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Special Issue Reprint

Spatial-Temporal Evolution Analysis of Land Use

Edited by
Alma Zavodnik Lamovšek, Gregor Čok, Mojca Foški, Lea Petrović Krajnik, Dorota Jopek and Samo Drobne

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Guest Editors

Alma Zavodnik Lamovšek
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana
Slovenia

Gregor Čok
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana
Slovenia

Mojca Foški
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana
Slovenia

Lea Petrović Krajnik
Department of Urban Planning, Spatial Planning and Landscape Architecture
University of Zagreb
Zagreb
Croatia

Dorota Jopek
Faculty of Public Economy and Administration
Cracow University of Economics
Cracow
Poland

Samo Drobne
Faculty of Civil and Geodetic Engineering
University of Ljubljana
Ljubljana
Slovenia

Editorial Office

MDPI AG
Grosspeteranlage 5
4052 Basel, Switzerland

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Contents

About the Editors . . . . . **vii**

Preface . . . . . **xi**

Pengyue Dai, Yanfang Wang, Jinhong Ye, Jing Chen, Runze Li and Xiping Cheng
Evolution and Attribution Analysis of Habitat Quality in China's First Batch of National Parks
Reprinted from: *Land* **2025**, *14*, 33, https://doi.org/10.3390/land14010033 . . . . . **1**

Zhen Zhong, Bochuan Zhou, Lingqiang Kong and Xuening Fang
When to Use What: A Comparison of Three Approaches to Quantify Relationships Among Ecosystem Services
Reprinted from: *Land* **2025**, *14*, 644, https://doi.org/10.3390/land14030644 . . . . . **18**

Shu Wang, Quanli Xu, Junhua Yi, Qinghong Wang, Qihong Ren, Youyou Li, et al.
An Ecological Risk Assessment of the Dianchi Basin Based on Multi-Scenario Land Use Change Under the Constraint of an Ecological Defense Zone
Reprinted from: *Land* **2025**, *14*, 868, https://doi.org/10.3390/land14040868 . . . . . **40**

Peter Lamovec, Katarina Kuk, Barbara Černič, Tomaž Černe and Ines Lupše
A GIS-Based Approach to Land Take Monitoring and Actual Land Use Analysis
Reprinted from: *Land* **2025**, *14*, 1322, https://doi.org/10.3390/land14071322 . . . . . **61**

Thomas Gloaguen, Sébastien Gadal, Jūratė Kamičaitytė and Kęstutis Zaleckis
Structural Evolution of the Coastal Landscape in Klaipėda Region, Lithuania: 125 Years of Political and Sociocultural Transformations
Reprinted from: *Land* **2025**, *14*, 1356, https://doi.org/10.3390/land14071356 . . . . . **81**

Vineet Chaturvedi and Walter Timo de Vries
Residential Location Preferences in a Post-Conflict Context: An Agent-Based Modeling Approach to Assess High-Demand Areas in Kabul New City, Afghanistan
Reprinted from: *Land* **2025**, *14*, 1502, https://doi.org/10.3390/land14071502 . . . . . **114**

Chenxi Li, Huimin Chen and Yingying Fang
Influence Mechanism, Simulation, and Prediction of Urban Expansion in Shaanxi Province, China
Reprinted from: *Land* **2025**, *14*, 1637, https://doi.org/10.3390/land14081637 . . . . . **130**

Sanja Hajdinjak, Jasenka Kranjčević and Božo Benić
Spatiotemporal Evolution and the Impact of Changing Political–Economic Systems on Tourism Spatial Planning and Land Use: The Case of Kupari, Dubrovnik, Croatia
Reprinted from: *Land* **2026**, *15*, 41, https://doi.org/10.3390/land15010041 . . . . . **146**

About the Editors

Alma Zavodnik Lamovšek

Alma Zavodnik Lamovšek has been permanently employed at the Faculty of Civil and Geodetic Engineering, University of Ljubljana (UL FGG), where she also obtained her doctorate. Since 2016, she has taught at all three levels of Bologna study programmes. She regularly participates as a guest lecturer or mentor at summer schools and student workshops at faculties in Zagreb, Osijek, and Kraków, and occasionally in Belgrade and Vienna. She holds management positions at the faculty and, with a few interruptions, heads the Department of Spatial Planning. She has also served as vice-dean, most recently for economic activities. For more than two decades, she has been active in the Town and Spatial Planning Association of Slovenia (TSPAS), which she has led for the past four years. Each year, she helps organise professional meetings through which the association responds to current spatial challenges. In her professional work and research, she has focused on the development of settlements and related spatial processes: land use and access to public services and infrastructure, especially ICT in rural and remote areas. Recently, she has focused primarily on the issue of balanced regional development on the one hand, and the development of cycling connections in Slovenia on the other. She has led or participated in domestic and European projects (Interreg, ESPON, Urbact, Horizon), and regularly publishes the results in periodicals. She is also the author, co-author, or editor of numerous monographs. She is the recipient of two Maks Fabiani awards, presented every two years by TSPAS in 2015 and 2019. In 2025, she received a faculty award for her significant contribution to the development, quality, and reputation of UL FGG.

Gregor Čok

Gregor Čok graduated and obtained his PhD from the Faculty of Architecture, University of Ljubljana, and is currently employed at the Faculty of Civil and Geodetic Engineering, Chair of Spatial Planning (UL FGG). He teaches courses in spatial planning and urban design at various faculties and study programmes. He completed an extended study exchange in Poland and, as a guest lecturer, has also participated at faculties in Belgrade and Skopje. Most of his professional and research work focuses on the spatial planning of industrial, commercial and business zones, the spatial regulation of home-based work, and support for planning spatial development projects at the transnational cross-border level (in the fields of infrastructure, tourism and nature conservation). Recently, he has focused on Maritime Spatial Planning (MSP) and coastal zone planning at the municipal level (Protocol ICZM). He is a co-author of the first national maritime spatial plan of the Republic of Slovenia. He has led or participated in numerous national and European research or applied projects (Interreg, CAMP, SHAPE, SUPREME, MSP-MED), associations (UNESCO Ecomed Task Force), and specialist training programmes (MSP development in Turkey). He presents the results of his work at national and international conferences and symposia (AGORA CAUMME, European Aerosol Conference, Sustainable Development Symposium, Urban Studies Congress, etc.). He is also the author or co-author of various professional and scientific works, and the recipient of competition awards.

Mojca Foški

Mojca Foški is a geodetic engineer by profession; she completed her master's degree in 2000 through the Interdisciplinary Graduate Study in Spatial and Urban Planning (IPŠPUP) and received her PhD in 2017. Since 2007, she has been a senior lecturer in spatial planning at the University of

Ljubljana, Faculty of Civil and Geodetic Engineering. Her professional and research interests focus primarily on challenges at the local level, approaches to spatial planning implementation, regulatory mechanisms in urban and rural areas, and regional planning. She is actively involved with the scientific journal *Geodetski vestnik* (Scientific Journal of the Association of Surveyors of Slovenia) and is a member of national and international professional associations in the fields of geodesy and spatial planning.

Lea Petrović Krajnik

Lea Petrović Krajnik has been employed at the Department of Urban Planning, Spatial Planning and Landscape Architecture, Faculty of Architecture, University of Zagreb, since 2004. In the same year, a scholarship from the University of Hannover, Alfred Toepfer Stiftung F.V.S., Hamburg, Germany, was awarded. In 2009, she obtained a PhD from Graz University of Technology, Austria, defending the doctoral dissertation *The Impact of World Exhibitions on Urban and Regional Development*. Training in scientific, teaching, and professional skills was completed at internationally recognised institutions across several European countries. She is a full professor and Head of the Spatial Planning Cabinet at the department, where courses in Spatial Planning and Sustainability in Urban and Spatial Planning are taught within the Master's programme. Her teaching activities also include doctoral and postgraduate specialist programmes. In addition, she lectures at the Faculty of Forestry, University of Zagreb, in the course Introduction to Spatial Planning. Her research activities include participation in international and Croatian scientific projects and service on editorial boards, as well as peer review for scholarly journals in Croatia and abroad. Her scientific papers are published in Croatian and international scholarly journals, as well as other professional publications. Her main research interests include regional planning, urban transformation, and large-scale events. Her professional practice includes architecture, urban planning, and spatial planning.

Dorota Jopek

Dorota Jopek is a researcher at the Department of Spatial Management at the Krakow University of Economics. She also collaborates on scientific projects at the Institute of Urban and Regional Development in Kraków. Her research interests focus on urban development, spatial planning, city landscape formation, strategic urban management, cities' adaptation to climate change, and the revitalisation of degraded areas. She is a member of a research team working on implementing nature-based solutions (NbS) for cities, including the EU-funded project AQUAlive (2026–2028). Moreover, she is the author and co-author of numerous publications on the spatial development of large cities in the context of urban design and revitalisation planning. She has participated in international scientific fellowships (e.g., in France, Germany, Slovenia, and the Czech Republic) and has delivered lectures and urban workshops. Since 2005, she has held an unlimited qualification in architectural design issued by the Małopolska Chamber of Architects. Her professional experience encompasses a wide range of architectural and urban design projects carried out by Polish and international design studios—including in New York City—in which she has served as author or co-author. She has also been involved in developing municipal revitalisation programmes. Dorota is a member of the Society of Polish Town Planners, the Małopolska Chamber of Architects, and the Association of European Schools of Planning. She is an educator in youth programmes related to space and urban design organised by the Chamber, and an organiser of international urban workshops under inter-university cooperation agreements. She is also a co-author of a scientific analysis concerning the establishment of SIM units for Kraków and other planning studies.

Samo Drobne

Samo Drobne is an Associate Professor of Geodesy and Geoinformatics at the University of Ljubljana, Faculty of Civil and Geodetic Engineering (UL FGG), where he has been employed since 1989. He graduated in Surveying Engineering (1989), obtained an MSc in Spatial Planning (1993), and a PhD in Built Environment—Spatial Planning (2016), all at UL FGG. He has held several management positions, including Head of the part-time Geodesy programme (2001–2009), Vice Head of the Department of Geodetic Engineering (2009–2013), and Vice Dean for Educational Affairs (2017–2021). He teaches geoinformatics, GIS, statistics, spatial analysis in GIS, and computer science, and has previously taught spatial statistics, GIS models and simulations, spatial systems and cartographic surveys, and transport and space. He has supervised over 140 student theses, several of which have received University and Faculty Prešeren awards, and is active in the doctoral programme Built Environment. His research focuses on geoinformatics, spatial data modelling and analysis, and spatial decision support systems for spatial planning. He is the author or co-author of over 440 bibliographic units and has participated in numerous national and international projects (Tempus, Erasmus+, ESPON, Interreg). He has been a visiting researcher or lecturer at the Hungarian Academy of Sciences (Pécs), University of Cartagena (Spain), Xiamen University and the Chinese Academy of Sciences (China), Iowa State University (USA), Savitribai Phule Pune University (India), and the University of Zagreb (Croatia). He serves as a committee member and reviewer for conferences, projects, and journals, is Executive Secretary of SSI-SOR, and is active in several professional associations. He has organised more than 20 international conferences and symposia, and has received the SSI Award (2007), SSI Golden Badge of Honour (2022), and the Prize of the National Council of Slovenia (2022).

Preface

Changes in land use, ecological risks, and spatial planning have become central challenges in achieving sustainable development during periods of rapid environmental, social, and political change. In various geographical contexts—from national parks and urban areas to coastal tourist areas and cities—land use is increasingly shaped by complex interactions among ecological processes, socio-economic factors, management frameworks, and historical heritage. This Reprint addresses these challenges in eight contributions, ranging from analyses of land use change dynamics and ecological risks to spatial planning practices. It examines different spatial levels (local, regional, and national) and the political, economic, and cultural circumstances that influence current land use and its future planning. Drawing on case studies from Europe, China, the Middle East, and the Baltic region, the Reprint offers a comparative and internationally grounded perspective on changes in land use and spatial management.

The main objective of this scientific work is to deepen understanding of how land use dynamics resulting from various activities, such as tourism and urban development, affect natural factors and human decision-making under different institutional and politica–economic conditions. The reprint aims to (1) assess the spatial and temporal patterns of land use and landscape change, (2) evaluate their ecological and social consequences, (3) test and compare modelling and analytical approaches, and (4) identify key factors and management mechanisms that shape sustainable or unsustainable outcomes.

The authors identify several gaps in existing research. Many studies focus only on individual methods or static snapshots, overlooking the long-term dynamics and socio-political factors that influence land use change. The authors also note that, despite the increasing availability of geospatial data and simulation tools, the formulation of sectoral policies and strategies remains insufficiently integrated. By bringing together diverse case studies and methodological approaches, this Reprint responds to the urgent need for interdisciplinary, policy-relevant research that bridges science and practice.

The Reprint is intended for researchers and scientists in geography, environmental sciences, landscape ecology, urban and regional planning, tourism studies, and sustainability sciences. It is also relevant for policymakers, planners, and public authorities responsible for land use regulation, environmental conservation, and spatial development, who require scientifically based tools and insights to support decision-making. Finally, the Reprint serves as a valuable resource for graduate students and professionals seeking to understand the complexity of land use change processes and to apply advanced analytical methods in real-world planning and management contexts.

Alma Zavodnik Lamovšek, Gregor Čok, Mojca Foški, Lea Petrović Krajnik, Dorota Jopek, and Samo Drobne

Guest Editors

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Article

Evolution and Attribution Analysis of Habitat Quality in China's First Batch of National Parks

Pengyue Dai [1], Yanfang Wang [1], Jinhong Ye [1], Jing Chen [2], Runze Li [1] and Xiping Cheng [1,*]

[1] College of Soil and Water Conservation, Southwest Forestry University, Kunming 650224, China
[2] College of Gardening and Horticulture, Southwest Forestry University, Kunming 650224, China
* Correspondence: xipingcheng@swfu.edu.cn

Abstract: In October 2021, China established its first group of national parks, representing a milestone in enhancing the country's nature reserve system and aligning with global trends in ecological conservation. This study aims to assess habitat quality changes and identify the driving factors in five national parks using multi-temporal land use data from 2000 to 2020. By integrating the land use transfer matrix with the InVEST model, we quantified habitat quality changes, while the geographical detector method was employed to analyze the key natural and socioeconomic drivers. Results showed that grassland and cultivated land were predominantly converted into forestland, leading to improvements in habitat quality in some parks. Specifically, Wuyishan National Park exhibited the highest and most stable habitat quality index, while Three-River-Source National Park experienced significant improvement (+34.10%). However, the Giant Panda, Northeast China Tiger and Leopard, and Hainan Tropical Rainforest National Parks experienced habitat degradation, with decreases of 15.15%, 14.50%, and 13.90%, respectively. Key drivers, such as NDVI, temperature, precipitation, elevation, and population density, were found to significantly influence habitat quality across the parks. This study highlights the ecological benefits of forestland restoration and the risks posed by the conversion of forest to cultivated or construction land, providing valuable insights for optimizing conservation strategies in China's national parks.

Keywords: national parks; habitat quality; geographical detector; ecological contribution rate

1. Introduction

Habitat quality reflects an ecosystem's ability to support the survival and reproduction of organisms; it serves as a core indicator for evaluating the state of the ecological environment. It is closely related to biodiversity and ecological health and is essential for regional sustainable development [1,2]. Changes in habitat quality directly impact the ecosystem's ability to maintain biodiversity and provide ecosystem services, which are critical for regional sustainability [3]. Humans indirectly shape habitat quality through land use changes; therefore, an in-depth study of changes in land use over time and space helps us reveal patterns and the causes of changes in habitat quality [4–6].

Since the 1960s, the field of habitat quality research has gradually emerged, initially focusing on the quality assessment of animal and plant habitats and the effects of human activities on these habitats. These early studies relied heavily on field investigations and established basic frameworks for habitat quality evaluation. However, advances in

geographic information technology have enabled broader and more detailed assessments of habitat quality dynamics, particularly through the integration of spatial data and ecological models. These studies gathered key habitat quality parameters through field investigations and established assessment indicator systems, mainly for small-scale nature reserves or single-species studies within specific water systems [7,8]. The development of geographic information technology has given rise to a new land use-based method for habitat quality research, increasingly relying on ecological models for quantitative analysis [9,10]. Models, such as MaxEnt [11], InVEST [12], and SoilVES [13], have been applied in this field, with the InVEST model being particularly popular due to its wide applicability, accuracy, and effective result visualization. MaxEnt excels in modelling species distribution, while SoilVES focuses on soil ecosystem services. In contrast, the InVEST model integrates ecological processes and human activities, making it particularly effective for evaluating habitat quality across various spatial scales [14–17]. Despite its wide applicability, the use of the InVEST model requires careful calibration to account for specific ecological and socioeconomic conditions. Habitat quality is influenced by both natural and anthropogenic factors. Natural conditions, such as topography, climate, and vegetation, play a critical role in shaping habitat suitability [18,19]. Simultaneously, socioeconomic factors, such as population density and land use intensity, have increasingly altered habitat composition and quality [20–22]. Despite considerable advancements in habitat quality research, several key challenges persist. Specifically, the interactions between natural and anthropogenic drivers and their combined impacts on habitat quality changes at the landscape scale remain insufficiently quantified. Moreover, the influence of land use changes on habitat quality dynamics within protected areas is still poorly understood. Despite the fact that habitat quality has been extensively studied both at home and abroad, how to comprehensively and systematically reveal the mechanisms influencing changes in habitat quality and assess the contribution of land use change to habitat quality remains an important scientific issue in current research. In particular, under the complex interaction of natural and social factors, the changes in habitat quality and how its spatial distribution is affected by different factors have not been fully quantified and explained. To address these gaps, this study adopts an innovative approach by integrating the InVEST model with land use transfer matrix and ecological contribution rate analysis to quantify the impacts of land use change on habitat quality. Furthermore, the geographical detector method is employed to reveal the joint and interactive effects of natural and socioeconomic drivers on habitat quality.

The official establishment of China's first set of national parks on 12 October 2021, signifies a new stage in the evolution of the country's nature reserve system. China, as one of the global biodiversity hotspots, established its first set of national parks to enhance the protection of critical ecosystems. Among these, the five national parks studied in this research are distributed across diverse ecological regions, each representing unique environmental and conservation challenges. Systematically evaluating and understanding habitat quality changes and their driving factors in these parks is critical for guiding conservation strategies and optimizing land management practices. By focusing on China's newly established national parks, this research provides novel insights into the mechanisms underlying habitat quality changes and offers actionable recommendations for improving conservation strategies. This study not only advances the understanding of habitat quality dynamics in protected areas but also fills a critical knowledge gap in the application of ecological models to large-scale, multi-factor analyses.

2. Materials and Methods

2.1. Study Area Overview

This study focuses on China's first batch of national parks. These parks are distributed across different geographical regions of China, with latitudes ranging from 18° N to 89° N and longitudes from 97° E to 131° E, covering various ecological environments from the high-altitude Qinghai–Tibet Plateau to the low-altitude tropical rainforests (Figure 1). Three-River-Source National Park's geographic coordinates range from 32°26′4″ N to 36°16′49″ N, and from 89°24′6″ E to 99°6′46″ E, covering a total area of approximately 190,700 square kilometers. The Giant Panda National Park includes the Minshan and Qionglai–Daxiangling regions, the Qinling region, and the Baishuijiang region, with a total area of approximately 27,900 square kilometers. Its geographic coordinates range from 102°11′10″ E to 108°30′52″ E and from 28°51′03″ N to 34°10′07″ N. The Northeast China Tiger and Leopard National Park is situated in the southern region of the Laoyeling Mountains, along the border between Jilin and Heilongjiang Provinces, with geographic coordinates ranging from 42°38′45″ N to 44°18′36″ N and from 129°05′01″ E to 131°18′52″ E, encompassing an area of roughly 14,100 square kilometers. The National Park of Hainan Tropical Rainforest is located in the central part of Hainan Island, with geographic coordinates from 18°33′16″ N to 19°14′16″ N and from 108°44′32″ E to 110°04′43″ E. The park spans a total area of 4269 square kilometers, with a core protection area of 2331 square kilometers. Wuyishan National Park is located in the northern section of the Wuyi Mountains at the border between Fujian and Jiangxi Provinces, covering an area of approximately 1280 square kilometers and geographic coordinates ranging from 117°24′13″ E to 117°59′19″ E and from 27°31′20″ N to 27°55′49″ N.

