint Conditions
Total area constraint	The total area of each land use type	$x_1 + x_2 +, \cdots, +x_8 =$ The total area of the study area
Planning objective constraints	Cultivated land area	$x_1 + x_2 \geq$ planning value in 2020
	Forest area	$x_3 \geq$ planning value in 2020
	Urban land area	$x_6 \geq$ planning value in 2020
	Unused land area	$x_3 \leq$ planning value in 2020
Ecological environment constraints	Total area of ecological land	$x_1 + x_2 + x_3 + x_4 + x_5 + x_8 >$ Total area of ecological land in 2018
	Grassland area	Predicted Value in 2035 $\leq x_3 \leq$ Value in 2018
	Water area	Predicted Value in 2035 $\geq x_4 \geq$ Value in 2018
	habitat quality	E_m in 2035 $> E_m$ in 2018
Intensive development constraints	Urban land area	$x_6 \leq$ Predicted value of urban population in 2035 $\times$ Upper limit of per capita urban land area
	Rural residential area	Value in 2018 $\times$ 60% $\leq x_7 \leq$ Value in 2018

3.3. Optimization of the Land Use Spatial Configuration Based on the FLUS Model

The FLUS model is a scientific method suitable for the simulation of future land use changes [67]. This model is composed of two main modules: (1) an artificial neural network (ANN)-based probability of occurrence estimation module; and (2) a self-adaptive inertial competition mechanism CA module with roulette selection.

3.3.1. ANN-Based Probability of Occurrence Estimation Module

An ANN is a machine learning model based on biological neural network simulation. It is usually used to simulate and calculate nonlinear functions with many variables. It can continuously fit the complex relationship between input data and training targets through a large number of learning and recall iterations to ensure the generation of a higher suitability probability distribution and establish the relationship between the probability of each land use type and the factors that determine land use type [44,67]. The ANN can be expressed as follows:

$$SP(p,k,t) = \sum_j \omega_{j,k} \times sigmoid\left(net_j(p,t)\right) = \sum_j \omega_{j,k} \times \frac{1}{1 + e^{-net_j(p,t)}} \quad (4)$$

$$\sum_k SP(p,k,t) = 1 \quad (5)$$

where $SP(p,k,t)$ represents the probability of suitability for land use type k on grid cell p at time t; $\omega_{j,k}$ and $sigmoid$ are the weight and activation function between the hidden layer and the output layer, respectively; and $net_j(p,t)$ is the signal received from grid cell p in the hidden layer at time t.

Based on the results of relevant studies [68,69], 14 factors considered driving forces were selected to build the ANN to determine the probability of suitability for each landscape type in this study. The natural factors include elevation, slope, annual average temperature, annual average precipitation, soil texture, and soil organic matter content. The socioeconomic factors include population and GDP. The distance factors include the distances to rivers, railways, highways, roads, residential areas, and town areas. Because of the uneven distribution of land use types in the study area, random sampling was performed to obtain training samples. Due to the large number of pixels in the study area, the sampling ratio was set to 1% of the effective number of pixels in the study area. Since the unit of the sampling ratio was one thousandth, the sampling ratio parameter was set to 20. Moreover, the number of hidden layers in the ANN was set to 12. Finally, the ANN model was applied to generate accurate images of the probability of suitability for each land use type (Figure 4). The deeper the red is, the more suitable the landscape is.

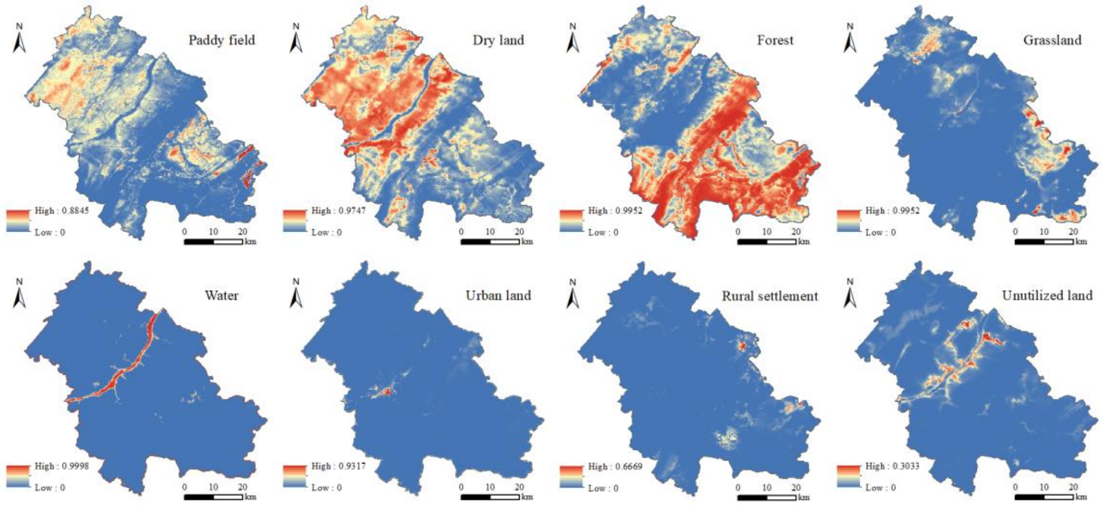

Figure 4. Probability of suitability for each land use type.