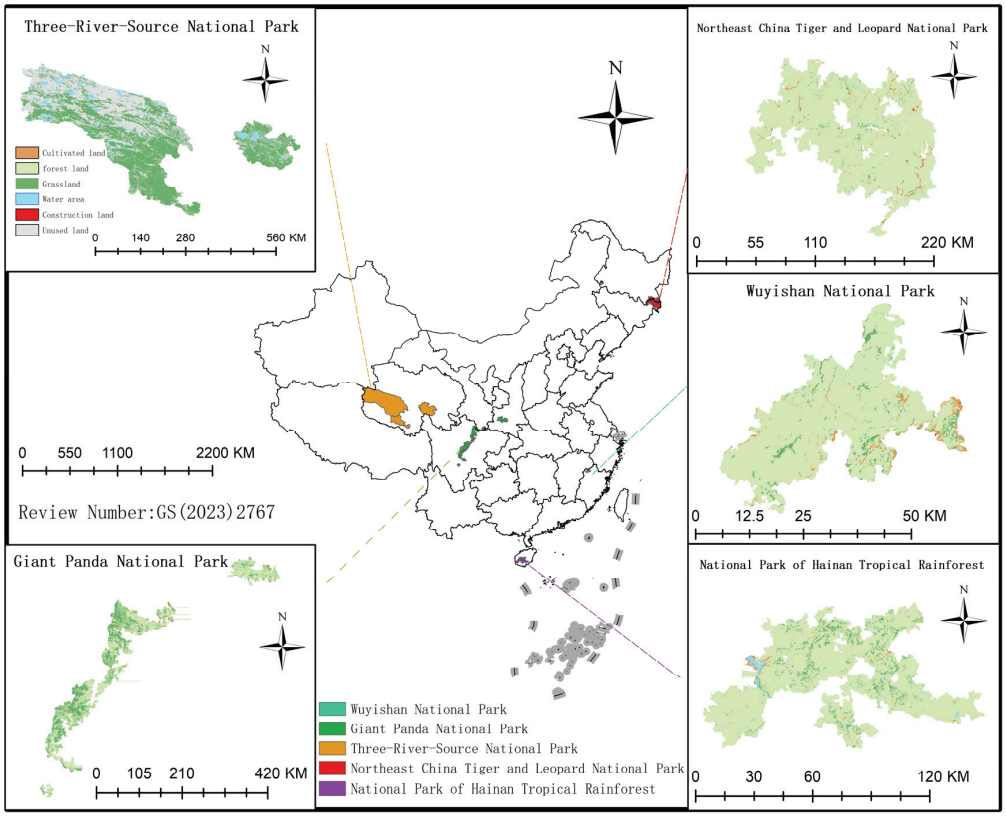


Figure 1. Study area location and land use categories.

2.2. Data Sources and Processing

The terrain data employed in this study were obtained from the Geospatial Data Cloud platform (http://www.gscloud.cn/, accessed on 10 May 2024), using the ASTER DEM product with a 30 m resolution, provided by NASA (National Aeronautics and Space Administration, Washington, DC, USA) and the Japan Earth Observation System (EOSDIS, Tokyo, Japan). Slope data were extracted using the slope extraction tool in ArcGIS version 10.8 (Esri, Redlands, CA, USA). Additionally, meteorological, vegetation index, and socioeconomic data were acquired from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/, accessed on 24 May 2024). Specifically, the meteorological data included annual average temperature and annual average precipitation, provided as a spatially interpolated dataset with a 1 km resolution. Vegetation coverage (NDVI) was derived from remote sensing images using the maximum value composite method and is also presented as a dataset with a 1-km resolution. The socioeconomic dataset includes population density and GDP from 2000 to 2020, provided as gridded interpolations with a 1 km resolution. The land use dataset is based on three time points: 2000, 2010, and 2020. The data were provided by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (http://www.igsnrr.ac.cn/, accessed on 1 March 2024), with a spatial resolution of 30 m. Land use types were categorized into a secondary classification system based on the specific requirements of this study and the land cover characteristics of the research sites (Table 1).

Table 1. Land use classification system.

Primary Classification	Secondary Classification
Cultivated land	Paddy field, dryland
Forest land	Woodland, shrubland, sparse forest land, other forest land
Grassland	High-coverage grassland, medium-coverage grassland, low-coverage grassland
Water area	River channel, reservoir, pond, beach
Construction land	Urban land, rural settlement, other construction land
Unused land	Marsh, bare land, bare rock

2.3. Research Methods

2.3.1. Land Use Transfer Matrix

The land use transfer matrix offers a quantitative method for describing the state of land use types before and after transformation, specifically illustrating the conversion relationships between different land use types [23,24]. This matrix not only records the specific area status of each land use type before and after transformation but also shows the relative area proportion of various land use types within a specific period. The matrix is expressed as follows [25]:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix} \quad (1)$$

where n denotes the number of land use categories before and after the transfer; S_{ij} refers to the area of type i land converted to type j land before the transfer.

2.3.2. Habitat Quality Module

The core of this method lies in directly linking habitat quality to potential threats. The level of habitat degradation is assessed by analyzing the adverse impacts of these threat factors on the habitats. Subsequently, by combining habitat suitability and degradation levels, a comprehensive evaluation of habitat quality can be conducted [26]. The formula for calculating habitat degradation is as follows:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{W_r}{\sum_{r=1}^{R} W_r} \right) r_y i_{rxy} s_{jr} \quad (2)$$

where D_{xj} represents the degree of stress on grid cell x within land use type j; W_r represents the weight of threat factor r; r_y represents the intensity of the threat factor; i_{rxy} represents the influence of the threat factor on each grid cell; and S_{jr} represents the varying sensitivity of land use types to different threat factors. Habitat quality calculation formula:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \quad (3)$$

where Q_{xj} represents the habitat quality level of grid cell x within land use type j; H_j represents the habitat suitability.

In this study, based on the common characteristics of each park, cultivated land, construction land, and unused land were identified as the primary threat factors. This selection was based on the potential negative impacts that these land use types could have on biodiversity and natural habitats [27]. The maximum impact distance, weight, and decay functions of these threat factors were also specified (Table 2). Furthermore, the habitat suitability of different land use types in the study area was assessed to examine their sensitivity to the identified threat factors (Table 3).

Table 2. The impact range and weight of threat sources.

Threat Factors	Maximum Impact Distance (km)	Weight	Decay Type
Cultivated land	1	0.2	Linear
Construction land	10	1	Exponential
Unused land	5	0.6	Exponential

Table 3. Suitability of the habitat and relative sensitivity to various threat sources.

Code	Land Type Name	Habitat Suitability	Cultivated Land	Construction Land	Unused Land
1	Cultivated land	0.3	0.1	0.6	0.3
2	Forest land	1	0.4	0.7	0.5
3	Grassland	0.7	0.2	0.6	0.4
4	Water area	0.9	0.2	0.7	0.4
5	Construction Land	0.1	0.1	0.1	0.2
6	Unused land	0.2	0.3	0.6	0.1

2.3.3. Geographical Detector

The geographical detector is a statistical analysis tool that can detect spatial differentiation phenomena in landscapes and reveal the underlying driving factors behind these phenomena. Identifying the influencing factors is crucial for improving regional habitat quality [28]. These factors include both natural and social factors. In this study, the "factor detector" module of the geographical detector was used to explore the explanatory power

of various driving factors on habitat quality changes, with social and natural factors as independent variables and habitat quality as the dependent variable. Social factors, including population density, gross domestic product (GDP), and land use, were chosen to evaluate the impact of human activities on regional habitat quality. Meanwhile, natural factors are key determinants in shaping the spatial and temporal distribution of habitat quality. Among these, climatic conditions significantly impact biodiversity and hydrological environments; therefore, we selected annual average precipitation and temperature as climate factors. Given the complexity of the terrain in different national parks, elevation, and slope were incorporated as terrain factors to capture the influence of topography on habitat changes. Additionally, the vegetation coverage index was included in the study as a key indicator of natural factors. Finally, to conduct an effective spatial analysis, the independent variables were reclassified into nine different categories using the natural breaks method, and a 1 km resolution grid system was established. Sampling was conducted at the center point of each grid to ensure data representativeness and accuracy in the analysis.

2.3.4. Ecological Contribution Rate

The ecological contribution rate acts as a crucial indicator for evaluating the effects of land use changes on regional habitat quality. This study identified the primary land use transfer processes for representative years, aiming to accurately assess the specific impact of land use changes on habitat quality through quantitative analysis methods [29]. Equation (4) is as follows:

$$R_{ij} = \frac{(H_i - H_j) S_i}{S_t} \tag{4}$$

where R_{ij} represents the ecological contribution rate when land use type *i* is converted to land use type *j*. *H* represents the habitat quality variable. S_i is the area involved in the land use change, while S_j is the total area of the study region.

3. Results

3.1. Land Use Changes

Between 2000 and 2020, land use transformations across the different national parks exhibited different trends and characteristics (Figure 2). First, data from Three-River-Source National Park show a significant reduction in grassland and water areas, particularly due to their conversion to unused land. Specifically, 1520.22 square kilometers of grassland and 140.12 square kilometers of water areas were converted into unused land. Meanwhile, forestland remained relatively stable, with only a small portion converted to other land types. The growth in construction land was relatively small. In the Giant Panda National Park, the main land use change involved the conversion of forest and grassland to unused land, with 70.60 square kilometers of forest and 21.76 square kilometers of grassland being transformed into unused land. Cultivated land also showed a trend of conversion to forest and grassland, with 131.06 square kilometers and 119.61 square kilometers being converted, respectively. Although the construction land area was small, 35.74 square kilometers were derived from the conversion of grassland. In the Northeast China Tiger and Leopard National Park, land use changes were mainly characterized through the conversion of grassland and cultivated land into forestland, with forestland significantly expanding. The area of grassland converted to forest reached 116.21 square kilometers, and the conversion of cultivated land to grassland was also documented, covering an area of 44.62 square kilometers. Construction land increased by 5.12 square kilometers, while the area of unused land grew by 31.31 square kilometers in the National Park of Hainan Tropical Rainforest, and use changes were marked by the transition of grassland and

cultivated land into forestland, with 42.94 square kilometers of grassland and 5.08 square kilometers of cultivated land converted to forestland. Construction land increased by 0.701 square kilometers, while the water area significantly increased by 27.66 square kilometers. Finally, land use analysis in Wuyishan National Park shows that, as the largest land type within the park, forestland remained stable in the area over the 20 years. The transformation of grassland and cultivated land into forestland was substantial, with 5.71 square kilometers and 3.47 square kilometers converted, respectively. Construction land increased by 0.11 square kilometers.

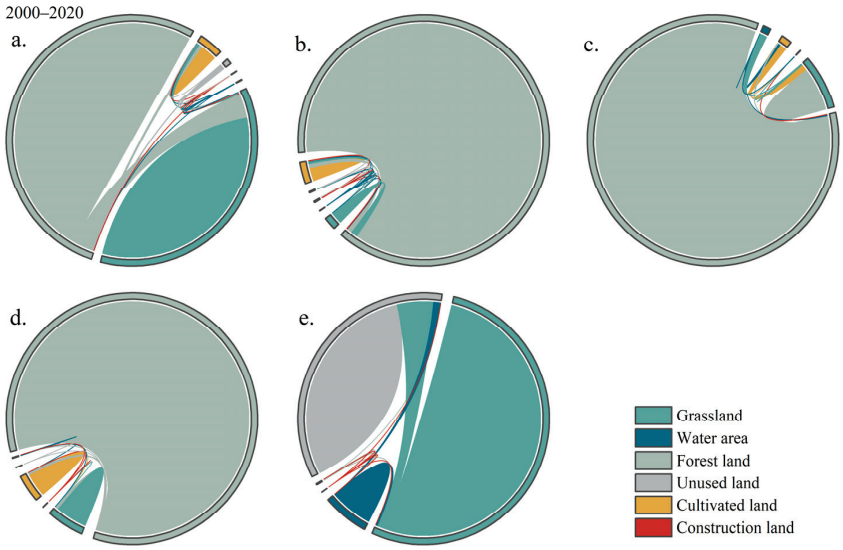


Figure 2. Land use transitions in the national parks between 2000 and 2020: (**a**) Giant Panda National Park, (**b**) National Park of Hainan Tropical Rainforest, (**c**) Northeast China Tiger and Leopard National Park, (**d**) Wuyishan National Park, and (**e**) Three-River-Source National Park.

3.2. Habitat Quality Changes

The habitat quality index serves to evaluate the ecological health and biodiversity of biological habitats within a specific area. A rise in the index signifies an improvement in the ecological environment and a boost in ecosystem services. Conversely, if the index declines, it indicates that the habitat may be under degradation pressure and biodiversity may be at risk of loss. Analysis of the habitat quality index in various national parks from 2000 to 2020 reveals notable differences in habitat quality changes across the parks. The ranking of habitat quality from highest to lowest is as follows: Wuyishan, Giant Panda, Hainan Tropical Rainforest, Northeast China Tiger and Leopard, and Three-River-Source. Specifically, the habitat quality index of Three-River-Source National Park increased from 0.2032 in 2000 to 0.2725 in 2020, showing an improvement trend, with a change rate of 34.10%. However, the habitat quality index of the Giant Panda National Park decreased from 0.6107 in 2000 to 0.5145 in 2020, with a change rate of −15.75%. This indicates that, despite the Giant Panda' status as a flagship species attracting widespread attention, its habitat continues to face ongoing degradation pressure. The Northeast China Tiger and Leopard National Park faces similar issues, with its habitat quality index decreasing from 0.3544 in 2000 to 0.303 in 2020, showing a change rate of −14.50%. The habitat quality index of the National Park of Hainan Tropical Rainforest also shows a declining trend, dropping from 0.5402 in 2000 to 0.4651 in 2020, with a change rate of −13.90%. In contrast, Wuyishan National Park's habitat quality index remained relatively stable, slightly increasing from 0.8031 in 2000 to 0.8255 in 2020, with a change rate of 2.79%. This slight positive change

suggests that the measures taken in habitat protection and management in Wuyishan National Park have effectively maintained its habitat quality (Figure 3).

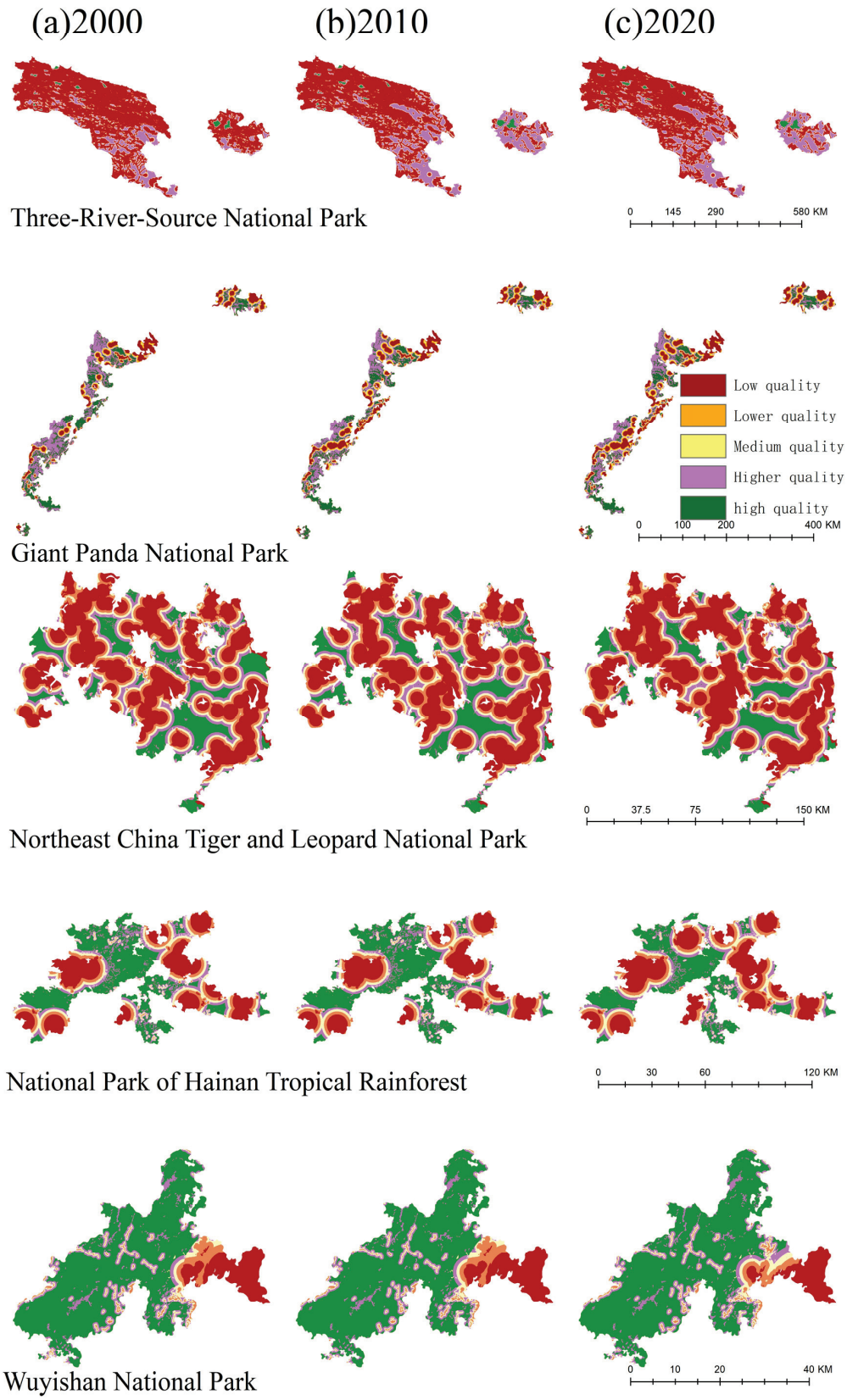


Figure 3. Habitat quality index.

3.3. Ecological Contribution Rate Analysis

In the ecological contribution rate analysis of Three-River-Source National Park, the conversion of unused land to grassland greatly enhanced habitat quality, with an ecological improvement rate reaching 0.4891, and an improvement ratio as high as 87.44%. However, the transformation of grassland into construction land and water areas, particularly to unused land, led to an ecological degradation rate of 0.4535 and a degradation ratio of 88.94%. The ecological contribution analysis of the Giant Panda National Park revealed a significant positive impact of grassland conversion to forestland on habitat quality, with an ecological improvement rate of 0.0463, accounting for 30.24% of the total improvement rate. Furthermore, the transformation of cultivated land into grassland also positively contributed to habitat quality, with an ecological improvement rate of 0.0400 and an improvement ratio of 26.14%. Similarly, the transformation of cultivated land into forestland also resulted in notable ecological benefits, with an ecological improvement rate of 0.05 and an improvement ratio of 32.64%. However, the transformation of forestland into unused land, grassland, and cultivated land led to an increase in ecological degradation rates, highlighting the need to strengthen forest resource protection. The ecological contribution rate analysis of the Northeast China Tiger and Leopard National Park indicated that the conversion of cultivated land to grassland significantly enhanced habitat quality, with an ecological improvement rate of 0.0687 and an improvement ratio of 24.39%. The transformation of cultivated land into forestland had an even more significant impact on habitat quality, with an ecological improvement rate of 0.1417 and an improvement ratio as high as 50.29%. However, the transformation of forestland into cultivated land caused a significant rise in the ecological degradation rate, reaching 0.1322, with a degradation ratio of 44.74%. Additionally, the transformation of forestland into unused land also led to an increase in the ecological degradation rate, reaching 0.0877, with a degradation ratio of 29.66%. The ecological contribution rate data analysis of the National Park of Hainan Tropical Rainforest shows that the transformation of cultivated land into water areas significantly contributed to ecological improvement, with an improvement rate as high as 0.0644 and an improvement ratio reaching 43.58%. Conversely, the transformation of forestland into cultivated land led to an increase in the ecological degradation rate, reaching 0.0397 with a degradation ratio of 26.21%. The ecological contribution rate analysis of Wuyishan National Park revealed that the shift from cultivated land to forestland significantly contributed to the improvement of habitat quality, with an ecological improvement rate of 0.0016 and an improvement ratio as high as 76.98%. However, the transformation of forestland into cultivated land led to a significant increase in the ecological degradation rate, reaching 0.0016 with a degradation ratio of 77.25% (Table 4).

Table 4. Ecological contribution rate with a change ratio greater than 1%.