3.3.2. Self-Adaptive Inertial Competition Mechanism CA Module

The FLUS model introduces a self-adaptive inertial competition mechanism into the CA model, and combines the probability of occurrence, the influence of the neighborhood between cells, the conversion cost, and the inertia coefficient to calculate the total probability of the conversion of each land use type in each cell. Then, the roulette mechanism is used to reflect the competition among various land use types and determine the conversion and distribution of land use types in a cell to achieve more accurate land use change simulation [70,71]. The equation is expressed as follows:

$$TProb^t_{p,k} = SP(p,k,t) \times Intertia^t_k \times \theta^t_{p,k} \times (1 - sc_{c\rightarrow k}) \quad (6)$$

where $TProb^t_{p,k}$ indicates the probability of grid cell p being converted from the initial land use type to the target land use type k at iteration time t; $Intertia^t_k$ indicates the inertia coefficient of land use type k at iteration time t; $\theta^t_{p,k}$ is the neighborhood effect of land use type k on grid cell p at iteration time t; and $sc_{c\rightarrow k}$ represents the conversion cost of the initial land use type c to the target land use type k.

Spatial constraints are areas where a land use type will not change, and three types of spatial constraints are included in this research: ecological conservation redline areas; basic farmland conservation areas; and ecological safety network areas (Figure A1). The ecological safety network is constructed based on landscape security pattern theory [72]. First, the *Getis–Ord Gi** statistics are calculated by ArcGIS software version 10.7 to describe the spatial locations of cold spots and hot spots of ESVs in Fengdu County, and the hot spots with a confidence level of more than 90% are considered ecological sources and extracted [73]. Second, a minimum cumulative resistance model is used to construct an ecological resistance surface of Fengdu County, and Linkage Mapper software is used to calculate the distance path with the lowest cumulative consumption and, then, identify ecological corridors [74]. Finally, we analyzed buffer zones around the corridors and found that the corridor width does not include construction land within 300 m, and that the effects of human intervention are small. Considering that the extent to which land use types are excluded from ecological corridors differs by scenario, the widths of the ecological corridors in the SEC scenario, MEC scenario, and REC scenario were set to 300 m, 200 m, and 100 m, respectively [75]. Neighborhood factors refer to the difficulty of conversion between different land use types, with values ranging from 0 to 1: the closer the value is to 1, the stronger the expansion ability of the land use type is. The conversion cost is represented by a matrix, which is used to characterize the difficulty of converting from the current land use type to the demand type, where 1 represents a scenario in which the conversion between the two land types is allowed, and 0 represents a scenario in which there is no conversion. The neighborhood weight parameters (Tables A1–A5) and conversion cost matrices (Tables A2–A5) for different scenarios included in this research were determined based on the results of related research [76,77]. Finally, the number of iterations was set to 1000, and the neighborhood size was set to 3 to simulate the spatial configuration of land use under the different ecological constraint scenarios.

3.3.3. Model Validation

To better simulate land use changes in the future, the figure of merit (FoM) coefficient and Kappa coefficient were introduced to verify the results of the FLUS model [78–80]. The larger the FoM coefficient is, the better the simulation effect and the higher the accuracy—however, practical verification shows that FoM coefficients are mostly maintained within the range of 0–0.3, with values from 0.1 to 0.2 being the most common [80]. The closer the Kappa coefficient is to 1, the better the simulation accuracy. Kappa coefficients greater than 0.8 indicate that the simulation accuracy has reached an ideal state [79]. Based on land use data from 2010 and the FLUS model, the simulation result was obtained for 2018. Then, the simulation results for 2018 are compared with the observed results for 2018, and the results demonstrate that the overall accuracy of the model simulation is 93.20%, the FoM coefficient is 0.165, and the Kappa coefficient is 0.88. The validation results show that the FLUS model produces a highly accurate simulation of land use change in Fengdu County; therefore, this model can be applied for the following multiscenario simulation.

4. Results

4.1. Multiscenario Optimization of Land Use in Fengdu County

4.1.1. Results of the Land Use Type Area Optimization

The results of the land use type area optimization under the three scenarios were calculated by Lingo software version 12 (Table 4). The results showed that there were large differences in the areas of various types of land use under the three scenarios.

Table 4. Optimization of the area of each land use type in Fengdu County under different scenarios (unit: km^2).

Land Use Types		2018	SEC Scenario	MEC Scenario	REC Scenario
ISLs	Forest	1316.42	1438.64	1371.54	1369.96
	Grassland	181.77	180.09	180.09	181.77
	Water	52.33	57.89	57.89	52.23
	Subtotal	1550.52	1676.62	1609.52	1603.96
CSLs	Paddy field	367.18	327.12	335.84	350.24
	Dry land	950.20	863.31	905.76	893.08
	Unused land	0.05	0	0	0
	Subtotal	1317.43	1190.43	1241.60	1243.32
SLs	Urban land	24.68	28.89	41.54	45.38
	Rural settlement	8.24	4.92	8.20	8.24
	Subtotal	32.92	33.81	49.74	53.58

(1) Under the SEC scenario, the area of ISLs increased, reaching the maximum of the three scenarios (1676.62 km^2), and the area of CSLs was greatly reduced, reaching the minimum of the three scenarios (1190.43 km^2). There was no significant change in the area of SLs since 2018 (33.81 km^2). The areas of forest and water increased to 1438.64 km^2 and 57.89 km^2, respectively, and the areas of paddy fields, dry land, and grassland decreased to 327.12 km^2, 863.31 km^2, and 180.09 km^2, respectively. Although there was an increase in urban land area, it increased only to the lower limit of the constraint (28.89 km^2), whereas the rural residential area was significantly reduced to 4.92 km^2.