Park	Habitat Quality Improvement			Habitat Quality Degradation		
	Land Transfer	Ecological Improvement Rate	Improvement Ratio	Land Transfer	Ecological Degradation Rate	Degradation Ratio
A	Unused land–grassland	0.48916848	87.44%	Grassland–water area	0.02481455	4.87%
	Unused land–water area	0.06852983	12.25%	Grassland–unused land	0.45352277	88.94%
				Water area–unused land	0.03046454	5.97%
B	Grassland–forestland	0.04629466	30.24%	Grassland–unused land	0.01214093	6.27%
	Cultivated land–grassland	0.04000931	26.14%	Grassland–cultivated land	0.03030709	15.66%
	Cultivated land–forestland	0.04995730	32.64%	Grassland–construction land	0.01757371	9.08%
	Cultivated land–water area	0.00153009	1.00%	Forestland–grassland	0.04179281	21.59%
	Unused land–grassland	0.00578440	3.78%	Forestland–cultivated land	0.04230286	21.86%
	Unused land–forestland	0.00840298	5.49%	Forestland–unused land	0.04339528	22.42%

Table 4. *Cont.*

Park	Habitat Quality Improvement			Habitat Quality Degradation		
	Land Transfer	Ecological Improvement Rate	Improvement Ratio	Land Transfer	Ecological Degradation Rate	Degradation Ratio
C	Grassland–forestland	0.02498093	8.86%	Grassland–cultivated land	0.01230034	4.16%
	Cultivated land–grassland	0.06874652	24.39%	Grassland–unused land	0.00577923	1.96%
	Cultivated land–forestland	0.14174170	50.29%	Cultivated land–unused land	0.00410586	1.39%
	Cultivated land–water area	0.00874700	3.10%	Forestland–grassland	0.02663169	9.01%
	Construction land–forestland	0.00597095	2.12%	Forestland–cultivated land	0.13223611	44.74%
	Unused land–forestland	0.01001952	3.56%	Forestland–construction land	0.01628809	5.51%
	Unused land–water area	0.01400359	4.97%	Forestland–water area	0.00622502	2.11%
				Forestland–unused land	0.08767904	29.66%
D	Grassland–forestland	0.03982471	26.93%	Grassland–cultivated land	0.00388572	2.56%
	Cultivated land–forestland	0.03849131	26.03%	Grassland–water area	0.03378103	22.29%
	Cultivated land–water area	0.06445495	43.58%	Forestland–grassland	0.03340347	22.04%
	Water area–forestland	0.00236062	1.60%	Forestland–cultivated land	0.03972335	26.21%
				Forestland–construction land	0.01520831	10.03%
				Forestland–water area	0.02388200	15.76%
E	Grassland–forestland	0.00032951	15.49%	Grassland–cultivated land	0.00009839	4.70%
	Cultivated land–grassland	0.00009266	4.36%	Forestland–grassland	0.00032933	15.74%
	Cultivated land–forestland	0.00163777	76.98%	Forestland–cultivated land	0.00161598	77.25%
	Cultivated land–water area	0.00004312	2.03%			

The letters in the table represent the following national parks: A: Three-River-Source National Park; B: Giant Panda National Park; C: Northeast China Tiger and Leopard National Park; D: National Park of Hainan Tropical Rainforest; E: Wuyishan National Park.

3.4. Analysis of the Driving Forces of Habitat Quality

In the habitat quality analysis of Three-River-Source National Park, single-factor detection revealed NDVI, land use, and precipitation as the three key natural factors, with NDVI leading with an explanatory power of 0.2495, followed closely by land use and precipitation at 0.2415 and 0.2414, respectively. Although the impacts of temperature, elevation, population density, and slope were smaller, their roles in the ecosystem cannot be overlooked. Overall, natural factors are vital in shaping the spatial distribution of habitat quality, while socioeconomic factors, particularly GDP, also exert a substantial influence on habitat quality. The habitat quality analysis of Giant Panda National Park identified population density, elevation, and precipitation as significant influencing factors, with population density having the most significant impact at 0.1031, followed by elevation and precipitation. This suggests that natural factors are the primary drivers of spatial variations in habitat quality, but the contribution of population density to habitat quality cannot be overlooked. The analysis of the Northeast China Tiger and Leopard National Park found that temperature, population density, and elevation was one of the key factors influencing habitat quality, with temperature having the most significant impact at 0.0566. Precipitation and NDVI also had significant impacts on habitat quality, with influence values of 0.0330 and 0.0260, respectively. The results for the National Park of Hainan Tropical Rainforest showed that elevation had a strong explanatory power on habitat quality, with an impact value of 0.0623, highlighting the importance of topographical features on its ecosystem. Temperature and GDP also had significant impacts on habitat quality, with influence values of 0.0524 and 0.0423, respectively. This indicates that natural factors, particularly elevation and temperature, underpin the spatial differences in habitat quality. The habitat quality analysis of Wuyishan National Park showed that temperature, precipitation, and elevation were the main natural factors affecting habitat quality, with temperature leading to an influence value of 0.6696. This indicates that in Wuyishan National Park, natural factors, such as temperature and precipitation, are essential for analyzing the factors influencing habitat quality (Figure 4).

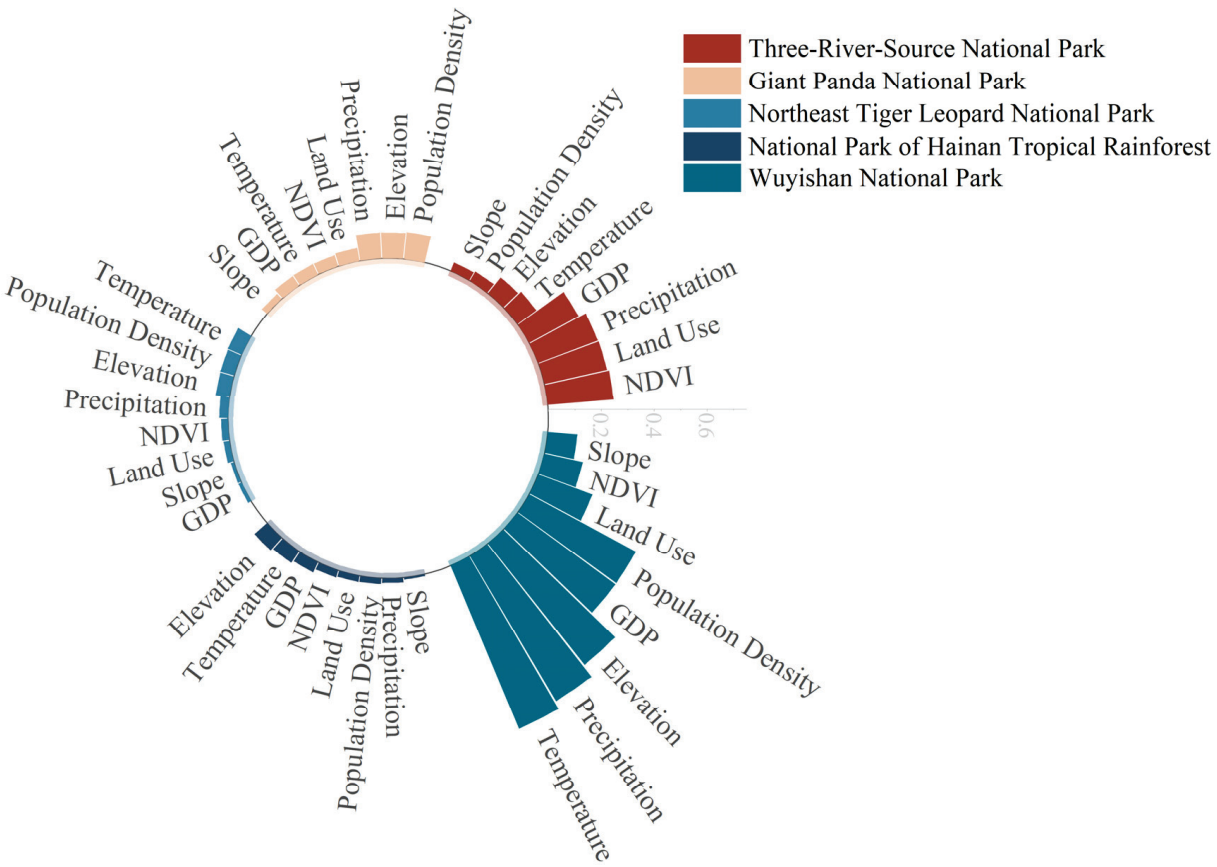


Figure 4. Drivers of habitat quality.

The interactive detector results from the geographic detector analysis reveal distinct spatial patterns of habitat quality drivers across the five national parks (Table 5). In Wuyishan National Park, the interactions are between GDP and precipitation (0.7353) and GDP and temperature (0.7603), reflecting the significant interplay between socioeconomic factors and climatic variables. Similarly, land use exhibits a high interaction strength with precipitation (0.7343) and temperature (0.7724), suggesting that land use dynamics are heavily influenced by temperature and precipitation patterns in this region. In contrast, Three-River-Source National Park shows moderate interaction values, with precipitation and land use (0.3742) and NDVI and land use (0.3523) being key contributors to habitat quality, indicating the importance of climate and vegetation factors in this alpine ecosystem. Giant Panda National Park exhibits relatively weaker interactions, with slope and precipitation (0.2465) and precipitation and temperature (0.2544) being notable, highlighting the role of topography and rainfall in shaping habitat quality. The Northeast China Tiger and Leopard National Park demonstrates the weakest interactions overall, with most values below 0.2, emphasizing simpler ecological relationships dominated by natural factors, like precipitation and temperature. Finally, in the National Park of Hainan Tropical Rainforest, interactions between GDP and precipitation (0.1994) and precipitation and temperature (0.1997) underscore the significance of economic activities and climatic variables in this tropical ecosystem.

Table 5. Interaction detector form.

	Driving Factors	DEM	Slope	Precipitation	Temperature	NDVI	Population	GDP	Land Use
A	DEM	0.0759							
	Slope	0.1919	0.0342						
	Precipitation	0.3218	0.2966	0.2414					
	Temperature	0.2188	0.1786	0.3105	0.0881				
	NDVI	0.3104	0.3079	0.3537	0.2978	0.2495			
	Population	0.1117	0.0731	0.2627	0.1334	0.2783	0.0400		
	GDP	0.3177	0.2423	0.3441	0.2955	0.3385	0.2325	0.2117	
	Land use	0.3087	0.2689	0.3742	0.3051	0.3523	0.2628	0.3024	0.2415
B	DEM	0.0990							
	Slope	0.2764	0.0257						
	Precipitation	0.2860	0.2465	0.0983					
	Temperature	0.1517	0.1849	0.2544	0.0436				
	NDVI	0.1993	0.1479	0.2195	0.1741	0.0440			
	Population	0.1865	0.1621	0.2442	0.1361	0.1555	0.1031		
	GDP	0.2401	0.2119	0.2130	0.1991	0.1625	0.1980	0.0424	
	Land use	0.1524	0.0818	0.1637	0.1218	0.1022	0.1372	0.1058	0.0491
C	DEM	0.0530							
	Slope	0.1094	0.0135						
	Precipitation	0.1594	0.0859	0.0330					
	Temperature	0.1115	0.1083	0.2041	0.0566				
	NDVI	0.0903	0.0516	0.0756	0.1056	0.0260			
	Population	0.1059	0.0795	0.1207	0.1397	0.0702	0.0541		
	GDP	0.0861	0.0474	0.0799	0.1007	0.0545	0.0788	0.0127	
	Land use	0.0727	0.0366	0.0557	0.0797	0.0422	0.0734	0.0361	0.0233
D	DEM	0.0623							
	Slope	0.1860	0.0074						
	Precipitation	0.1890	0.1637	0.0176					
	Temperature	0.1426	0.1747	0.1997	0.0524				
	NDVI	0.1603	0.1246	0.1828	0.1534	0.0280			
	Population	0.1388	0.0998	0.1591	0.1366	0.1073	0.0215		
	GDP	0.2092	0.1653	0.1994	0.1951	0.1355	0.1406	0.0423	
	Land use	0.0920	0.0580	0.0535	0.0755	0.0593	0.0638	0.0757	0.0234
E	DEM	0.5877							
	Slope	0.6181	0.1122						
	Precipitation	0.6616	0.6769	0.6395					
	Temperature	0.6859	0.7013	0.6748	0.6696				
	NDVI	0.6467	0.3321	0.6781	0.7078	0.1488			
	Population	0.6363	0.4862	0.6638	0.6910	0.5272	0.4585		
	GDP	0.7287	0.5031	0.7353	0.7603	0.5519	0.6195	0.4590	
	Land use	0.6753	0.2853	0.7343	0.7724	0.3415	0.5601	0.5413	0.2184

The letters in the table represent the following national parks: A: Three-River-Source National Park; B: Giant Panda National Park; C: Northeast China Tiger and Leopard National Park; D: National Park of Hainan Tropical Rainforest; E: Wuyishan National Park.

4. Discussion

4.1. Habitat Quality Changes in National Parks

The analysis of the habitat degradation indices shows that the degradation indices of the Giant Panda, Northeast China Tiger and Leopard, and Hainan Tropical Rainforest National Parks have increased, indicating that these areas are facing pressures of habitat quality degradation. Furthermore, the analysis of habitat quality indices reveals differences in the habitat quality indices across the parks. Wuyishan National Park's habitat quality index has remained stable, while Three-River-Source National Park has experienced significant improvements in habitat quality. Research by the scholars Wang Hongjie [30], Liu Lanyue [31], and others indicates that between 2000 and 2010, the habitat quality for

wildlife habitats in the Three-River-Source area remained at a relatively high level in most regions, with little overall change in quality. The average quality index in this region was about 0.6, with a slight increase of 0.27% in 2010 compared to 2000. In Wuyishan, during the period from 2010 to 2020, the proportion of areas rated as having high habitat quality decreased from 95.43% to 88.92%. Meanwhile, the share of areas with moderate habitat quality increased from 3.67% to 9.54%. Nonetheless, the overall habitat quality in Wuyishan has consistently remained at a relatively high level, reflecting the positive results of ecological protection measures in recent years. Research by the scholars Hu Lu [32], Zhang Bin [33], Lei Jinrui [34], and others indicates a rising level of habitat degradation in the Giant Panda reserves, as the average habitat degradation index grew from 0.018 in 2000 to 0.022 in 2020. The SDG 15.1.2 indicator score for the Northeast China Tiger and Leopard National Park has consistently been above 50%, belonging to the highest grade, but the score shows a declining trend. On Hainan Island, between 1980 and 2020, the overall rate of habitat quality change across the three major river basins declined by 0.5%, with degradation being more pronounced, especially between 2010 and 2020.

4.2. Attribution of Habitat Quality in National Parks

The analysis of ecological contribution rates reveals the close relationship between habitat quality and land use patterns. Alterations in land use types, whether in proportion, structure, or intensity, have profoundly reshaped the composition and distribution of ecosystems, thereby affecting the diversity of habitat quality. Different land use types have varying impacts on the suitability of biological organisms [9,10]. Forest ecosystems provide rich living spaces for plants and animals, while wetland ecosystems offer critical habitats for aquatic organisms. However, the presence of construction land limits the living conditions for plants and animals. Additionally, the diversity of land use types also impacts local climate, microtopography, and soil conditions, which in turn affect the exchange of materials and energy between habitat patches, exacerbating differences in habitat suitability. Research by the scholars Zhu Zengyun [35] and Yang Jie [36] supports this view. Furthermore, this paper uses geographical detector analysis to reveal the significant impact of natural and socioeconomic factors on habitat quality. The results show that natural factors are crucial in determining the spatial distribution of habitat quality, while socioeconomic factors, particularly population density, are becoming increasingly significant in terms of their impact on habitat quality. For example, research by the scholar Dong Xin [37] and others shows that natural factors are the key drivers of ecological changes in Sichuan's Giant Panda National Park, followed by human factors. The contribution of each natural factor is ranked as follows: NDVI > dryness index > humidity factor > elevation > land use > temperature, with NDVI showing strong interactions with other factors. The main influencing factors differ among the various national parks and are related to their geographical location, climatic conditions, and patterns of human activity. As determined through in-depth analysis, the evolution of land use is a significant indicator of socioeconomic progress. This evolution directly influences habitat quality, while human activities indirectly impact it by modifying land use patterns. In light of this, it is necessary to adopt a socioecological systems perspective to explore land use changes and their impact on socioeconomic development and habitat quality [38,39]. The research revealed that land use changes in each national park exhibit distinct regional characteristics. In Three-River-Source National Park, the reduction in grassland and water areas is particularly significant. In contrast, Giant Panda National Park faces the challenge of forest and grassland being converted into unused land. Land use changes in Northeast China Tiger and Leopard National Park are primarily characterized by the transformation of grassland and agricultural

land into forests, suggesting a trend toward ecological restoration. Similarly, in Hainan Tropical Rainforest National Park, land use changes are marked by the shift from grassland and cultivated land to forested areas. Finally, the forestland in Wuyishan National Park has remained stable, demonstrating effective land management. The analysis suggests that in the early 21st century, with the acceleration of urbanization and the continuous advancement of socioeconomic activities, surface cover types across different regions of China underwent significant transformations, leading to profound changes in the spatial distribution patterns of surface landscapes. These changes have not only reshaped the appearance of the Earth's surface but have also had a broad and profound impact on the evolution and development of the Earth's surface system [40,41]. However, in recent years, the emphasis on ecological civilization construction has increased, and stricter control measures have been implemented for activities that may damage the ecological environment, such as land reclamation and deforestation [42].

4.3. Deficiencies and Prospects

This study provides valuable insights into the spatial and temporal evolution of habitat quality in China's first national parks; however, it has certain limitations. First, while the habitat quality module of the InVEST model was effective in assessing habitat quality, the model primarily focused on changes in habitat quality and did not comprehensively encompass all critical dimensions of ecosystem health, such as ecosystem productivity, carrying capacity, and resilience. Regarding habitat quality measurement, although the model captured the trends in habitat quality change with reasonable accuracy, the parameter settings (e.g., threat source selection, impact distance, weight, habitat suitability, and sensitivity) were influenced by subjective judgments of the researchers. This subjectivity may have impacted the accuracy of the assessment results.

While this study provides an in-depth analysis of habitat quality and its driving factors in five national parks, future research could explore the integration of these factors at a national scale. Such an approach would offer more comprehensive insights to support policy management and ecological conservation strategies across China. However, this requires extensive data collection and modelling to account for the variability in ecological, climatic, and socioeconomic conditions nationwide.

Building upon the findings and limitations of this study, future research will focus on optimizing the InVEST model through field data integration to enhance parameter calibration. Expanding the spatial scope to a national level will allow for a more comprehensive understanding of habitat quality dynamics across diverse regions. Additionally, incorporating broader ecosystem health indicators, such as resilience and productivity, will provide a more holistic perspective. Finally, advanced temporal and statistical analysis methods will be employed to capture both short-term and long-term changes, offering deeper insights into the mechanisms driving habitat quality dynamics.

5. Conclusions

In China's first batch of national parks, a general trend of converting grassland and cultivated land into forestland was observed from 2000 to 2020. Additionally, an increase in unused land area is a common feature among these parks. Furthermore, construction land has increased in all the national parks, but the extent of this growth has been relatively imited.

Over the 20 years, the habitat quality of Three-River-Source and Wuyishan significantly improved. In contrast, other parks showed a declining trend. Wuyishan National Park's habitat quality has consistently remained high, with only minor fluctuations and a

slight upward trend. Despite the high proportion of unused land in Three-River-Source National Park, resulting in the lowest habitat quality ranking among the five national parks, it achieved a significant improvement in habitat quality, with a growth rate of 34.10%, primarily resulting from the transformation of unused land into grassland. On the other hand, Giant Panda National Park showed the highest degradation rate at 39.65%, with population density being a key contributing factor. The Northeast China Tiger and Leopard National Park also faced significant habitat degradation, with a degradation rate of 20.53%. In comparison, the National Park of Hainan Tropical Rainforest had a slower habitat degradation rate of 12.24%. Natural factors are essential in shaping the habitat quality of all national parks. However, in Giant Panda National Park and the Northeast China Tiger and Leopard National Park, socioeconomic factors, particularly population density, also exert a major influence on habitat quality. The analysis of ecological contribution rates further reveals that cultivated land is the main factor contributing to habitat degradation in most national parks. Moreover, while construction land constitutes a small portion of the total area in each national park, its contribution to habitat degradation has steadily increased over the past 20 years, highlighting the need for further attention.

Based on the above analysis, it is recommended that each national park adopt targeted ecological protection and management measures. For instance, Three-River-Source National Park should reduce the conversion of grassland to unused land and promote the natural restoration of unused land. Giant Panda National Park should focus on protecting forestland and grassland areas while strengthening the protection of forest resources. The Northeast China Tiger and Leopard National Park should emphasize the protection and restoration of forestland and grassland. The National Park of Hainan Tropical Rainforest should prioritize the protection and restoration of its forest and aquatic ecosystems. Wuyishan National Park should continue to maintain the stability of its forestland.

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References

1. Liu, M.Z.; Zhang, H.J.; Wang, Y.F.; Pei, H.W. Characteristics of Habitat Quality in the Agro-Pastoral Ecotone of Northern China Based on Land Uses. *Soil Water Conserv. Res.* **2021**, *28*, 156–162. [CrossRef]
2. Gong, J.; Xie, Y.; Cao, E.; Huang, Q.; Li, H. Integration of InVEST-Habitat Quality Model with Landscape Pattern Indexes to Assess Mountain Plant Biodiversity Change: A Case Study of Bailongjiang Watershed in Gansu Province. *J. Geogr. Sci.* **2019**, *29*, 1193–1210. [CrossRef]
3. Zhong, L.; Wang, J. Evaluation on Effect of Land Consolidation on Habitat Quality Based on InVEST Model. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 250–255. [CrossRef]
4. Newbold, T.; Hudson, L.N.; Hill, S.L.L.; Contu, S.; Lysenko, I.; Senior, R.A.; Börger, L.; Bennett, D.J.; Choimes, A.; Collen, B.; et al. Global Effects of Land Use on Local Terrestrial Biodiversity. *Nature* **2015**, *520*, 45–50. [CrossRef] [PubMed]
5. Nie, Y.; Zhang, X.; Yang, Y.; Liu, Z.; He, C.; Chen, X.; Lu, T. Assessing the Impacts of Historical and Future Land-Use/Cover Change on Habitat Quality in the Urbanizing Lhasa River Basin on the Tibetan Plateau. *Ecol. Indic.* **2023**, *148*, 110147. [CrossRef]

6. Mengist, W.; Soromessa, T.; Feyisa, G.L. Landscape Change Effects on Habitat Quality in a Forest Biosphere Reserve: Implications for the Conservation of Native Habitats. *J. Clean. Prod.* **2021**, *329*, 129778. [CrossRef]
7. Li, J.; Hu, J.; Luo, H.; Jia, H. Interference Intensity of Human Activities on Wintering Habitats of Black-Necked Crane in Napahai Wetlands and Their Patterns. *Wetl. Sci.* **2017**, *15*, 343–350. [CrossRef]
8. Yang, H.; Huang, Q.; Zhang, J.; Songer, M.; Liu, J. Range-Wide Assessment of the Impact of China's Nature Reserves on Giant Panda Habitat Quality. *Sci. Total Environ.* **2021**, *769*, 145081. [CrossRef] [PubMed]
9. Zhang, L.; Yuan, Z.; Bi, J.; Zhang, B.; Liu, B. Eco-Industrial Parks: National Pilot Practices in China. *J. Clean. Prod.* **2010**, *18*, 504–509. [CrossRef]
10. He, S.; Jiao, W. Adapting Traditional Industries to National Park Management: A Conceptual Framework and Insights from Two Chinese Cases. *J. Clean. Prod.* **2022**, *367*, 133007. [CrossRef]
11. Wei, B.; Wang, R.; Hou, K.; Wang, X.; Wu, W. Predicting the Current and Future Cultivation Regions of *Carthamus tinctorius* L. Using MaxEnt Model under Climate Change in China. *Glob. Ecol. Conserv.* **2018**, *16*, e00477. [CrossRef]
12. Yang, D.; Liu, W.; Tang, L.; Chen, L.; Li, X.; Xu, X. Estimation of Water Provision Service for Monsoon Catchments of South China: Applicability of the InVEST Model. *Landsc. Urban Plan.* **2019**, *182*, 133–143. [CrossRef]
13. Noilhan, J.; Planton, S. A Simple Parameterization of Land Surface Processes for Meteorological Models. *Mon. Weather. Rev.* **1989**, *117*, 536–549. [CrossRef]
14. Li, M.; Liang, D.; Xia, J.; Song, J.; Cheng, D.; Wu, J.; Cao, Y.; Sun, H.; Li, Q. Evaluation of Water Conservation Function of Danjiang River Basin in Qinling Mountains, China Based on InVEST Model. *J. Environ. Manag.* **2021**, *286*, 112212. [CrossRef] [PubMed]
15. Caro, C.; Marques, J.C.; Cunha, P.P.; Teixeira, Z. Ecosystem Services as a Resilience Descriptor in Habitat Risk Assessment Using the InVEST Model. *Ecol. Indic.* **2020**, *115*, 106426. [CrossRef]
16. Babbar, D.; Areendran, G.; Sahana, M.; Sarma, K.; Raj, K.; Sivadas, A. Assessment and Prediction of Carbon Sequestration Using Markov Chain and InVEST Model in Sariska Tiger Reserve, India. *J. Clean. Prod.* **2021**, *278*, 123333. [CrossRef]
17. Gashaw, T.; Bantider, A.; Zeleke, G.; Alamirew, T.; Jemberu, W.; Worqlul, A.W.; Dile, Y.T.; Bewket, W.; Meshesha, D.T.; Adem, A.A.; et al. Evaluating InVEST Model for Estimating Soil Loss and Sediment Export in Data Scarce Regions of the Abbay (Upper Blue Nile) Basin: Implications for Land Managers. *Environ. Chall.* **2021**, *5*, 100381. [CrossRef]
18. Chen, S.; Jin, Y.; Hu, Y. Spatio-Temporal Variations of Habitat Quality and Its Underlying Mechanism in the Central Region of Yangtze River Delta. *Chin. J. Ecol.* **2023**, *42*, 1175. [CrossRef]
19. Huang, E.; Chen, Y.; Fang, M.; Zheng, Y.; Yu, S. Environmental Drivers of Plant Distributions at Global and Regional Scales. *Glob. Ecol. Biogeogr.* **2021**, *30*, 697–709. [CrossRef]
20. Wang, Q.; Kang, Q.; Zhao, B.; Li, H.; Lu, H.; Liu, J.; Yan, C. Effect of Land-Use and Land-Cover Change on Mangrove Soil Carbon Fraction and Metal Pollution Risk in Zhangjiang Estuary, China. *Sci. Total Environ.* **2022**, *807*, 150973. [CrossRef]
21. Liu, S.; Li, X.; Chen, D.; Duan, Y.; Ji, H.; Zhang, L.; Chai, Q.; Hu, X. Understanding Land Use/Land Cover Dynamics and Impacts of Human Activities in the Mekong Delta over the Last 40 Years. *Glob. Ecol. Conserv.* **2020**, *22*, e00991. [CrossRef]
22. Bucała, A. The Impact of Human Activities on Land Use and Land Cover Changes and Environmental Processes in the Gorce Mountains (Western Polish Carpathians) in the Past 50 Years. *J. Environ. Manag.* **2014**, *138*, 4–14. [CrossRef]
23. Otto, C.R.; Roth, C.L.; Carlson, B.L.; Smart, M.D. Land-Use Change Reduces Habitat Suitability for Supporting Managed Honey Bee Colonies in the Northern Great Plains. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 10430–10435. [CrossRef] [PubMed]
24. Wei, W.; Shi, S.; Zhang, X.; Zhou, L.; Xie, B.; Zhou, J.; Li, C. Regional-Scale Assessment of Environmental Vulnerability in an Arid Inland Basin. *Ecol. Indic.* **2020**, *109*, 105792. [CrossRef]
25. Wei, Q.; Abudureheman, M.; Halike, A.; Yao, K.; Yao, L.; Tang, H.; Tuheti, B. Temporal and Spatial Variation Analysis of Habitat Quality on the PLUS-InVEST Model for Ebinur Lake Basin, China. *Ecol. Indic.* **2022**, *145*, 109632. [CrossRef]
26. Chen, Y.; Qiao, F.; Jiang, L. Effects of Land Use Pattern Change on Regional Scale Habitat Quality Based on InVEST Model—A Case Study in Beijing. *Acta Sci. Nat. Univ. Pekin.* **2016**, *52*, 553–562. [CrossRef]
27. Nelson, E.; Mendoza, G.; Regetz, J.; Polasky, S.; Tallis, H.; Cameron, D.R.; Chan, K.M.; Daily, G.C.; Goldstein, J.; Kareiva, P.M. Modeling Multiple Ecosystem Services, Biodiversity Conservation, Commodity Production, and Tradeoffs at Landscape Scales. *Front. Ecol. Environ.* **2009**, *7*, 4–11. [CrossRef]
28. Zhu, L.; Meng, J.; Zhu, L. Applying Geodetector to Disentangle the Contributions of Natural and Anthropogenic Factors to NDVI Variations in the Middle Reaches of the Heihe River Basin. *Ecol. Indic.* **2020**, *117*, 106545. [CrossRef]
29. Liu, Q.; Zhongyang, Y.; Yiqing, C.; Jinrui, L.; Zongzhu, C.; Xiaohua, C. Multi-Scenario Simulation of Land Use Change and Its Eco-Environmental Effect in Hainan Island Based on CA-Markov Model. *Ecol. Environ.* **2021**, *30*, 1522. [CrossRef]
30. Wang, H. Evaluation of the Ecological Quality for Sanjiangyuan Based on InVEST. *Value Eng.* **2016**, *35*, 66–70. [CrossRef]
31. Liu, L.; Zhang, P.; Wu, W.; Wang, J. Spatiotemporal Analysis of Habitat Quality in Wuyishan City Based on Integrated Valuation of Ecosystem Services and Trade-Offs Model. *Territ. Nat. Resour. Study* **2024**, *1*, 15–19. [CrossRef]

32. Hu, L.; Feng, B.; Bai, W.; Dong, X.; Xiao, Q.; Zhang, J.; Huang, Y.; Zhou, C. Spatiotemporal Variations of Habitat Quality in Protected Area of Giant Panda in Sichuan Province. *Chin. J. Ecol.* **2023**, *42*, 2204. [CrossRef]
33. Zhang, B. Evaluation for Biodiversity and Habitat Suitability Based on Remote Sensing at the Living Area of Amur Tiger (*Panthera tigris altaica*) and Amur Leopard (*Panthera pardus orientalis*). Master's Thesis, Jilin University, Changchun, China, 2024.
34. Lei, J.; Chen, Y.; Chen, Z.; Chen, X.; Wu, T.; Li, Y. Spatiotemporal Evolution of Habitat Quality in Three Basins of Hainan Island Based on InVEST Model. *Yingyong Shengtai Xuebao* **2022**, *33*, 1–10. [CrossRef]
35. Zhu, Z.; Alimujiang, K. Spatial-Temporal Evolution of Habitat Quality in Yili Valley Based on Geographical Detector and Its Influencing Factors. *Chin. J. Ecol.* **2020**, *39*, 3408. [CrossRef]
36. Yang, J.; Xie, B.; Zhang, D. Spatial-Temporal Evolution of Habitat Quality and Its Influencing Factors in the Yellow River Basin Based on InVEST Model and GeoDetector. *J. Desert Res.* **2021**, *41*, 12. [CrossRef]
37. Dong, X.; Chen, X.; Li, Y.; Gu, X.; Yang, C. Spatiotemporal Variation and Driving Forces of Ecological Environment of Giant Panda National Park in Sichuan Province Based on Geographical Detector. *Chin. J. Ecol.* **2023**, *42*, 946. [CrossRef]
38. Peng, J.; Lyu, D.; Dong, J.; Liu, Y.; Liu, Q.; Li, B. Processes Coupling and Spatial Integration: Characterizing Ecological Restoration of Territorial Space in View of Landscape Ecology. *J. Nat. Resour.* **2020**, *35*, 3–13. [CrossRef]
39. Yang, P.; Jiao, Z. Application of Coupling Method of Eco-Socioeconomic System in National Territory Spatial Ecological Restoration Planning System of Counties: A Case Study of Weiyuan County. *J. Nat. Resour.* **2021**, *36*, 2308–2319. [CrossRef]
40. Ma, L.J.; Lin, C. Development of Towns in China: A Case Study of Guangdong Province. *Popul. Dev. Rev.* **1993**, *19*, 583–606. [CrossRef]
41. Bishop, P. Long-Term Landscape Evolution: Linking Tectonics and Surface Processes. *Earth Surf. Process. Landf.* **2007**, *32*, 329–365. [CrossRef]
42. Xie, Z. China's Historical Evolution of Environmental Protection along with the Forty Years' Reform and Opening-Up. *Environ. Sci. Ecotechnol.* **2020**, *1*, 100001. [CrossRef]

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When to Use What: A Comparison of Three Approaches to Quantify Relationships Among Ecosystem Services

Zhen Zhong [1,†], Bochuan Zhou [2,†], Lingqiang Kong [3] and Xuening Fang [1,4,*]

[1] School of Environmental and Geographical Sciences, Shanghai Normal University, Shanghai 200234, China; 1000500356@smail.shnu.edu.cn
[2] School of Finance and Business, Shanghai Normal University, Shanghai 200234, China; 1000553566@smail.shnu.edu.cn
[3] School of Public Administration, Zhejiang University of Finance and Economics, Hangzhou 310018, China; lingqiang.kong@zufe.edu.cn
[4] Yangtze River Delta Urban Wetland Ecosystem National Field Scientific Observation and Research Station, Shanghai 200234, China
* Correspondence: fxn@shnu.edu.cn
† Co-first author of this work.

Abstract: Sustainable landscape management requires accurately identifying the trade-offs and synergies among ecosystem services (ES). Three commonly utilized approaches to quantify ES trade-off/synergy relationships include the space-for-time approach, landscape background-adjusted space-for-time approach, and temporal trend approach. However, the similarities and differences among these three approaches in identifying ES relationships in the same area remain unclear. Thus, we conducted a case study in the rapidly urbanizing Yangtze River Delta region, comparing the three approaches based on annual data spanning from 2001 to 2020 for 12 types of ES. We found that: (1) the ES trade-off/synergy relationships detected by the three approaches exhibit significant divergence, with only 1.45% consistency among the 66 pairs of ES relationships. (2) All three approaches can overlook ES trade-offs, miss ES synergies, and erroneously detect interactions where none exist. (3) The mechanisms contributing to the misidentification of ES relationships by the three approaches include: neglecting the underlying assumptions of different approaches, insufficient time interval length, short time series of ES data, data aggregation effects, non-linear changes in ESs, time lag effects of ES relationships, among others. Our results indicate that each of the three approaches has its own advantages and disadvantages in identifying ES relationships. Prior to selecting an approach for identifying relationships between ESs in a specific study area, careful consideration of the availability of time series data, the characteristics of the chosen ES type, and thorough examination of the underlying assumptions and uncertainties of each approach are imperative.

Keywords: space for time; landscape sustainability; ecosystem services; trade-offs; synergies

1. Introduction

Sustainable development requires landscapes to simultaneously provide multiple ecosystem services (ESs) to enhance human well-being [1–6]. However, different types of ES are not isolated but rather exhibit complex relationships with each other [7]. On one hand, there are "synergistic" relationships among ESs, where an increase in one ES leads to growth in several other ESs. On the other hand, there are "trade-off" relationships, where an increase in one ES results in a decrease in several other ESs [8,9]. The reasons behind

the trade-off or synergistic relationships among ESs are twofold: some types of ESs are directly linked, while others share common drivers [10]. Therefore, constructing sustainable landscapes requires accurately identifying the trade-offs and synergies among ESs to take effective measures to mitigate their negative tradeoffs and enhance their synergistic effects.

Currently, there are various approaches for identifying relationships among ESs. Among them, the most commonly used approach is spatial overlay analysis of different ES maps from a single time point [11–15]. This approach often calculates the spatial correlation of different ES types and judges whether there is a trade-off or synergy relationship between ESs based on the positive or negative correlation coefficient [16,17], or determines ESs that consistently co-occur in space through spatial clustering as synergy relationships [11]. The basic principle of these approaches is Space-for-time (SFT), initially applied in the field of ecology to address the lack of long-term observational data [18]. The assumption underlying the use of SFT approach to study ES trade-offs and synergies is the comparability of variability in ESs over time and space. This requires the initial conditions of all ESs to be homogeneous across the entire study area, and the driving factors causing changes in ESs to be consistent across the entire study area. However, research has shown that it is difficult to simultaneously meet these two conditions in large-scale ES studies [13], leading to potential misidentification of ES relationships.

Recently, many studies have highlighted the importance of considering temporal changes in identifying synergistic and trade-off relationships among ESs [13,19–21]. One such approach is the landscape Background Adjusted Space-For-Time method (referred to as BA-SFT). This approach involves spatially substituting time by analyzing the difference between the current ES values and historical landscape ES values. Its underlying assumption is that landscape history significantly influences the relationships among ESs [22]. For example, Shifaw et al. [23] estimated the changes in multiple ESs in the Upper Blue Nile Basin from 2000 to 2020. Results indicated that water yield, carbon sequestration, and soil retention primarily exhibited synergistic relationships, while habitat quality showed either no significant association with other ESs or trade-offs in some cases; Hu, et al. [24] assessed the variations in multiple ESs in Shanxi Province, China, from 2000 to 2020 and employed multiscale geographically weighted regression to identify the key drivers of ES changes; Wang et al. [25] mapped the spatial distribution of ES variations in the Sanjiangyuan region over the same period, revealing that most areas experienced simultaneous increases in provisioning and regulating ESs. Studies have shown that the BA-SFT approach, which considers landscape historical context, can mitigate some of the limitations of traditional SFT methods to some extent [13].

Additionally, with the development of remote sensing technology and Google Earth Engine, it has become possible to observe changes in ESs over long time series. Consequently, there has been a series of recent studies on the long-term temporal trends (TT) of ESs and their relationships. For instance, Liu, et al. [26] evaluated the impact of ecological policies on the long-term trends of ES using Inner Mongolia as a case study. Zhong, et al. [27] identified three linear and non-linear trends of ESs in the Yangtze River Delta (YRD) as an example. Qiu, Carpenter, Booth, Motew, Zipper, Kucharik, Loheide Ii, and Turner [21] explored changes in ES relationships at different scales based on future scenario data of ES. Temporal trend-based approaches often identify trade-offs and synergies among ESs by comparing the trends of various ESs [19]. If multiple ESs show the same increasing or decreasing trend over time, it indicates a synergistic relationship. Conversely, if one ES increases over time while another ES decreases, it indicates a trade-off relationship.

Currently, there are many case studies focusing on each of these approaches individually. However, it is not clear how the relationships between ESs identified by these

three approaches differ, what are the advantages and disadvantages of each approach, and in what scenarios each approach should be chosen. Various methods have been applied within the SFT, BA-SFT, and TT frameworks to reveal complex relationships between ESs. These include traditional approaches like correlation analysis [28,29] and newer techniques such as Bayesian Belief Networks [30], Structural Equation Modeling [31], and dynamic models [32]. However, compared to correlation analysis, these new methods are less widely applicable within the SFT, BA-SFT, and TT frameworks. They also focus more on modeling causal relationships and dynamic changes between ESs, rather than directly identifying the type of interaction (synergy or trade-off) between specific ESs.

To compare the advantages and disadvantages of SFT, BA-SFT, and TT, we adopt correlation analysis as a unified method. Using the rapidly urbanizing YRD as a case study, we identify the synergy or trade-off relationships between 12 ESs based on annual data from 2001 to 2020. The study aims to address three questions: (1) Are the relationships among ESs identified by the three approaches the same? (2) Do the three approaches have different characteristics in identifying the relationships among ESs? (3) How to determine which approach should be adopted to quantify the relationships among ESs under what conditions?

2. Materials and Methods

2.1. Study Area

The YRD region is located in the eastern coastal region of China (Figure 1), encompassing cities such as Shanghai, Suzhou, and Nanjing, with a total area of approximately 211,700 km^2 [27]. The climate characteristics of the YRD are mainly subtropical monsoon. The summers are hot and humid, with average temperatures ranging from 26 °C to 30 °C, and abundant rainfall, concentrated from June to August, accounting for 60% to 70% of the annual precipitation. Winters are relatively cold, with average temperatures ranging from 2 °C to 8 °C, and precipitation is relatively low, but often overcast and rainy. The terrain is predominantly flat, intersected by rivers such as the Yangtze and Huangpu Rivers. Soils consist mainly of alluvial and saline-alkali soils, conducive to crop cultivation. Major land use types in YRD include forests, croplands, urban land, and water bodies. The YRD is one of the most densely populated regions in China. Over the past few decades, this area has undergone rapid urbanization. While the rapid urbanization has greatly promoted the region's economic development, it has also triggered a series of negative impacts, such as urban heat island, air pollution, and water scarcity. Recently, addressing urban ecological and environmental problems through nature-based solutions has become a key focus of high-quality development in this region [33].