(2) Under the MEC scenario, the areas of the ISLs and SLs increased to 1609.52 km^2 and 49.74 km2, respectively, whereas the area of the CSLs decreased to 1241.60 km^2.

Compared with those in the SEC scenario, there were significantly smaller increases in the ISLs and reductions in the CSLs, and significantly higher increases in the SLs. Under this scenario, the areas covered by forest, water, and urban land increased to 1371.54 km^2, 57.89 km^2, and 41.54 km^2, respectively, and the areas covered by paddy fields, dry land, grassland, and rural residential sites decreased to 335.84 km^2, 905.76 km^2, 180.09 km^2, and 8.20 km^2, respectively.

(3) Under the REC scenario, the areas of the ISLs, CSLs, and SLs were 1603.96 km^2, 1243.32 km^2, and 53.58 km^2, respectively. With the relaxation of the ecological constraints, the increases in the ISLs and the reductions in the CSLs were further reduced, whereas the increases in the SLs were further increased. The areas of forest and urban land increased to 1369.96 km^2 and 45.38 km^2, and the areas of paddy fields and dry land decreased to 350.24 km^2 and 893.08 m^2, respectively. The areas of rural residential sites, grassland, and water remained unchanged.

4.1.2. Optimization of the Spatial Configuration of Land Use

Based on the 2018 land use data, the corresponding quantitative structure, and spatial criteria, the spatial configuration of the land use types in the study area in 2035 under the three ecological constraint scenarios was optimized (Figure 5).

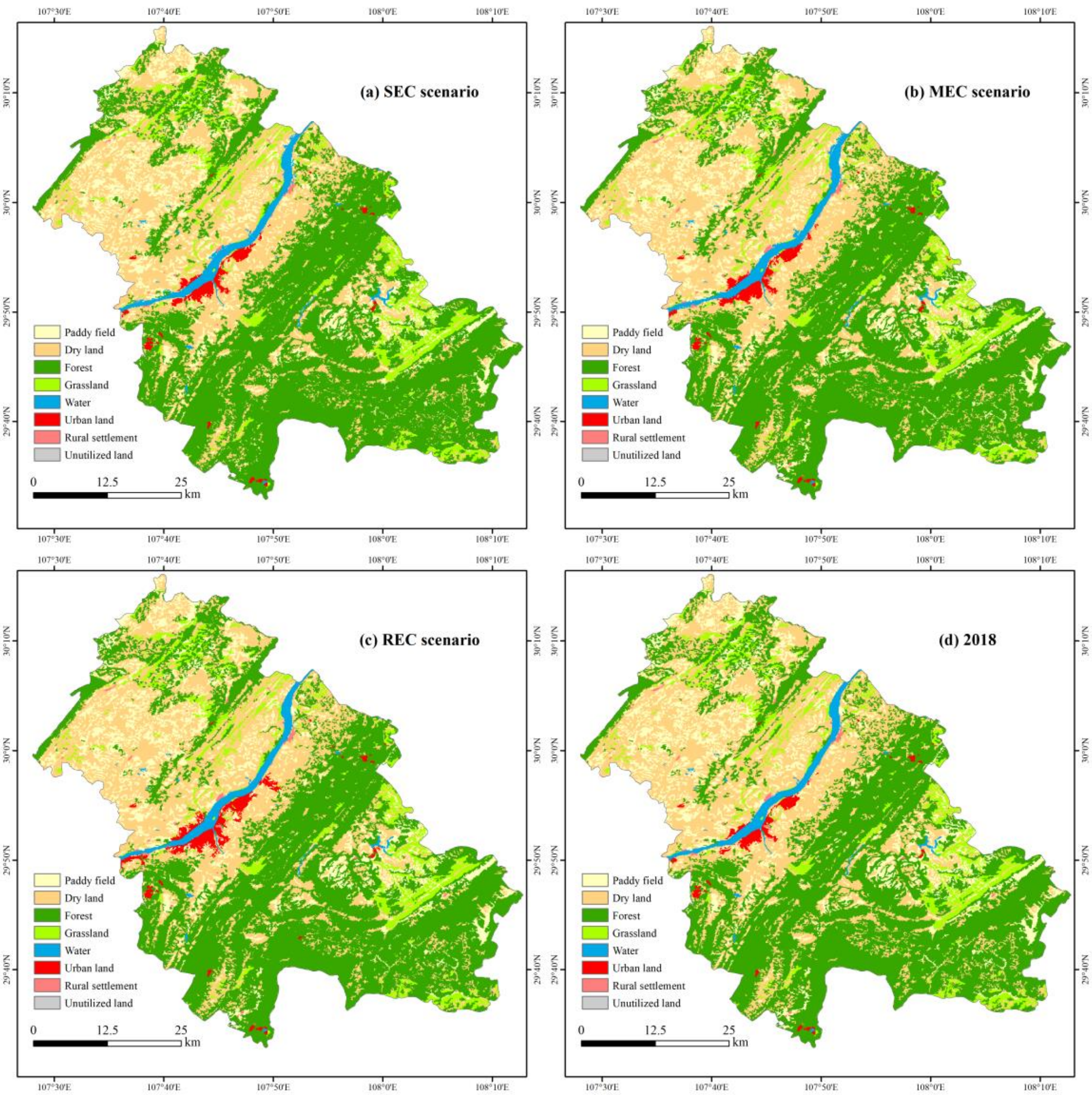

Figure 5. Optimization of the spatial configuration of land use types under (**a**) SEC scenario, (**b**) SME scenario, and (**c**) REC scenario in 2035 and (**d**) status quo in 2018.