2.2. Data Acquisition and Pre-Processing

We followed the classification of the United Nations Millennium Ecosystem Assessment [34] and selected ecosystem services (ES) that encompass all four ES categories, considering their relevance to the YRD region and data availability [35,36]. The selected ESs include one supporting service (habitat quality), two provisioning services (crop production and water yield), nine regulating services (urban cooling, flood risk mitigation, soil conservation, water retention, air purification, nitrogen retention, phosphorus retention, and carbon sequestration), and one cultural service (outdoor recreation). All the above ES data was primarily sourced from publicly available datasets previously published by our team [27]. Detailed methods for calculating each ES type are provided in the Supplementary Materials, and are summarized in Table 1. Due to the fact that county-level administrative units serve as both crucial administrative entities for ES management and the smallest

units for available statistical data, this study selected county-level administrative units (n = 164) as the basic analysis units. Prior to calculating ES relationships, we aggregate all ES data at the raster scale into county-level administrative units and normalize them.

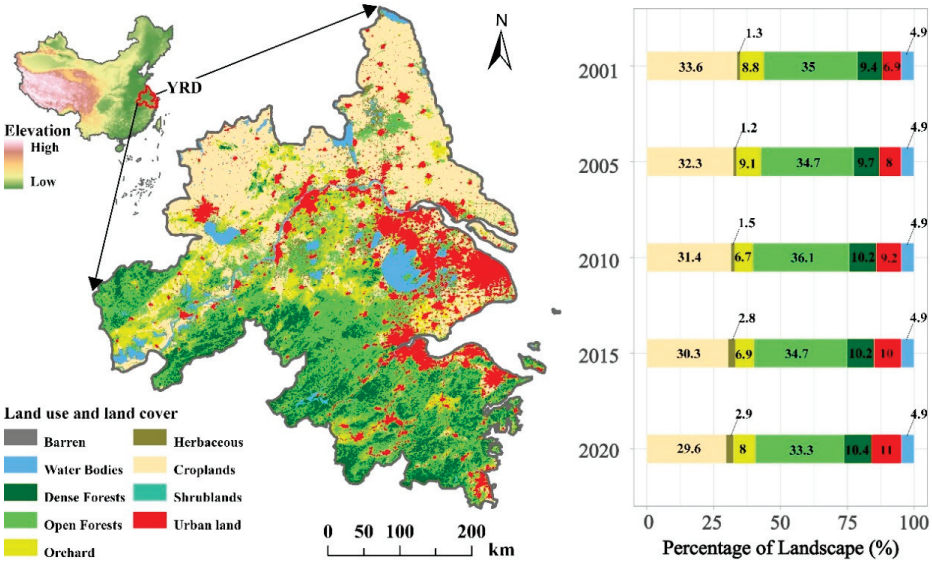


Figure 1. The location and land use/cover change of the study area.

Table 1. The selected ecosystem services, along with their descriptions and calculation methods.

Ecosystem Service Types	Description	Quantification Methods
1. Habitat quality	The ability of ecosystems to provide organisms with resources for survival and reproduction	InVEST
2. Crop production	Capacity of farmland to produce crop	[37]
3. Water yield	Capacity of ecosystems to provide freshwater	InVEST
4. Urban cooling	Capacity of ecosystems to reduce the urban heat island effect	Urban InVEST
5. Flood risk mitigation	Capacity of urban ecosystems to reduce urban flood risk	Urban InVEST
6. Soil conservation	Reduction in soil erosion due to the presence of vegetation	InVEST
7. Water retention	Available water retained by ecosystems	InVEST
8. Air purification	Amount of airborne pollutants absorbed by ecosystems.	[38]
9. Nitrogen retention	Amount of nitrogen pollutants prevented from entering runoff by ecosystems	InVEST
10. Phosphorus retention	Amount of phosphorus pollutants prevented from entering runoff by ecosystems	InVEST
11. Carbon sequestration	Amount of carbon dioxide fixed by ecosystems	[39]
12. Outdoor recreation	Opportunities for outdoor activities provided by ecosystems	[40]

2.3. Three Approaches for Calculating Ecosystem Service Trade-Offs and Synergies

2.3.1. Space-for-Time Approach

For the space-for-time (SFT) approach, we utilize the Spearman correlation analysis to identify the relationships among ESs [20]. Specifically, we select 164 county-level administrative units in the YRD as sample points for a particular year and compute the Spearman correlation coefficient between each pair of the 12 types of ESs. A significant negative correlation between two types of ESs indicates a trade-off relationship, while a significant positive correlation suggests a synergistic relationship. Conversely, if there is no significant relationship between two types of ESs, we consider them to have no apparent relationship. Moreover, to evaluate the stability of the calculated relationships among ESs over time, we employ the SFT approach to calculate these relationships for each year spanning from 2001 to 2020. Subsequently, we utilize hierarchical clustering to group the relationships among ESs over time.

2.3.2. Landscape Baseline-Adjusted Space-for-Time Approach

Tomscha and Gergel [13] found that ignoring landscape history in the SFT approach can lead to misunderstandings of relationships among ESs. Therefore, the second approach employed in this study incorporates landscape history and is termed the baseline-adjusted space-for-time (BA-SFT) approach. Specifically, we first select two sets of ES maps for different time periods: one representing the current state of ES and the other representing the landscape baseline ES. Next, we subtract the landscape baseline ES map from the current ES map to obtain the spatial distribution map of ES changes (ΔES). Finally, we calculate the Spearman correlation coefficient and its significance level between changes in pairs of ESs and determine relationships between the two ESs based on this analysis. Additionally, to test the sensitivity of the identified relationships between ESs to different landscape history intervals, we compared the results of ES relationships for landscape history intervals of 5, 10, 15, and 20 years.

2.3.3. Temporal Trend Approach

Studies have shown that ESs and their relationships exhibit complex temporal dynamics [21,26]. Considering only a few snapshots in time can easily overlook the nonlinear changes and time lag effects of ES, leading to incorrect results. Therefore, the third approach used in this study is the temporal trend (TT) approach. Specifically, we first aggregate ESs at the county level administrative units in the study area to the entire study area scale. Then, we calculate the Spearman correlation coefficient between pairs of ES time series data spanning 20 years. Based on the correlation coefficient and its significance level, we determine the relationships between ESs.

Additionally, to further explore the spatial heterogeneity of ES relationships, we quantified the spatiotemporal patterns of each type of ES trend based on Sen's slope and MK test methods [26]. If two ESs both show significant increasing or decreasing relationships, we consider there to be a synergy relationship between them. If one ES shows a significant increasing trend while the other shows a significant decreasing trend, we consider there to be a trade-off relationship between them.

Finally, we utilize the TLCC method to identify whether there is a time lag effect between different ES relationships, as well as its direction and strength [41,42]. The TLCC method determines the optimal time span required to achieve the best correlation by adjusting the time relative offset between different ESs, which can help determine the time lag patterns between two ESs. We assume that the relationship between the time series of ESs is correlated with any duration of time lag, represented by Equation (1):

$$r_k(x,y) = c_k(x,y)/\delta_x\delta_{y+k}, \tag{1}$$

where r_k is the correlation coefficient at time lag point k, c_k is the covariance between time series x_t and time series y_{t+k}, δ_x is the standard deviation of time series x_t, and δ_{y+k} is the standard deviation of time series y_{t+k}. The calculation of these statistical parameters is given by Equation (2):

$$\begin{cases} c_k(x,y) = \left[\sum_{t=1}^{n-k}(x_t - \overline{x_t})(y_{t+k} - \overline{y_{t+k}})\right]/(n-k) \\ \delta_x = \sqrt{\left[\sum_{t=1}^{n-k}(x_t - \overline{x_t})^2\right]/(n-k)} \\ \delta_{y+k} = \sqrt{\left[\sum_{t=1}^{n-k}(y_{t+k} - \overline{y_{t+k}})^2\right]/(n-k)} \end{cases}, \tag{2}$$

where the time lag k equals 0, ±1, ±2. . .Based on empirical evidence, the absolute value of the time lag k should be less than or equal to $n/4$ [41,42], which is 5 years in this study; $\overline{y_{t+k}}$ is the mean of the lagged series y_{t+k}, and $\overline{x_t}$ is the mean of the time series x_t.

2.4. Three Possible Incorrect Ecosystem Service Relationships

We compared the similarity between the SFT, BA-SFT, and TT methods by calculating the proportion of ES relationships identified by both methods in each ES. This proportion was determined by dividing the number of common relationships identified by the two methods by the total number of ES relationships related to that specific ES. For example, for air purification services, the similarity between SFT and BA-SFT is calculated as the percentage of collaborative/trade-off relationships identified by both methods out of the 11 relationships associated with air purification.

Based on Tomscha and Gergel [13], three potential errors in identifying relationships between ESs using different approaches are illustrated in Figure 2: (1) If the true relationship between two ESs is a trade-off, but the relationship identified by statistical methods is a synergy or no relationship, we refer to this as a trade-off missed. (2) If the true relationship between two ESs is a synergy, but the relationship identified by statistical methods is a trade-off or no relationship, we refer to this as synergy missed. (3) If there is no true relationship between two ESs, but statistical methods identify a trade-off or synergy relationship, we refer to this as an "interaction detected where none occur".

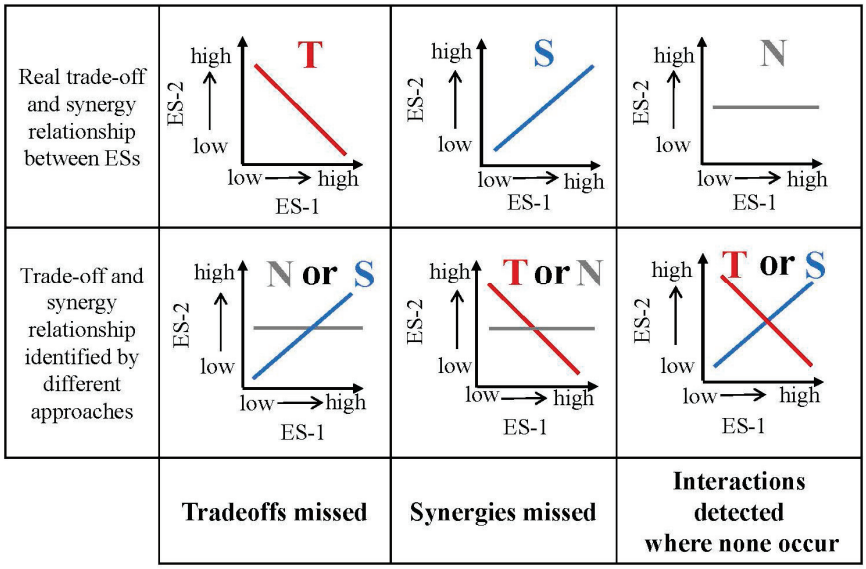


Figure 2. Different approaches with limitations can identify three incorrect ecosystem service relationships: trade-offs missed, synergies missed, interactions detected where none occur. "T": Trade-off, "S": Synergy, "N": No interaction. This figure is adapted from Tomscha and Gergel [13].

We referenced a large number of existing studies to determine whether the ES relationships were correctly identified and based our judgment on two criteria: (1) ES trade-offs or synergies that are widely confirmed in the literature. For example, it is commonly found in the literature that there is a trade-off between food production and water retention, as agricultural land generally has lower water retention capacity compared to forest and grassland [14]; (2) the specific environmental and policy context of the YRD region. For instance, agricultural land expansion in the YRD occurred mainly before 2000, while the ES time scale we calculated is from 2001 to 2020, which could lead to misinterpretation of the relationship between crop production and soil conservation.

3. Results

3.1. Space-for-Time Approaches in Different Time Frames

Figure 3 illustrates the relationships between different types of ESs identified by the space-for-time (SFT) approach in 2020. Regarding provisioning services, positive significant correlations are observed between crop production and air purification, carbon sequestration, and water purification, while negative significant correlations are observed with outdoor recreation, soil conservation, urban cooling, and water yield. Water yield shows significant negative correlations with most ESs (except outdoor recreation, soil conservation, and water purification). As for regulating services, except for water purification, most types of regulating services show significant positive correlations with each other, while regulating services exhibit significant negative correlations or no significant relationship with provisioning services. Water purification service is negatively correlated with most regulating services, supporting services, and cultural services but positively correlated with provisioning services. Regarding cultural services, outdoor recreation is positively correlated with most regulating services but negatively correlated with crop production and water purification.

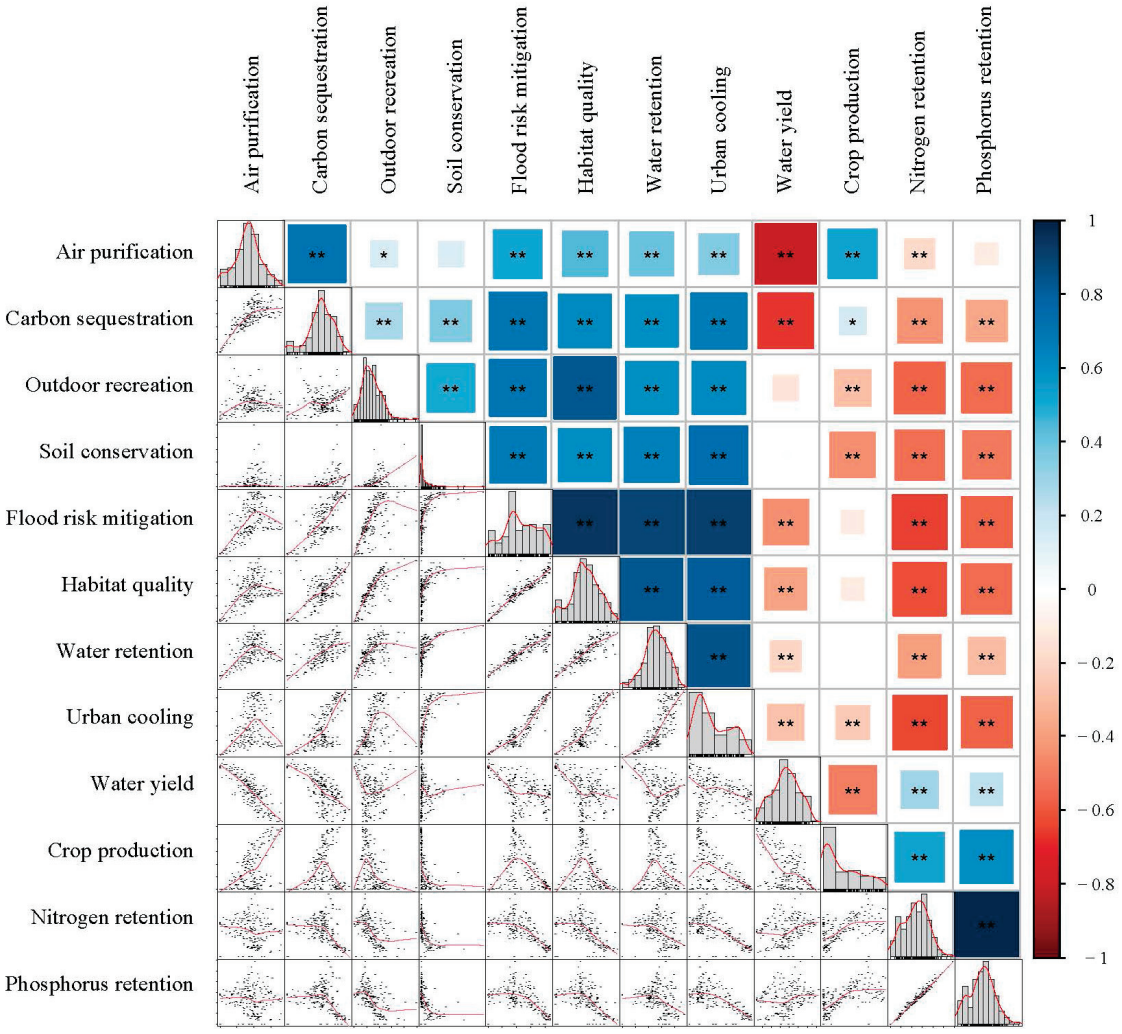


Figure 3. Matrix of Spearman correlations between different ecosystem services based on the space-for-time approach. *: Significant at the 0.05 level. **: Significant at the 0.01 level.

The hierarchical clustering results indicate that over the 20-year period from 2001 to 2020, most ES relationships remained stable, with a few ES relationships transitioning between trade-offs, synergies, and no significant relationships (Figure 4). The hierarchical clustering analysis categorizes changes of ES relationships into five groups. Category 1: No stable trade-offs or synergies, consisting mainly of ES relationships closely related to rainfall variability (water yield, soil conservation, water retention, flood risk mitigation) and air purification. Category 2: Strong trade-off relationships, primarily involving the relationships between water purification and other regulating, supporting, and cultural services. Category 3: Weak trade-off relationships, dominated by trade-offs between provisioning services and other regulating, cultural, and supporting services. Category 4: Weak synergy relationships, encompassing types of ESs where synergies between provisioning, regulating, supporting, and cultural services are relatively weak. Category 5: Strong synergy relationships, mainly involving various types of regulating services synergizing with each other.

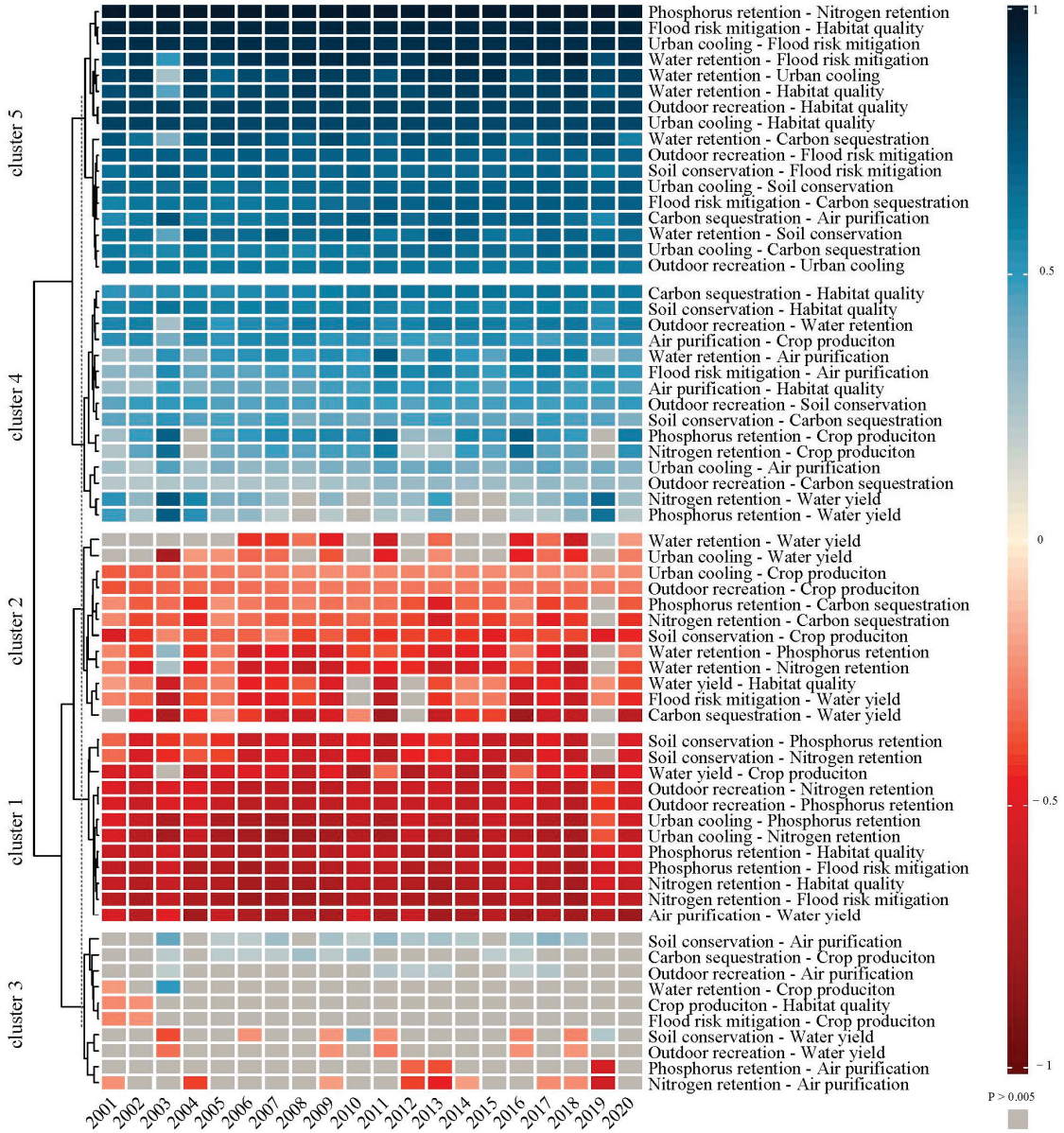


Figure 4. Temporal stability of relationships between ecosystem services based on the space-for-time approach.