(1) The development goals of the SEC scenario are to ensure regional ecological security, reduce regional ecological problems through a series of ecological restoration projects, and comprehensively improve ES functions. As shown in Figure 5a, under this scenario, the spatial scope of the ISL expanded rapidly, and the area of the source landscapes was generally greater than that of the Sins—this balance provided support for improving the overall ES function of the study area. The advancement of the Grain for Green Program has transformed many dry land areas and paddy fields with large farming radii and steep slopes into forestland. The area covered by water also expanded significantly. The newly added water was mainly concentrated along the Yangtze River. The low-lying terrain of this area is conducive to the formation of water features. With the effective implementation of prevention and control measures for rocky desertification, all the unused land in the study area has been transformed into other land use types. Urban land mainly expanded to the west, but the expansion was not obvious. Most of the newly added urban land was transformed from dry land, and the new urban land area was mainly concentrated in the Mingshan subdistrict and Sanhe subdistrict. Moreover, some rural settlements located in remote mountainous areas, with underdeveloped transportation systems and extreme rates of population decrease, were transformed into forests, dry land, or paddy fields after the abandonment of the settlements. The mean patch fractal dimension (MPFD), landscape division index (DIVISION), Shannon's diversity index (SHDI), and aggregation index (AI) were calculated in Fragstats software version 4.2. The results showed that the MPFD was 1.09, DIVISION was 0.94, SHDI was 1.58, and AI was 93.37. The configuration of the central town was relatively regular, the degree of fragmentation was low, and the spatial aggregation of different landscape types was relatively high.

(2) The development goal of the MEC scenario is to consider both economic growth and ecological protection. As shown in Figure 5b, under this scenario, the development of the source and sink landscapes was consistent, and the increases in the ISLs and the reductions in the CSLs were less than those in the SEC scenario, but the spatial change trend was similar to that in the SEC scenario. Among the land use types in the sink landscapes, whereas urban land continued to expand westward, there was also a trend of eastward expansion. The newly added urban land was mainly concentrated in the Mingshan subdistrict and Sanhe subdistrict, Shuanglu town, and Xingyi town. Moreover, a small number of rural settlements were transformed into forests, dry land, and paddy fields. Under this scenario, the MPFD of the study area was 1.16, the DIVISION was 0.96, the SHDI was 1.32, and the AI was 93.67. The configuration of the central town was relatively regular, the degree of fragmentation was moderate, and the spatial aggregation of different landscape types was moderate.

(3) The development goal of the REC scenario is to maximize economic benefits. As shown in Figure 5c, under this scenario, the spatial scope of the sink landscapes was significantly expanded, the area occupied by sink landscapes exceeded that occupied by source landscapes, and the ES supply in the study area faced very large decreasing pressure. Of the three scenarios, the increase in urban land use was highest in this scenario. In addition to Mingshan subdistrict, Sanhe subdistrict, Shuanglu town, and Xingyi town, urban land also increased significantly within Zhanpu town. The urban land area expanded from east to west along the Yangtze River. The main reason for this trend is that regions to the south and north are densely covered by basic farmland protection areas of existing towns, restricting the expansion of urban land. In addition, the western part of the county has flat terrain, dense road networks, excellent geographic locations, and functional water and land transportation facilities; therefore, it is suitable for urban development. The increases in the ISLs and the decreases in the CSLs in this scenario were further reduced compared with those in the SEC scenario, and the spatial change trend was similar to that in the SEC scenario. In the REC scenario, the MPFD of the study area was 1.38, the DIVISION was 0.98,

the SHDI was 1.23, and the AI was 92.08. The configuration of the central town was relatively scattered, the degree of fragmentation was high, and the degree of spatial aggregation of different landscape types was low.

4.2. Land Use Regionalization and Control Strategy in Fengdu County

We used ArcGIS software version 10.7 to superimpose the optimized spatial distributions of the source and sink landscapes under the three ecological constraint scenarios. With the objective of optimizing the ES function of the study area, the results of this superposition were amended, and Fengdu County was divided into seven types of areas (Figure 6). The amendment rules are as follows:

(1) Priority was given to ensuring ecological areas in Fengdu County and the grid cells that contained only ISL under all three ecological constraint scenarios were allocated to the ecological conservation area (ECA). Second, the grid cells that contained only CSLs and the grid cells that contained only SLs under the three scenarios were allocated to the agricultural production area (APA) and construction optimization area (COA). (2) The grid cells with different landscape types under the three scenarios were allocated to flexible control areas with multiple spatial functions, including the construction-ecological area (CEA), ecological-agricultural area (EAA), agricultural-construction area (ACA), and integrated development area (IDA). (3) Within the study area, the grid cells in the COA, CEA, and IDA that exceeded the boundaries of the permitted construction area were allocated to the ECA, and the grid cells that exceeded the boundaries of the permitted construction area in the ACA were allocated to the APA. (4) To ensure agricultural and ecological stability relative to the spatial configuration of the seven types of areas, a small number of COAs with heavy fragmentation were allocated to the ECAs or APAs based on their suitability.