3.2. Landscape Baseline-Adjusted Space-for-Time Approach

The comparison between 2020 and 2001 reveals both enhancements and declines in the distribution of the 12 types of ESs (Figure 5). Most ESs in 2020 show a decrease in areas with significant urbanization, particularly in the vicinity of Shanghai, compared to 2001. However, there are increases in crop production and air purification around Shanghai. Apart from a few ESs significantly influenced by rainfall variability (such as water yield, crop production, and water retention), most types of ESs exhibit increased capacity in the peripheral regions of the YRD, where urbanization is not as intense.

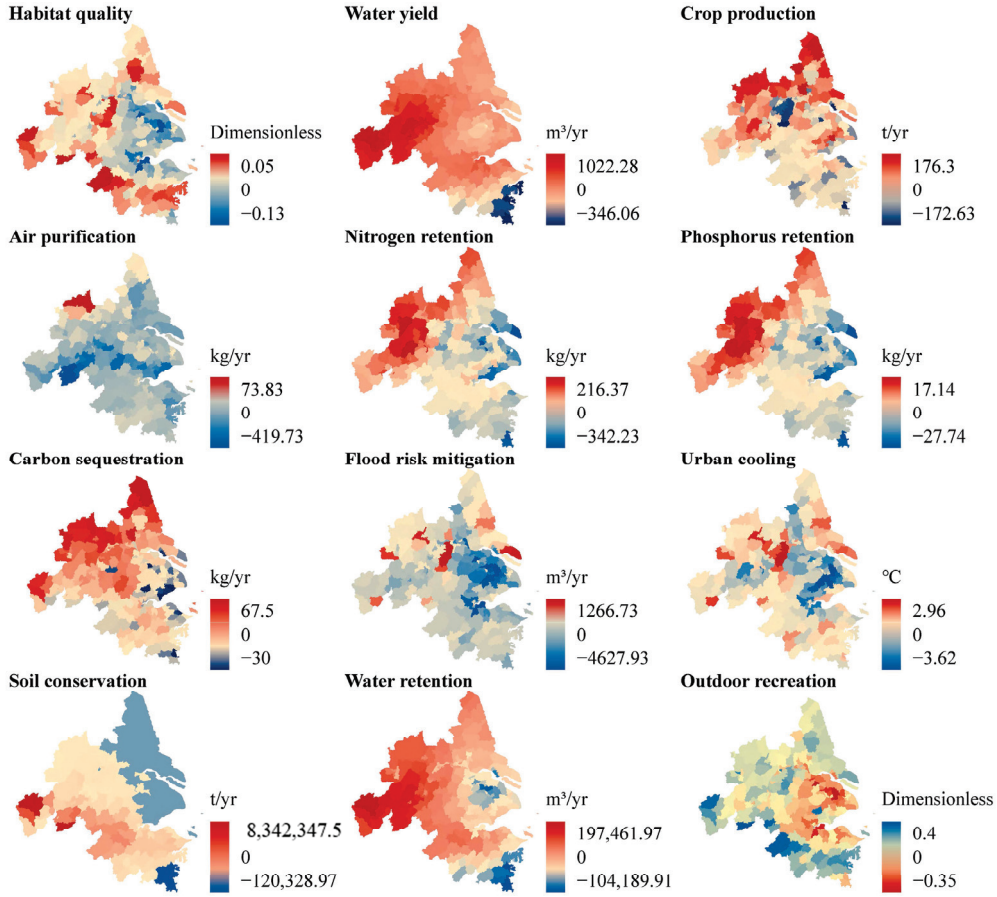


Figure 5. The spatial distribution of differences in ecosystem services from 2001 to 2020 (ΔES).

When employing the BA-SFT method, we detected significant trade-off or synergy relationships in only 44 out of 66 pairs of ES relationships (Figure 6). This contrasts significantly with the results obtained using the single-time-point SFT method. Specifically, there are synergistic relationships between crop provisioning and water retention, as well as water yield. Crop production exhibits no significant correlation with outdoor recreation or soil conservation. Water yield has no significant relationship with air purification, flood risk mitigation, habitat quality, or urban cooling, but it shows a significant positive correlation with carbon sequestration, water retention, and crop production. For regulating services, there is generally a positive correlation between regulating services and provisioning services, while water purification shows synergy relationships with most regulating services. In terms of cultural services, they correlated positively with most regulating services, including water purification, and show no significant relationship with crop production.

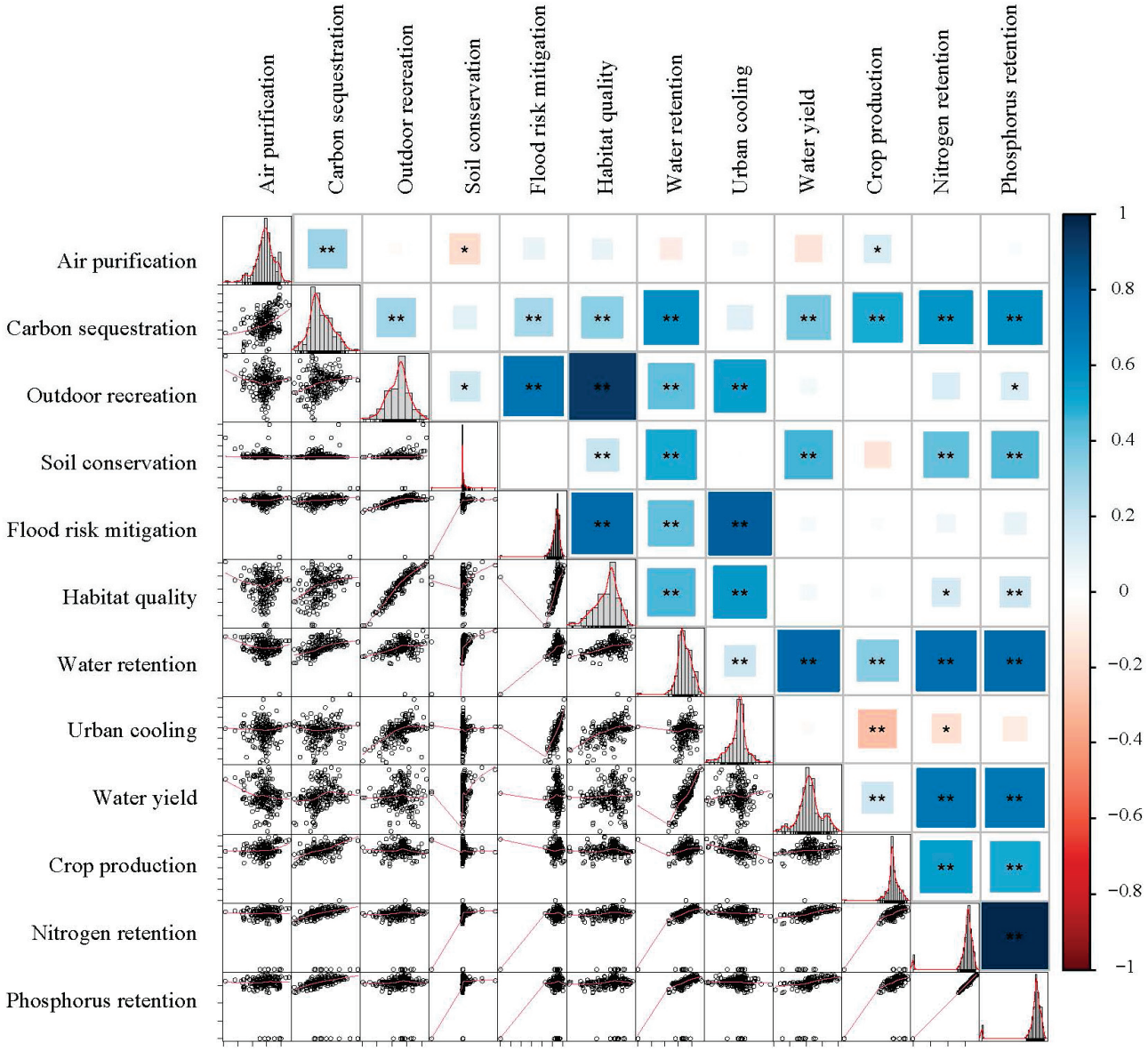


Figure 6. Matrix of spearman correlations between different ecosystem services based on the landscape baseline-adjusted space-for-time approach. *: Significant at the 0.05 level. **: Significant at the 0.01 level.

The relationships among ESs identified using the BA-SFT method are sensitive to the temporal intervals distancing from the landscape baseline (Figure 7). For instance, when the temporal interval is set to 5 years, flood risk mitigation exhibits a trade-off relationship with carbon sequestration, while crop production shows trade-off relationships with soil conservation and urban cooling, and air purification shows a trade-off relationship with urban cooling. However, when the temporal interval is changed to 10 years, 15 years, and 20 years, the trade-off relationship between flood risk mitigation and carbon sequestration may disappear or transform into a synergistic relationship, and the trade-off relationship between crop production and soil conservation may appear and disappear intermittently. The trade-off relationship between air purification and urban cooling disappears with longer time intervals, but a trade-off relationship between air purification and soil conservation emerges when the temporal interval is set to 20 years.

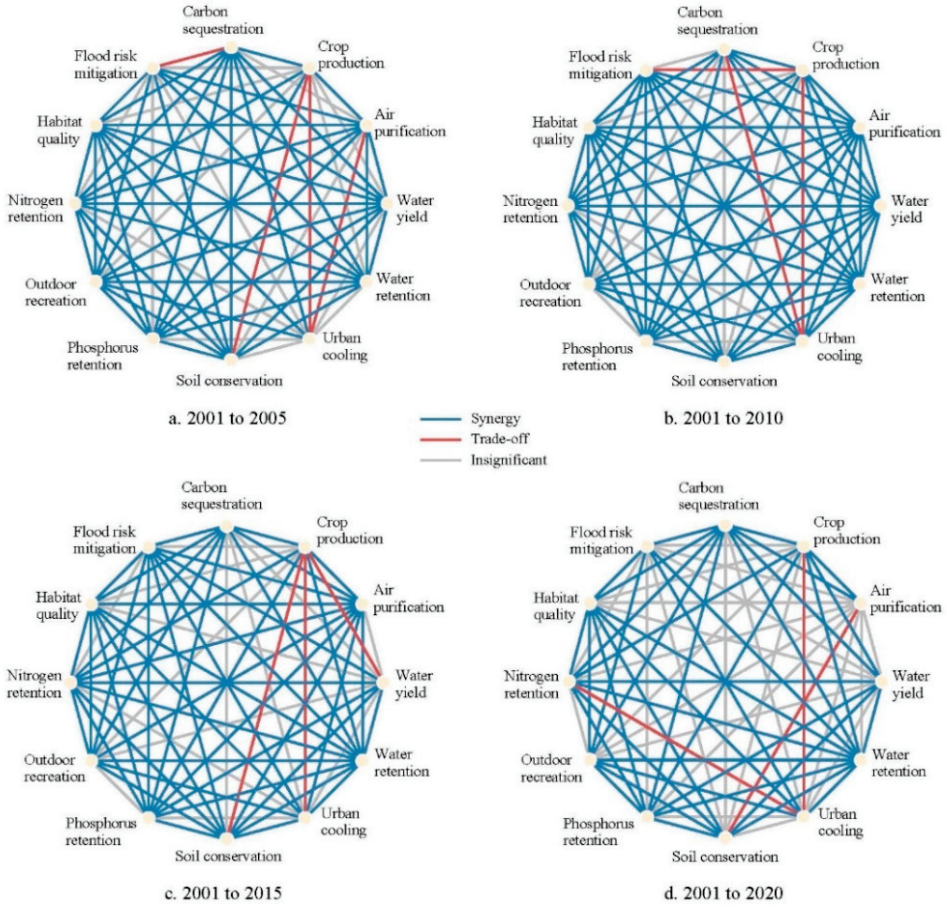


Figure 7. Sensitivity to time intervals of relationships between ecosystem services identified based on the landscape baseline-adjusted approach.

3.3. Temporal Trend Approach

At the regional scale, all 12 types of ESs exhibit three types of temporal trends (Figure 8): (1) Monotonic decreasing trend, such as habitat quality; (2) Fluctuating trend, mainly including several ES types closely related to precipitation fluctuations, such as water yield, flood risk mitigation, soil conservation, and water retention. (3) Unimodal trend. For example, water purification, crop production, and carbon sequestration mainly exhibit a trend of initially decreasing and then increasing, while air purification shows a trend of initially increasing and then decreasing.

The trends of all ES types exhibit significant spatial heterogeneity across different regions of the Yangtze River Delta (Figure 9). Specifically, the significant declining trends in habitat quality, urban cooling, flood risk mitigation, and outdoor recreation are primarily concentrated in highly urbanized areas such as Shanghai. For water yield, soil conservation, and water retention, they exhibit an increasing trend in most parts of the YRD, with significant growth trends mainly concentrated in the southern regions, and only a small portion of the northern areas showing a significant decrease. As for crop production, most areas of the YRD demonstrated a significant increase, with only some central and southern regions showing a significant decrease. Regarding carbon sequestration, the majority of the YRD region exhibits a significant increase, with decreasing trends sparsely distributed along the coastal areas of the YRD.

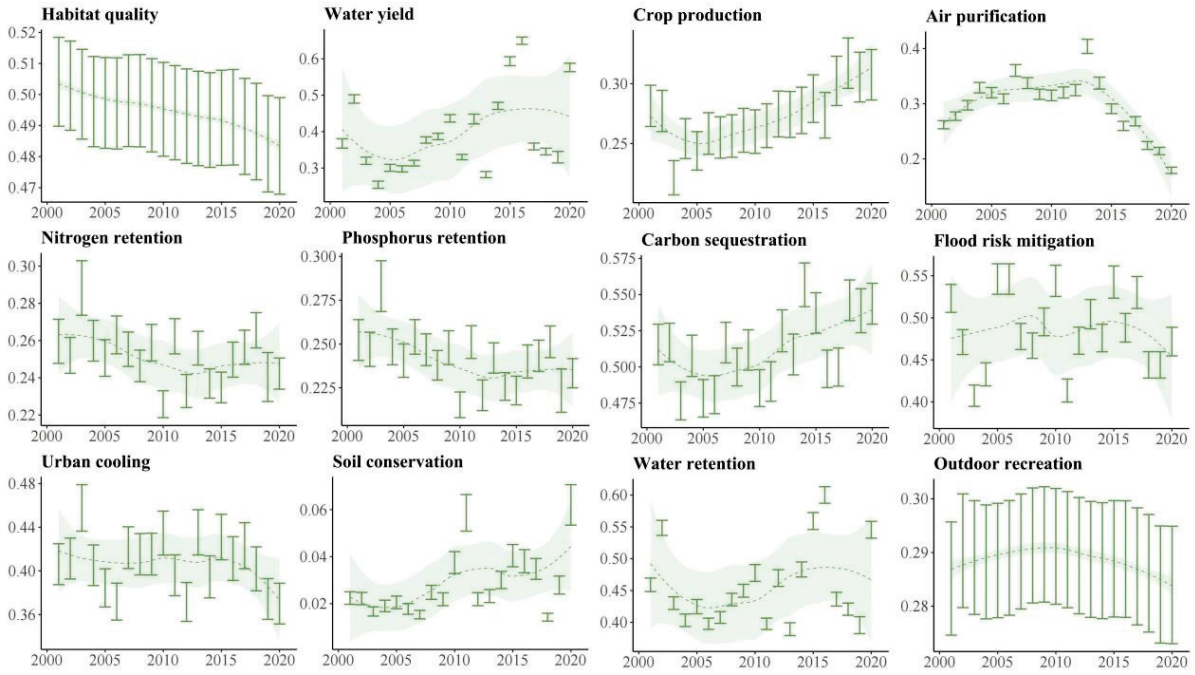


Figure 8. Trends in different ecosystem service types over time at the regional scale.

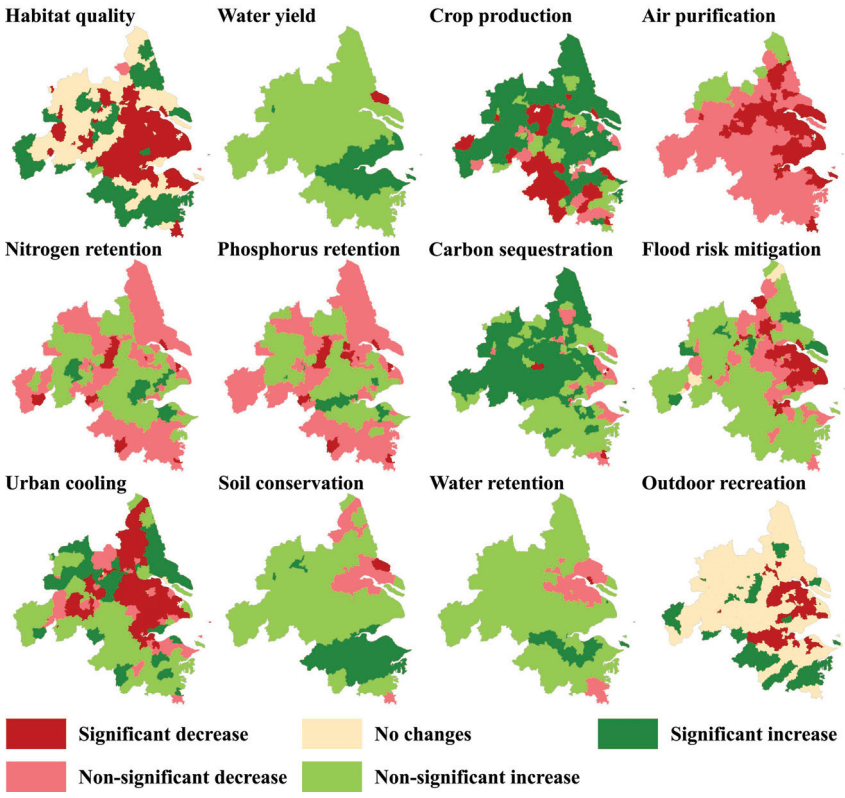


Figure 9. Spatial distribution of trends in different ecosystem service types.

At the regional scale, the Temporal Trend (TT) approach detected a very limited number of relationships among ESs, but they all exhibited synergy in direction (Figure 10). Specifically, the TT Approach identified a total of 10 significant relationships among ES, accounting for 15% of all ES relationships. For provisioning services, crop production showed a significant positive correlation with carbon sequestration and soil conservation. Water

yield was significantly positively correlated with habitat quality, outdoor recreation, and soil conservation. For regulating services, water retention was positively correlated with soil conservation and habitat quality, while urban cooling was positively correlated with habitat quality, and Nitrogen retention was positively correlated with Phosphorus retention. For cultural services, outdoor recreation was only significantly positively correlated with water yield.