(2) The ECA was the most widely distributed type of area in Fengdu County, and the highest concentrations of the ECA were located in the area south of the Yangtze River. The ECA covered 1556.83 km^2, accounting for approximately 53.67% of the total area of the study area. Urban and rural construction, and cultivated land reclamation activities, must be strictly prohibited in this area, and activities that destroy landscapes, vegetation, topography, and landforms, such as mining and borrowing are prohibited. Second, ecological restoration should be carried out in key areas that have been destroyed by human activities to optimize the vegetation coverage and the water environment. Moreover, it is possible to sustainably develop and utilize the ecological resources in this region, develop ecotourism, popularize science education and other projects, and enhance the cultural service values of the ecosystem. At the same time, it could be commented that better ecological corridors for the forest should be restored in the north of and along the Yangtze river.

(3) The APA was widely distributed throughout the study area, and the highest concentration was in the area north of the Yangtze River. The area of the APA was 1123.23 km^2, accounting for approximately 38.72% of the total area of the study area. First, it should be confirmed that the basic farmland in the study area is occupied and not abandoned. Second, the transformation of land should be encouraged to promote management of cultivated land at the appropriate scale. Moreover, to comprehensively improve the production environment and enhance agricultural modernization, high-quality farmland construction projects and rural land consolidation projects should be actively carried out, and appropriately planned ditches, mechanical tillage roads, breeding and seedling sites, greenhouses, hardening and drying yards, and other agricultural facilities should be allowed to occupy cultivated land. In addition, the demand for land associated with the development of agricultural science and technology research, ecological agricultural tourism, and other projects in the region should be supported.

(4) The COA is mainly distributed along the Yangtze River, with an area of 31.51 km^2, accounting for approximately 1.09% of the total area of the study area. First, develop-

ment and construction activities should be limited to suitable locations in this area. Moreover, it is necessary to strengthen the spatial matching between the permanent population and construction land, encourage the turnover of idle homesteads, and carry out cross-regional transactions and allocation of land use indicators to achieve a balance between the growth and decline in construction land between urban and rural areas. Second, the redevelopment of old urban areas and inefficient land should be actively carried out to develop emerging industries or green spaces. Furthermore, village renovation should be encouraged, and rural settlements should be guided to moderate concentration. The construction of transportation facilities, public service facilities, park squares, and other projects should also be carried out to comprehensively improve the living conditions of rural residents.

(5) The CEA was mainly distributed around the COA, and the area of the CEA was only 2.60 km^2. In the development and planning processes, the CEA should be prioritized for the protection and restoration of the ecological environment, and the development of eco-friendly spaces, such as country parks and ecologically friendly green spaces, should be encouraged. While adhering to the priority of ecological protection, the CEA can also be developed as construction land—however, the land in the area should not be transferred to high-polluting enterprises, such as the chemical and metal smelting industries.

(6) The EAA was mainly distributed around the ECA, with an area of 163.56 km^2, accounting for approximately 5.64% of the total area of the study area. In the future, this area should be given priority to be used as ecological space for the cultivation of forests. Moreover, it can be used for agricultural space to carry out production activities, such as grain and cash crop planting—however, green agriculture should be developed, and pollutants, such as pesticides and chemical fertilizers, should be completely prohibited. The EAA can also encourage the development of eco-agricultural tourism in accordance with local conditions to promote rural revitalization in Fengdu County.

(7) The ACA, which was largely in the middle of the study area, was mainly distributed around the ECA. The area of the ACA was 21.96 km^2, accounting for approximately 0.76% of the total area of the study area. This area can not only be used as agricultural land for the cultivation of agricultural products, but also can be developed to meet the land demand for economic development and residents' lives. Moreover, the ACA is close to urban and rural residential areas, giving it good geographic locations. Therefore, the cultivated land in the ACA should be planted mainly with high value-added cash crops to improve the economic benefits of land use.

(8) IDA was distributed mainly around the ECA, APA, and COA. This type of land had the smallest area in Fengdu County, with an area of only 1.17 km^2. The IDA had the most diverse land use functions related to the process of regional development, and its use should be focused on the protection of ecological spaces and the establishment of a good foundation for the improvement of ES functions in the study area. After those objectives are achieved, then, this area can be used as construction space to increase the living area of residents, and as agricultural space to increase the amount of arable land. Therefore, a highly flexible land use control policy should be implemented in the IDA, allowing this land use type to provide space for various types of land according to the development needs of Fengdu County, and promoting the coordinated development of space in the territory.

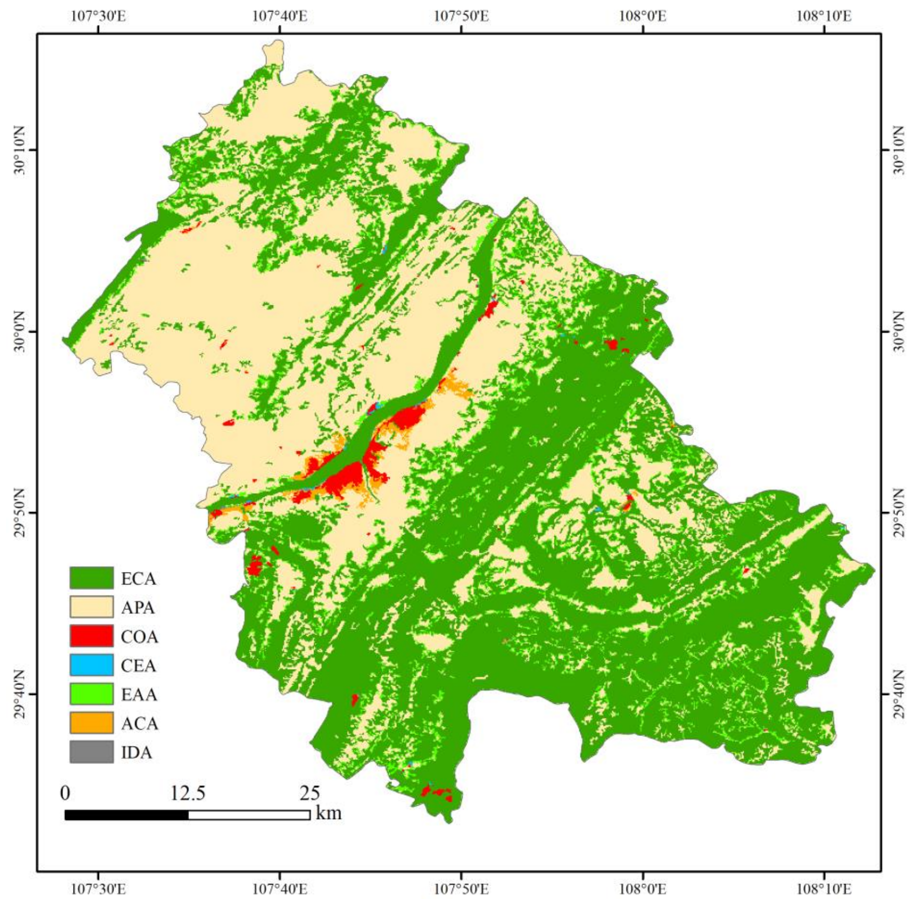

Figure 6. Land optimization zoning results of Fengdu County in 2030.

5. Discussion

5.1. Advantages of Land Use Optimization Models

On the basis of the observed situation in the study area and the source and sink landscapes associated with ESs, we proposed a method to optimize the areas of various land use types and their spatial configurations in Fengdu County by using a MOP-FLUS coupling model. When optimizing the areas of the land use types, we considered total area constraints, planning objective constraints, ecological environment constraints, and intensive development constraints, and established different objectives according to the varying emphasis on ecological and economic benefits in different scenarios. This optimization process is of great significance for improving the comprehensive benefits of space in a territory. We selected 18 driving factors of land use change, and 3 types of space-restricted areas to construct the FLUS model, thereby optimizing the spatial configuration of land use under different scenarios. The model validation results showed that the kappa coefficient was 0.88 and the FoM coefficient was 0.172, indicating that the model can effectively capture the trends in land use in Fengdu County, and that the results were more accurate than those of some studies that also use the FLUS model [64,69]. This finding may be because the land use data used in this study had a higher spatial resolution and fewer land use types than those used in other studies, and because the selection of driving factors was more comprehensive in this study than in other studies. In addition, spatial configuration optimization takes into account the areas occupied by ecological conservation redlines, basic farmland conservation areas, and ecological safety networks, which are of great significance for improving the overall ecological security of the region.

In summary, the method applied in this study addressed the problems that have arisen in recent land use optimization research, such as the lack of systematic constraints for determining the areas of various land use types, the lack of comprehensive spatial configuration optimization rules, and the unsatisfactory model accuracy, to a certain extent. Considering these issues, the predicted results had high credibility, and can provide valuable references for spatial planning in territories.

5.2. Feasibility of Land Use Regionalization

Due to the complexity of the natural environment, land use zoning of the TGRA is not only an effective way to plan and manage the land, but also a significant factor in the improvement of ES functions [64,81]. We divided Fengdu County into three areas with rigid control (the ECA, APA, and COA) and four areas with flexible control (the CEA, EAA, ACA, IDA). Among these areas, the COA was distributed mainly in the flat area along the Yangtze River, which is the core area for residential sites and economic development. The ECA was distributed mainly in high-altitude mountainous areas and along the main parts of the Yangtze River, which is the core area of ES supply. The APA was distributed mainly in the flat area between the two mountains in the study area. This is the main production area of grains in Fengdu County, and this area is of great significance for ensuring regional food security. The ECA and the ACA were distributed around the COA. These areas provide a buffer zone between the Sous and the Sins, which can effectively prevent the encroachment of important regional ecological spaces, and limit the pollution of soil, water, and air by various pollutants from construction land [82]. Moreover, the ECA and ACA can also alleviate the problem of overcrowded living spaces. The EAA, which establishes a natural barrier between agricultural space and ecological space, and can limit the damage of agricultural pollution to the ecological environment, was widely distributed around the APA. The IDA was distributed mainly around the COA, ECA, and ACA. The IDA has the most diverse spatial functions, and can provide space for the future development needs of Fengdu County.

In general, the land use regionalization plan proposed in this study is essentially a spatial functional regionalization plan. It does not only promote the preservation of values and appreciation of ESs, but also gives consideration to the coordinated development of urban areas, agriculture, and ecological functions in a space, which can provide the basis for delineating the "three zones and three lines" (three zones: ecological zone, agricultural zone, and urban zone; three lines: permanent basic farmland conservation redline, urban development boundary, and ecological conservation redline), and identifying key areas for ecological restoration in territorial spatial planning. Moreover, the land use regionalization plan reflects a moderately strict spatial management method for territories, which is in line with the observed status and future trends of the study area, and is highly feasible.