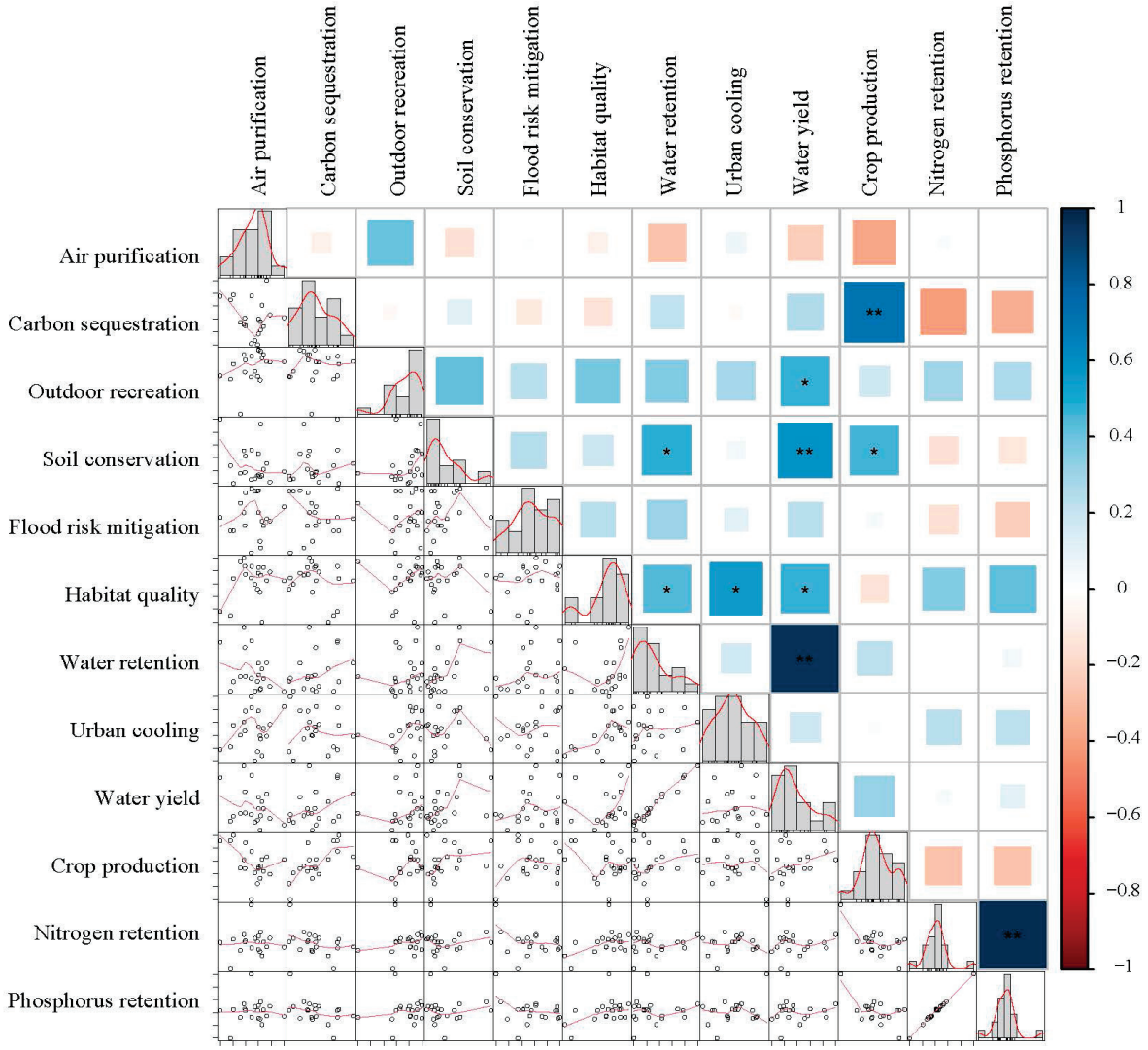


Figure 10. Matrix of Spearman correlations between different ecosystem services based on the temporal trend approach. *: Significant at the 0.05 level. **: Significant at the 0.01 level.

The Temporal Trend (TT) approach can identify spatial heterogeneity in the trade-offs and synergies among ESs. This study demonstrates the spatial distribution of trade-offs and synergies between crop production and other service types as an example (Figure 11). At the county level, there are regions where crop production exhibits both trade-offs and synergies with almost all other ES types. Trade-offs relationships, predominantly between crop production and habitat quality, air purification, urban cooling, and outdoor recreation, are mainly located in the central part of the YRD. Conversely, synergistic relationships, predominantly between crop production and carbon sequestration, are mainly distributed in the northern part of the YRD. Additionally, there are significant areas where crop production shows no significant relationship with any other ES type.

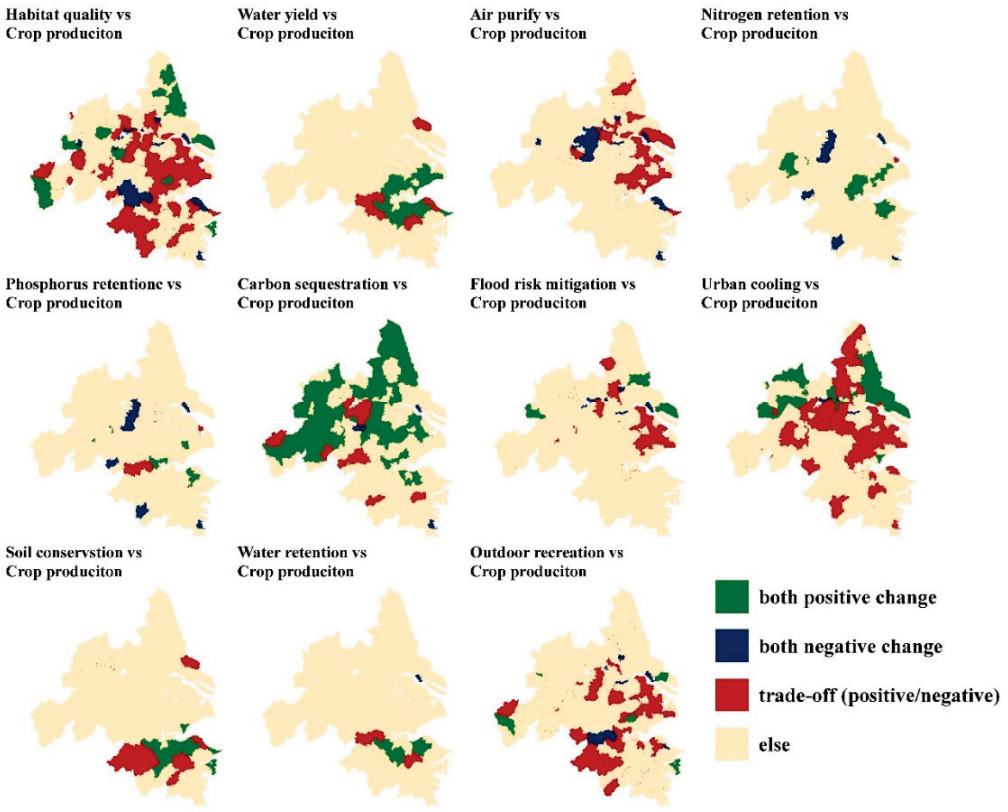


Figure 11. Spatial distribution of relationships between crop production and other types of ecosystem services.

4. Discussion

4.1. Little Disagreement Between Three Approaches

We deeply explored the advantages, disadvantages, and applicability of each method by comparing the overlap of ES relationships identified by the three approaches (SFT, BA-SFT, and TT). The results of this study demonstrate great differences in the relationships identified among ES by the three approaches (Table 2). The proportion of identical ES relationships identified by all three approaches was only 1.45%. The consistency in ES relationships detected by the BA-SFT method compared to the TT and SFT methods is 46.97% and 42.42%, respectively, while the consistency between the TT and SFT methods is only 15.15%. In the comparison between the BA-SFT and TT methods, ES relationships associated with air purification exhibit relatively high consistency, reaching 75%. However, in the comparison between the SFT and TT methods, ES relationships related to outdoor recreation and water production both show extremely low consistency, at only 8.33%.

By comparing the similarities in the relationships between ESs across three methods—SFT, BA-SFT, and TT—our results show that compared to the SFT method, the BA-SFT method identifies a greatly lower number of synergies and trade-offs between ESs (Figure 12). (1) For provisioning services, in the SFT method, crop production is unrelated to water retention and is in a trade-off relationship with water yield, whereas in the BA-SFT method, both are in a synergistic relationship. In the SFT method, crop production is negatively correlated with outdoor recreation and soil conservation, while in the BA-SFT method, there is no significant correlation. Water yield is negatively correlated with air purification, carbon sequestration, flood mitigation, habitat quality, water retention, and urban cooling in the SFT method, but shows no significant relationship with air purification, flood risk mitigation, habitat quality, and urban cooling in the BA-SFT method. However,

it is significantly positively correlated with carbon sequestration, water retention, and crop production. (2) For regulating services, in the SFT method, most regulating services were in trade-off relationships with habitat quality and provisioning services, while in the BA-SFT method, regulating services are mostly positively correlated with provisioning services. In the SFT method, water purification is in trade-off relationships with most regulating services, while in the BA-SFT method, they are mostly in synergy relationships. (3) For cultural services, in the SFT method, they are positively correlated with most regulating services but negatively correlated with crop production and water purification. In the BA-SFT method, they are positively correlated with most regulating services, including water purification, and not significantly correlated with crop production.

Table 2. Percentage of matches between ecosystem service relationships identified by the three methods.

Ecosystem Service Types	SFT & BA-SFT (%)	SFT & TT (%)	BA-SFT & TT (%)	Three Approaches (%)
Air purification	33.33	25.00	75.00	16.67
Crop production	66.67	41.67	41.67	33.33
Carbon sequestration	58.33	16.67	33.33	16.67
Flood risk mitigation	58.33	16.67	58.33	16.67
Habitat quality	66.67	33.33	41.67	33.33
Nitrogen retention	41.67	16.67	41.67	16.67
Outdoor recreation	66.67	8.33	33.33	8.33
Phosphorus retention	41.67	25.00	41.67	25.00
Soil conservation	33.33	25.00	50.00	16.67
Urban cooling	58.33	16.67	58.33	16.67
Water retention	58.33	33.33	41.67	25.00
Water yield	33.33	8.33	50.00	8.33
All	46.97	15.15	42.42	1.45

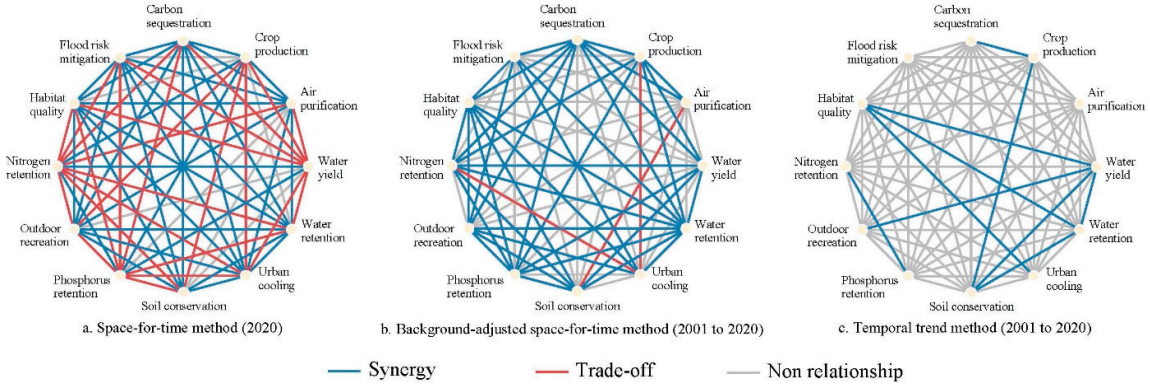


Figure 12. Comparison of the relationships between ecosystem services identified by three approaches.

Compared to the other two methods, the TT method identifies fewer significant trade-offs and synergies between ESs. On one hand, many ES relationships identified by the other two methods are not detected by the TT method. For example, both the SFT and BA-SFT methods show a trade-off relationship between crop production and urban cooling, but the TT method identifies no significant relationship between them. On the other hand, the TT method identifies trade-offs and synergies between ESs that are not detected by the other two methods. For instance, while both the SFT and BA-SFT methods show no relationship between water yield and outdoor recreation, the TT method reveals a significant positive correlation between them. Lastly, the TT method can identify relationships that are completely opposite to those identified by the other two methods. For

example, while the SFT method shows a trade-off relationship between crop production and soil conservation, the TT method identifies a synergy relationship between them.

4.2. Mechanisms by Which the Three Approaches Produce Different ES Relationships

4.2.1. Ignoring the Assumptions of the SFT Method May Lead to the Identification of Incorrect ES Relationships

The advantage of using the SFT method is that spatial variability and temporal variability are comparable [18]. Therefore, this method is only effective when landscape history is not important for ES and when the driving forces of ES remain consistent across the entire region. However, in regions like the YRD where there is strong spatial heterogeneity in topography, climate, and hydrology, this assumption is difficult to meet. For example, many studies have shown that crop production and water retention often show a trade-off relationship because agricultural land has a lower water retention capacity compared to other land use types such as forests and grasslands [14,43,44]. However, in this study, the SFT method did not detect this trade-off relationship in the YRD region. This could be because the factors affecting water retention include not only vegetation types but also rainfall and evapotranspiration, which vary significantly across the entire YRD and exhibit substantial spatial heterogeneity [27,45]. Therefore, the SFT method is likely to fail to identify the trade-off relationship between crop production and water retention.

4.2.2. The Lack of Sufficiently Early Landscape Background ES Data Leads to the Misidentification of ES Relationships by the BA-SFT Method

Our results indicate that the relationships between ESs identified based on the BA-SFT method are significantly influenced by the temporal interval from the historical landscape baseline (Figure 7). Compared to the SFT method, the BA-SFT method identifies fewer relationships between ESs, potentially leading to a higher number of missed trade-offs and synergies. For instance, under normal circumstances, there should be a trade-off relationship between crop production and soil conservation [14,46]. However, our BA-SFT results did not identify this trade-off relationship (Figure 6). The reason for missed trade-offs may be attributed to the short temporal interval of the distance landscape background values chosen in our study (only 20 years), whereas extensive expansion of agricultural land in YRD occurred before 2000, predating the earliest available landscape baseline data. Furthermore, the BA-SFT method may encounter identification errors when identifying relationships between ES types with strong fluctuations and other ESs. For example, flood risk mitigation and carbon sequestration often exhibit a synergistic relationship. However, our research findings indicate that only with longer temporal intervals from the landscape background (15 and 20 years), can the synergistic relationship be correctly identified, while at a 5-year temporal interval, it is identified as a trade-off relationship, and at a 10-year interval, it is identified as having no relationship (Figure 7).

4.2.3. The Time Span of Time Series Data, Data Aggregation Effects, and Time Lag Effects Lead to Errors in Identifying Relationships Between ES in the TT Method

Our results indicate that at the regional scale of the entire YRD area, the relationships between ES identified by the TT method are significantly lower compared to SFT and BA, and three types of identification errors, namely trade-off missed, synergy missed, and Interactions detected where none occur, are all present (Figure 12). For example, crop production and urban cooling are generally assumed to be in a trade-off relationship, but the TT method used in this study failed to identify this trade-off relationship. Crop production and soil conservation should ideally exhibit a trade-off relationship, but the TT method in this study identified a synergy relationship. Water retention and flood risk

mitigation are supposed to be in synergy but were identified as having no relationship in this study. Water yield and outdoor recreation were expected to have no relationship, but the TT method in this study identified a synergy relationship.

The reasons for the TT method's misidentification of trade-offs and synergies between ES may include three aspects: (1) Insufficient length of time series data for ES in this study may fail to capture long-term trade-offs and synergies resulting from changes in ES. For instance, trade-off relationships resulting from conversions between cropland and forests or grasslands may have occurred in earlier periods of the landscape. (2) Data aggregation effects may obscure ES relationships caused by local landscape changes. Previous studies have shown that data aggregation can influence the results of trade-offs and synergies in ES [13,21]. In this study, the TT method aggregated ES data to the regional scale, potentially masking relationships among ES due to local landscape changes. To verify this point, we analyzed the relationships between crop production and other ES at the grid scale. The results showed that trade-off and synergy areas exist between crop production and all other ES types across the landscape, indicating that aggregating data for the entire study area may obscure local variations. (3) Time lag effects may lead to the misidentification of relationships between some ES. Studies have suggested the existence of time lag effects between trade-offs and synergies among ecosystem services [28,47]. Our time lag analysis results also indicate that time lag effects exist between some ESs, especially those closely related to climate factors (such as water yield, urban cooling, and water retention), showing higher time lagged synergy relationships (Please see the Supplementary Materials). Time lag effects may lead to the misidentification of trade-offs and synergies between ES by the TT method.

4.3. Implications for Choosing Suitable Methods for Calculating ES Relationships

Correctly identifying trade-offs and synergies between ESs is of crucial importance for sustainable ecosystem management [8]. When trade-off relationships between ESs are mistakenly identified as synergies, management policies aimed at enhancing one ES capacity may lead to unexpected losses in other ESs. Conversely, if synergies between ESs are misidentified as trade-offs, opportunities to simultaneously enhance the functionality of both ESs may be missed [13,19]. The findings of this study provide several insights for selecting appropriate methods to identify trade-offs and synergies between ESs:

The advantage of using the SFT method lies in its minimal data requirements, as it can identify relationships between ESs without the need for time series data. However, its use is constrained by the assumption that the original conditions of ESs in the region are relatively consistent [18]. Our results indicate that in large regions such as the YRD, there are significant climatic differences, resulting in considerable variations in the original conditions of ESs related to climate. Consequently, this leads to the misidentification of trade-offs and synergies between related ESs. Therefore, we recommend carefully analyzing the initial conditions of each ES type to determine their homogeneity and whether the main drivers of ES changes are consistent across the entire study area before using the SFT method to identify relationships between ESs.

The BA-SFT method requires a higher level of data, necessitating spatial distribution data of ESs at different time points. Its advantage lies in its ability to overcome the limitations of the SFT method caused by background heterogeneity [13,19]. However, our results indicate that the BA-SFT method is sensitive to the selection of the landscape background's time intervals. Insufficient time intervals may result in the inability to identify many synergies and trade-offs between ESs. Additionally, our findings also suggest that the BA-SFT method may produce errors in identifying relationships between nonlinearly

changing ESs, such as those influenced by strong climate fluctuations like water retention and water yield.

The TT method has the highest data requirements, necessitating long-term time series data of ESs on an annual basis. Compared to the previous two methods, its advantages include: (1) the ability to explore relationships between ESs at the entire regional scale and spatially display the spatial heterogeneity of these relationships, (2) the capability to identify nonlinear relationships between ESs, (3) the ability to identify temporal lag effects between ESs. However, similar to the BA-SFT method, the TT method also requires long time series data to effectively identify the trade-offs and synergies between ESs caused by drivers with larger temporal scales of change.

Overall, our results indicate that the TT method is the preferred approach for identifying relationships between ESs given a sufficiently long time series of data. This method excels in recognizing both linear and nonlinear trade-offs and synergies between ESs, as well as detecting temporal lag effects between them. However, it is important to note that time series data may not be available in all regions. In areas where time series data are limited, the BA-SFT method performs better. Compared to the SFT method, BA-SFT can better account for the influence of landscape history. However, its accuracy is significantly influenced by the interval of distance landscape baseline data, and it is not suitable for analyzing relationships between ES with nonlinear changes. Additionally, both the TT method and the BA-SFT method require long historical data, or else there is a risk of misidentifying ES relationships. If historical ES data are unavailable, the SFT method is the only option. However, before using this method, it is essential to ensure that the initial conditions of ES in the study area are similar and that the drivers of ES change are consistent across the entire study area.

Moreover, this study has certain limitations. We employed correlation analysis as a unified method to compare the advantages and disadvantages of SFT, BA-SFT, and TT. However, correlation analysis can only identify linear relationships between ESs. Future research should overcome this limitation by exploring more advanced methods applicable within the SFT, BA-SFT, and TT frameworks. For instance, Bayesian Belief Networks [30], Structural Equation Modeling [31], dynamic models [32], and multivariate regression trees [48] can help uncover the complex nonlinear and causal relationships between ESs. Additionally, the spatial patterns of trade-offs and synergies among ESs should also be incorporated. Methods such as geographically weighted regression [49] and bivariate spatial autocorrelation analysis [50] can be used to identify the spatial heterogeneity of ES relationships.

5. Conclusions

This study systematically compared three approaches, namely space-for-time approach, landscape background-adjusted space-for-time approach, and temporal trend approach, for identifying relationships between ESs in the Yangtze River Delta region. We found great differences in the relationships detected among ESs by these three approaches, with only 1.45% consistency observed among 66 pairs of ES relationships. All three approaches exhibited errors such as trade-offs missed, synergies missed, and interactions detected where none occur. The reasons for misidentifying ES relationships by these approaches include ignoring the assumptions of the research methods, short time intervals in distance landscape background, insufficient time series data of ES, data aggregation effects, nonlinear changes in ESs, and time lag effects. Our study results indicate that each of the three approaches has its strengths and limitations in identifying trade-offs and synergies between ES. Before selecting a method to identify relationships between ES in a particular

study area, it is important to consider the availability of time series data, the characteristics of ES changes, and carefully assess the assumptions and uncertainties of each method.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14030644/s1. Refs. [38,40,51–70] are cited in the Supplementary Materials file.