5.3. Implications for Spatial Management in the TGRA Territory

Since the United Nations issued the 2030 Sustainable Development Goals in 2015, territorial spatial governance has gradually become a hot topic in global change and sustainable development research [83]. The terrain of the TGRA is dominated by mountains and hills, and the water network is dense. Various ecological elements, including mountains, water, forestland, lakes, and grass, are integrated in the TGRA, and the natural background conditions are good. However, due to the very large natural and artificial disturbances associated with the construction of the Three Gorges Dam, and the rapid urbanization and industrialization that began when Chongqing became a municipality in 1997, the original ecosystem structure and functions of the TGRA have been seriously negatively affected, and a series of ecological and environmental problems have followed, such as forest vegetation degradation, water capacity decline, and frequent geological disasters [52]. Therefore, there is a need to strengthen the territorial spatial management in the region and build a strong ecological security barrier. Combining the source and sink landscape theory and the results of this research, we suggest that the spatial governance strategy of the TGRA should focus on the following two aspects:

(1) At the macro level, in the TGRA, a more coordinated spatial development and protection plan should be developed, and the direct expansion of Sins into Sous should be

slowed. First, a control policy related to the three zones and three lines must be strictly implemented in the TGRA, the system for delineating the main functional zones needs to be improved, and the ecological, agricultural, and urban spaces need to be rationally distributed. Moreover, the potential of the existing construction land needs to be fully exploited, and the renovation of rural residential sites needs to be vigorously carried out to continuously improve the compactness of the construction space. In addition, a market-oriented and diversified regional ecological compensation mechanism should be established to improve the enthusiasm and sustainability of ecological environmental protection.

(2) At the micro level, the TGRA should take ecological protection and restoration measures in response to the main problems faced by Sous. (a) The TRGA should continue to implement the Grain for Green project and Closing Hills for Afforestation project, especially in karst rocky desertification areas. Moreover, ecological restoration of mining areas should be implemented to repair damaged mountains, and continue to improve the vegetation coverage of the TGRA. In addition, the structure of natural forest vegetation should be optimized to prevent the formation of barren green deserts. (b) The prevention and management of urban and rural domestic sewage, industrial wastewater discharge and ship pollution, should be strengthened. Remediation projects in riparian zones should be implemented to prevent water-land cross-pollution. Comprehensive aquatic ecological restoration projects should also be launched to improve the quality of water sources and water biodiversity in reservoir areas. (c) It is necessary to optimize the configuration of agricultural lands, control agricultural nonpoint source pollution, and implement fallow fields on degraded cultivated land. Restoration projects should be implemented on sloping farmland in the TGRA to prevent further soil erosion.

5.4. Limitations

Due to the limited availability of basic data and the complexity of the model, the constraint conditions and optimization rules in this study are still relatively simple, and it is assumed that many driving factors of land use changes will continue as before, which may lead to results that are not robust or timely [63,64]. Therefore, although the results of this study provide a reference for regional spatial planning, they cannot provide an alternative proposal that can be implemented. In the future, more basic data and optimization rules should be added to the model, and the uncertainties in the driving factors of land use change should be considered more comprehensively and carefully to improve the accuracy of the land use optimization.

The demand for ESs is driven by the consumption of, or the hope to obtain, various services that support human society, and this demand is a potential determinant of optimal land use allocation [84]. As the strengthening of ES demand will inevitably cause stakeholders to balance, adjust, and control land use patterns, this will affect the direction, objectives, and planning of territorial spatial development. However, this study considered only the ES supply and did not consider the ES demand. In the future, the impacts of ES demand on territorial space should be fully considered, and the land use pattern should be optimized more accurately on the basis of the ES supply and demand relationship, spatial differentiation characteristics, and degree of matching.

6. Conclusions

(1) By integrating the MOP model and FLUS model, a study of county-level land use optimization was carried out according to the following flow: optimization of the areas of various land use types, followed by spatial configuration optimization and land use regionalization. This flow can effectively enhance the reliability and applicability of land use optimization results.

(2) The results of the land use optimization process showed that there were large differences in the areas and spatial distributions of the source and sink landscapes under the three ecological constraint scenarios. Under the SEC scenario, the areas of the ISLs, CSLs, and SLs were 1676.62 km^2, 1190.43 km^2, and 33.81 km^2, respectively. A

large area of CSLs and a small area of sink landscapes were transformed into ISLs, the degree of landscape fragmentation was low, and the area covered by source landscapes was generally greater than that covered by sink landscapes. Under the MEC scenario, the areas of the ISLs, CSLs, and SLs were 1609.22 km^2, 1241.60 km^2, and 49.74 km^2, respectively. The development of the source and sink landscapes was consistent, the degree of fragmentation was moderate, and the land use changes ranged from centralized development to balanced development. Under the MEC scenario, the areas of the ISLs, CSLs, and SLs were 1603.96 km^2, 1243.32 km^2, and 53.58 km^2, respectively. A large amount of CSLs were transformed into sink landscapes, the degree of fragmentation was high, and the area occupied by Sins was generally higher than that occupied by source landscapes.

(3) The results of land use optimization under different scenarios were superimposed, and the results indicated that Fengdu County is divided into seven types of areas: ecological conservation area; agricultural production area; construction optimization area; construction-ecological area; ecological-agricultural area; agricultural-construction area; and integrated development area. Different areas have different spatial functions, and differentiated land management policies should be adopted.

(4) In the future, the spatial governance of all the counties in the TGRA territory should be strengthened, more coordinated land space development and protection patterns should be developed, and ecological protection and restoration projects should be carried out in mountains, rivers, forests, fields, lakes, and grasslands to comprehensively improve regional ES functions.

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Abbreviations

Abbreviations

The abbreviations in this article:

ES	Ecosystem service
ESV	Ecosystem service value
SEC	Strict ecological constraint
MEC	Moderate ecological constraint
REC	Relaxed ecological constraint
TGRA	Three Gorges Reservoir Area
SL	Sink landscape
ISL	Important source landscape
CSL	Agricultural space
ECA	Ecological conservation area
APA	Agricultural production area
COA	Construction optimization area

CEA Construction-ecological area
EAA Ecological-agricultural area
ACA Agricultural-construction area
IDA Integrated development area

Appendix A

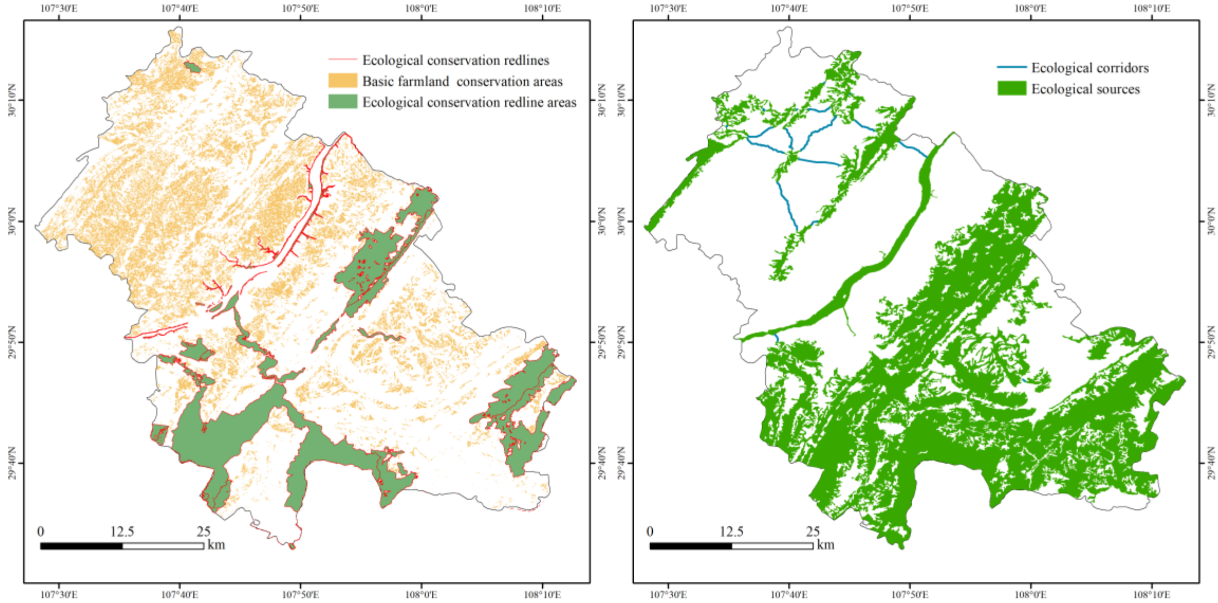

Figure A1. Spatial constraints area.

Table A1. Neighborhood factor parameters.

Scenarios	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Model validation	0.5	0.1	0.3	0.3	05	1.0	0.8	0.3
SE	0.5	0.1	0.8	0.4	0.8	0.8	0.5	0.3
ME	0.5	0.1	0.5	0.3	0.5	1.0	0.5	0.3
RE	0.5	0.1	0.2	0.3	0.2	1.0	0.5	0.3

Table A2. Land use conversion cost matrix of model validation.

Land Use Type	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Paddy field	1	1	1	1	1	1	1	1
Dry land	1	1	1	1	1	1	1	0
Forest	1	1	1	0	1	1	1	0
Grassland	1	1	1	1	1	1	1	0
Water	1	1	1	1	1	1	1	0
Urban land	0	1	0	0	1	1	0	0
Rural settlement	0	1	0	0	0	1	1	0
Unused land	0	1	1	0	1	0	0	1

Table A3. Land use conversion cost matrix of SEC scenario.

Land Use Type	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Paddy field	1	0	1	1	1	0	0	0
Dry land	1	1	1	1	1	1	1	0
Forest	0	0	1	0	1	0	0	0
Grassland	0	0	1	1	1	1	1	0
Water	0	0	0	0	1	0	0	0
Urban land	0	0	0	0	0	1	0	0
Rural settlement	1	1	1	0	1	1	1	0
Unused land	1	0	0	0	0	0	0	1

Table A4. Land use conversion cost matrix of MEC scenario.

Land Use Type	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Paddy field	1	0	1	0	0	1	1	1
Dry land	1	1	1	1	1	1	1	0
Forest	0	1	1	0	0	1	0	0
Grassland	1	1	1	1	1	1	1	0
Water	0	0	0	0	1	0	0	0
Urban land	0	0	0	0	0	1	0	0
Rural settlement	1	1	1	1	1	1	1	0
Unused land	1	1	1	1	1	1	1	1

Table A5. Land use conversion cost matrix of REC scenario.

Land Use Type	Paddy Field	Dry Land	Forest	Grassland	Water	Urban Land	Rural Settlement	Unused Land
Paddy field	1	1	1	1	1	1	1	0
Dry land	1	1	1	1	1	1	1	0
Forest	1	1	1	1	1	1	1	0
Grassland	1	1	1	1	1	1	1	0
Water	0	0	0	0	1	0	0	0
Urban land	0	0	0	0	0	1	0	0
Rural settlement	1	1	0	0	0	1	1	0
Unused land	0	0	0	0	0	0	0	1

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