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References

1. Wu, J. Landscape sustainability science: Ecosystem services and human well-being in changing landscapes. *Landsc. Ecol.* **2013**, *28*, 999–1023. [CrossRef]
2. Fang, X.; Ma, Q.; Liu, Z.; Wu, J. Landscape sustainability and land sustainability: A bibliometric analysis. *Land Use Policy* **2024**, *147*, 107374. [CrossRef]
3. Pereira, P.; Zhao, W. Geography and geographical knowledge contribute decisively to all sustainable development goals and targets. *Geogr. Sustain.* **2025**, *6*, 100267. [CrossRef]
4. Dade, M.C.; Bonn, A.; Eigenbrod, F.; Felipe-Lucia, M.R.; Fisher, B.; Goldstein, B.; Holland, R.A.; Hopping, K.A.; Lavorel, S.; lede Polain Waroux, Y.; et al. Landscapes—A lens for assessing sustainability. *Landsc. Ecol.* **2025**, *40*, 28. [CrossRef]
5. Qiu, J.; Nassauer, J.I.; Ahern, J.; Huang, L.; Reed, J.; Ding, S.; Guo, J.; Liu, Z.; Ou, W.; Ouyang, Z.; et al. Advancing landscape sustainability science: Key challenges and strategies for integration with landscape design and planning. *Landsc. Ecol.* **2025**, *40*, 1–10. [CrossRef]
6. Fu, B.; Wu, X.; Wang, S.; Zhao, W. Scientific principles for accelerating the Sustainable Development Goals. *Geogr. Sustain.* **2024**, *5*, 157–159. [CrossRef]
7. Rodríguez, J.P.; Beard, T.D., Jr.; Bennett, E.M.; Cumming, G.S. Trade-offs across Space, Time, and Ecosystem Services. *Ecol. Soc.* **2005**, *11*, 709–723. [CrossRef]
8. Chan, K.M.; Shaw, M.R.; Cameron, D.R.; Underwood, E.C.; Daily, G.C. Conservation planning for ecosystem services. *PLoS Biol.* **2006**, *4*, e379. [CrossRef]
9. Tallis, H.; Kareiva, P.; Marvier, M.; Chang, A. An ecosystem services framework to support both practical conservation and economic development. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 9457–9464. [CrossRef]
10. Bennett, E.M.; Peterson, G.D.; Gordon, L.J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **2009**, *12*, 1394–1404. [CrossRef]
11. Raudsepp-Hearne, C.; Peterson, G.D.; Bennett, E.M. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 5242–5247. [CrossRef] [PubMed]
12. Qiu, J.; Turner, M.G. Spatial interactions among ecosystem services in an urbanizing agricultural watershed. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 12149–12154. [CrossRef] [PubMed]
13. Tomscha, S.A.; Gergel, S.E. Ecosystem service trade-offs and synergies misunderstood without landscape history. *Ecol. Soc.* **2016**, *21*, 43. [CrossRef]
14. Xia, H.; Yuan, S.; Prishchepov, A.V. Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: Implications for spatial planning and management. *Resour. Conserv. Recycl.* **2023**, *189*, 106767. [CrossRef]
15. Liu, L.; Wu, J. Space cannot substitute for time in the study of the ecosystem services-human wellbeing relationship. *Geogr. Sustain.* **2025**, *6*, 100221. [CrossRef]
16. Cao, Y.; Cao, Y.; Li, G.; Tian, Y.; Fang, X.; Li, Y.; Tan, Y. Linking ecosystem services trade-offs, bundles and hotspot identification with cropland management in the coastal Hangzhou Bay area of China. *Land Use Policy* **2020**, *97*, 104689. [CrossRef]

17. Pereira, P.; Inácio, M.; Pinto, L.; Kalinauskas, M.; Bogdzevic, K.; Zhao, W. Mapping ecosystem services in urban and peri-urban areas. A systematic review. *Geogr. Sustain.* **2024**, *5*, 491–509. [CrossRef]
18. Pickett, S.T. Space-for-time substitution as an alternative to long-term studies. In *Long-Term Studies in Ecology: Approaches and Alternatives*; Springer: Berlin/Heidelberg, Germany, 1989; pp. 110–135.
19. Haase, D.; Schwarz, N.; Strohbach, M.; Kroll, F.; Seppelt, R. Synergies, Trade-offs, and Losses of Ecosystem Services in Urban Regions: An Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany. *Ecol. Soc.* **2012**, *17*, 22. [CrossRef]
20. Renard, D.; Rhemtulla, J.M.; Bennett, E.M. Historical dynamics in ecosystem service bundles. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, 13411–13416. [CrossRef]
21. Qiu, J.; Carpenter, S.R.; Booth, E.G.; Motew, M.; Zipper, S.C.; Kucharik, C.J.; Loheide Ii, S.P.; Turner, M.G. Understanding relationships among ecosystem services across spatial scales and over time. *Environ. Res. Lett.* **2018**, *13*, 054020. [CrossRef]
22. Bürgi, M.; Silbernagel, J.; Wu, J.; Kienast, F. Linking ecosystem services with landscape history. *Landsc. Ecol.* **2014**, *30*, 11–20. [CrossRef]
23. Shifaw, E.; Sha, J.; Li, X.; Bao, Z.; Ji, J.; Ji, Z.; Kassaye, A.Y.; Lai, S.; Yang, Y. Ecosystem services dynamics and their influencing factors: Synergies/tradeoffs interactions and implications, the case of upper Blue Nile basin, Ethiopia. *Sci. Total Environ.* **2024**, *938*, 173524. [CrossRef] [PubMed]
24. Hu, B.; Kang, F.; Han, H.; Cheng, X.; Li, Z. Exploring drivers of ecosystem services variation from a geospatial perspective: Insights from China's Shanxi Province. *Ecol. Indic.* **2021**, *131*, 108188. [CrossRef]
25. Wang, J.; Zhou, W.; Guan, Y. Optimization of management by analyzing ecosystem service value variations in different watersheds in the Three-River Headwaters Basin. *J. Environ. Manag.* **2022**, *321*, 115956. [CrossRef]
26. Liu, X.; Li, L.; Qin, F.; Li, Y.; Chen, J.; Fang, X. Ecological policies enhanced ecosystem services in the Hunshandak sandy land of China. *Ecol. Indic.* **2022**, *144*, 109450. [CrossRef]
27. Zhong, Z.; Fang, X.; Li, J.; Ma, Q.; Zhou, R.; Hu, Y.; Du, S. Linear and non-linear dynamics of ecosystem services supply, demand, and mismatches across a rapidly urbanizing region. *Ecol. Indic.* **2024**, *158*, 111614. [CrossRef]
28. Zhang, Z.; Liu, Y.; Wang, Y.; Liu, Y.; Zhang, Y.; Zhang, Y. What factors affect the synergy and tradeoff between ecosystem services, and how, from a geospatial perspective? *J. Clean. Prod.* **2020**, *257*, 120454. [CrossRef]
29. Deng, X.; Li, Z.; Gibson, J. A review on trade-off analysis of ecosystem services for sustainable land-use management. *J. Geogr. Sci.* **2016**, *26*, 953–968. [CrossRef]
30. Sun, X.; Ye, D.; Shan, R.; Peng, Q.; Zhao, Z.; Sun, J. Effect of physical geographic and socioeconomic processes on interactions among ecosystem services based on machine learning. *J. Clean. Prod.* **2022**, *359*, 131976. [CrossRef]
31. Li, X.; Deng, S.; Ma, X. Mechanism analysis of ecosystem services (ES) changes under the proposed supply-demand framework: A case study of Jiangsu Province, China. *Ecol. Indic.* **2022**, *144*, 109572. [CrossRef]
32. Rova, S.; Meire, P.; Müller, F.; Simeoni, M.; Pranovi, F. A Petri net modeling approach to explore the temporal dynamics of the provision of multiple ecosystem services. *Sci. Total Environ.* **2019**, *655*, 1047–1061. [CrossRef] [PubMed]
33. Fang, X.; Li, J.; Ma, Q.; Zhou, R.; Du, S. A quantitative review of nature-based solutions for urban sustainability (2016–2022): From science to implementation. *Sci. Total Environ.* **2024**, *927*, 172219. [CrossRef] [PubMed]
34. Reid, W.V.; Mooney, H.A.; Cropper, A.; Capistrano, D.; Carpenter, S.R.; Chopra, K.; Dasgupta, P.; Dietz, T.; Duraiappah, A.K.; Hassan, R. *Ecosystems and Human Well-Being-Synthesis: A Report of the Millennium Ecosystem Assessment*; Island Press: Washington, DC, USA, 2005.
35. Xu, X.; Yang, G.; Tan, Y.; Liu, J.; Hu, H. Ecosystem services trade-offs and determinants in China's Yangtze River Economic Belt from 2000 to 2015. *Sci. Total Environ.* **2018**, *634*, 1601–1614. [CrossRef]
36. Gao, J.; Yu, Z.; Wang, L.; Vejre, H. Suitability of regional development based on ecosystem service benefits and losses: A case study of the Yangtze River Delta urban agglomeration, China. *Ecol. Indic.* **2019**, *107*, 105579. [CrossRef]
37. Liu, W.; Zhan, J.; Zhao, F.; Zhang, F.; Teng, Y.; Wang, C.; Chu, X.; Kumi, M.A. The tradeoffs between food supply and demand from the perspective of ecosystem service flows: A case study in the Pearl River Delta, China. *J. Environ. Manage.* **2022**, *301*, 113814. [CrossRef]
38. Nowak, D.J.; Hirabayashi, S.; Bodine, A.; Hoehn, R. Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. *Environ. Pollut.* **2013**, *178*, 395–402. [CrossRef]
39. Jiang, B.; Bai, Y.; Chen, J.; Alatalo, J.M.; Xu, X.; Liu, G.; Wang, Q. Land management to reconcile ecosystem services supply and demand mismatches—A case study in Shanghai municipality, China. *Land Degrad. Dev.* **2020**, *31*, 2684–2699. [CrossRef]
40. Paracchini, M.L.; Zulian, G.; Kopperoinen, L.; Maes, J.; Schägner, J.P.; Termansen, M.; Zandersen, M.; Perez-Soba, M.; Scholefield, P.A.; Bidoglio, G. Mapping cultural ecosystem services: A framework to assess the potential for outdoor recreation across the EU. *Ecol. Indic.* **2014**, *45*, 371–385. [CrossRef]

41. Chen, Y.; Liu, J. Derivation and generalization of the urban gravitational model using fractal idea with an application to the spatial cross-correlation between Beijing and Tianjin. *Geogr. Res.* **2002**, *21*, 742–752.
42. Wei, Z.; Ren, Z.; Zhang, C. Analysis on the time-lag correlation between vegetation and climatic factors: Take Guangxi as an example. *Ecol. Environ. Sci.* **2013**, *22*, 1757–1762.
43. Asadolahi, Z.; Salmanmahiny, A.; Sakieh, Y.; Mirkarimi, S.H.; Baral, H.; Azimi, M. Dynamic trade-off analysis of multiple ecosystem services under land use change scenarios: Towards putting ecosystem services into planning in Iran. *Ecol. Complex.* **2018**, *36*, 250–260. [CrossRef]
44. Ouyang, Z.; Zheng, H.; Xiao, Y.; Polasky, S.; Liu, J.; Xu, W.; Wang, Q.; Zhang, L.; Xiao, Y.; Rao, E.; et al. Improvements in ecosystem services from investments in natural capital. *Science* **2016**, *352*, 1455–1459. [CrossRef] [PubMed]
45. Tao, Y.; Tao, Q.; Sun, X.; Qiu, J.; Pueppke, S.G.; Ou, W.; Guo, J.; Qi, J. Mapping ecosystem service supply and demand dynamics under rapid urban expansion: A case study in the Yangtze River Delta of China. *Ecosyst. Serv.* **2022**, *56*, 101448. [CrossRef]
46. Sun, X.; Li, F. Spatiotemporal assessment and trade-offs of multiple ecosystem services based on land use changes in Zengcheng, China. *Sci. Total Environ.* **2017**, *609*, 1569–1581. [CrossRef]
47. Li, B.; Chen, N.; Wang, Y.; Wang, W. Spatio-temporal quantification of the trade-offs and synergies among ecosystem services based on grid-cells: A case study of Guanzhong Basin, NW China. *Ecol. Indic.* **2018**, *94*, 246–253. [CrossRef]
48. De'Ath, G. Multivariate regression trees: A new technique for modeling species–environment relationships. *Ecology* **2002**, *83*, 1105–1117.
49. Zuo, L.; Gao, J. Investigating the compounding effects of environmental factors on ecosystem services relationships for Ecological Conservation Red Line areas. *Land Degrad. Dev.* **2021**, *32*, 4609–4623. [CrossRef]
50. Zheng, D.; Wang, Y.; Hao, S.; Xu, W.; Lv, L.; Yu, S. Spatial-temporal variation and tradeoffs/synergies analysis on multiple ecosystem services: A case study in the Three-River Headwaters region of China. *Ecol. Indic.* **2020**, *116*, 106494. [CrossRef]
51. Sun, X.; Jiang, Z.; Liu, F.; Zhang, D. Monitoring spatio-temporal dynamics of habitat quality in Nansihu Lake basin, eastern China, from 1980 to 2015. *Ecol. Indic.* **2019**, *102*, 716–723. [CrossRef]
52. Chen, D.; Jiang, P.; Li, M. Assessing potential ecosystem service dynamics driven by urbanization in the Yangtze River Economic Belt, China. *J. Environ. Manag.* **2021**, *292*, 112734. [CrossRef]
53. Donohue, R.J.; Roderick, M.L.; McVicar, T.R. Roots, storms and soil pores: Incorporating key ecohydrological processes into Budyko's hydrological model. *J. Hydrol.* **2012**, *436*, 35–50. [CrossRef]
54. Budyko, M.I. *Climate and Life*; Academic Press: Cambridge, MA, USA, 1974.
55. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M.J.F. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO Irrig. Drain. Pap.* **1998**, *56*, 29–64.
56. González-García, A.; Palomo, I.; González, J.A.; López, C.A.; Montes, C. Quantifying spatial supply-demand mismatches in ecosystem services provides insights for land-use planning. *Land Use Policy* **2020**, *94*, 104493. [CrossRef]
57. Zhou, R.; Lin, M.; Gong, J.; Wu, Z. Spatiotemporal heterogeneity and influencing mechanism of ecosystem services in the Pearl River Delta from the perspective of LUCC. *J. Geogr. Sci.* **2019**, *29*, 831–845. [CrossRef]
58. Wischmeier, W.H.; Smith, D.D. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*; Department of Agriculture, Science and Education Administration: Washington, DC, USA, 1978.
59. Zawadzka, J.; Harris, J.A.; Corstanje, R.J.L.; Planning, U. Assessment of heat mitigation capacity of urban greenspaces with the use of InVEST urban cooling model, verified with day-time land surface temperature data. *Landsc. Urban Plan.* **2021**, *214*, 104163. [CrossRef]
60. Stewart, I.D.; Oke, T.R. Local climate zones for urban temperature studies. *Bull. Am. Meteorol. Soc.* **2012**, *93*, 1879–1900. [CrossRef]
61. Taha, H.; Akbari, H.; Rosenfeld, A.; Huang, J. Residential cooling loads and the urban heat island—The effects of albedo. *Build. Environ.* **1988**, *23*, 271–283. [CrossRef]
62. NRCS, USDA. Estimation of direct runoff from storm rainfall. In *National Engineering HandbookÀPart*; NRCS, USDA: Washington, DC, USA, 2004; p. 630.
63. Zhong, Z.; Fang, X.; Zhang, Y.; Shu, X.; Guo, D. Mapping Ecosystem Service Supply–Demand Bundles for an Integrated Analysis of Tradeoffs in an Urban Agglomeration of China. *Land* **2022**, *11*, 1558. [CrossRef]
64. Jiang, H.; Peng, J.; Dong, J.; Zhang, Z.; Xu, Z.; Meersmans, J. Linking ecological background and demand to identify ecological security patterns across the Guangdong-Hong Kong-Macao Greater Bay Area in China. *Landsc. Ecol.* **2021**, *36*, 2135–2150. [CrossRef]
65. Hamel, P.; Guerry, A.D.; Polasky, S.; Han, B.; Douglass, J.A.; Hamann, M.; Janke, B.; Kuiper, J.J.; Levrel, H.; Liu, H.; et al. Mapping the benefits of nature in cities with the InVEST software. *Npj Urban Sustain.* **2021**, *1*, 25. [CrossRef]

66. Wu, Y.; Tao, Y.; Yang, G.; Ou, W.; Pueppke, S.; Sun, X.; Chen, G.; Tao, Q. Impact of land use change on multiple ecosystem services in the rapidly urbanizing Kunshan City of China: Past trajectories and future projections. *Land Use Policy* **2019**, *85*, 419–427. [CrossRef]
67. Zhao, J.; Li, C. Investigating Ecosystem Service Trade-Offs/Synergies and Their Influencing Factors in the Yangtze River Delta Region, China. *Land* **2022**, *11*, 106. [CrossRef]
68. Natural Capital Project. InVEST 3.12.0.post26+ug.g230fb3d User's Guide; Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, and Stockholm Resilience Centre. 2022. Available online: https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/index.html (accessed on 15 March 2025).
69. Villamagna, A.M.; Angermeier, P.L.; Bennett, E.M. Capacity, pressure, demand, and flow: A conceptual framework for analyzing ecosystem service provision and delivery. *Ecol. Complex.* **2013**, *15*, 114–121. [CrossRef]
70. Licheng, L.; Chunfang, L.; Chuan, W.; Pengjie, L.I. Supply and demand matching of ecosystem services in loess hilly region: A case study of Lanzhou. *Prog. Chem.* **2019**, *74*, 1921.

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An Ecological Risk Assessment of the Dianchi Basin Based on Multi-Scenario Land Use Change Under the Constraint of an Ecological Defense Zone

Shu Wang [1,2], Quanli Xu [1,2,*], Junhua Yi [3,*], Qinghong Wang [4], Qihong Ren [1,2], Youyou Li [1,2], Zhenheng Gao [1,2], You Li [1,2] and Huishan Wu [1,2]

[1] Faculty of Geography, Yunnan Normal University, Kunming 650500, China; 2433130023@ynnu.edu.cn (S.W.); 2381130012@ynnu.edu.cn (Q.R.); 2323130109@ynnu.edu.cn (Y.L.); 2323130101@ynnu.edu.cn (Z.G.); 234130076@ynnu.edu.cn (Y.L.); 234130083@ynnu.edu.cn (H.W.)
[2] GIS Technology Engineering Research Centre for West-China Resources and Environment of Educational Ministry, Kunming 650500, China
[3] Geomatics Engineering Faculty, Kunming Metallurgy College, Kunming 650033, China
[4] School of Economics and Management, Lijiang Culture and Tourism College, Lijiang 674199, China; wqh970929@163.com
* Correspondence: 4037@ynnu.edu.cn (Q.X.); yjh2ok@163.com (J.Y.)

Abstract: Ecological risk evaluation is a prerequisite for the rational allocation of land resources, which is of great significance for safeguarding ecosystem integrity and achieving ecological risk prevention and control. However, existing research lacks analysis of the ecosystem state after land use simulation within the restricted conversion zone, making it impossible to determine whether ecological risks have been mitigated under these constraints. Therefore, we selected the Dianchi basin as the study area, extracted the ecological defense zone as the restricted conversion zone, and used the PLUS (Patch-generating Land Use Simulation) model to simulate land use for 2030 under multiple scenarios. We then evaluated ecological risks based on landscape pattern indices, and analyzed ecological risks under multiple scenarios with and without the restricted conversion zone. By comparing ecological risks across scenarios with and without constraints, we clarified the critical role of ecological risk evaluation in the rational allocation of land resources. The results show the following: (1) The ecological defense zone was obtained by overlaying no-development zones (such as forest parks and nature reserves), areas of extreme importance in the evaluation of water resource protection, soil and water conservation, and biodiversity, as well as areas of extreme importance in the evaluation of soil and water erosion and rocky desertification sensitivity. (2) Cultivated land and woodland cover significant portions of the Dianchi basin. Overall, ecological risk deterioration was more pronounced in the economic scenario (ES), while the ecological scenario (PS) exhibited lower ecological risk compared to the natural scenario (NS). (3) After importing the ecological defense zone into the PLUS model as the restricted conversion zone for land use simulation, ecological risks in all scenarios showed a trend of improvement. The improvement trend was strongest in the NS, followed by the PS, and weakest in the ES. The results of this study can help to identify the most suitable land use planning model and provide a more effective strategy for ecological risk prevention and control.

Keywords: land use; ecological function importance; ecological sensitivity; PLUS model; Dianchi basin

1. Introduction

The dual economic and natural attributes of land make human activities the primary driver of land use change across 75% of the world [1]. Human interventions on land directly impact ecosystems, thereby inducing ecological risks [2,3]. Ecological risk is a recently developed natural resource management tool that enables the quantitative assessment of the negative consequences of natural or human-induced impacts on ecosystems based on land use change [4,5]. Higher ecological risks often hinder the ability of land to maintain biodiversity, water retention, and other ecological functions, leading to habitat fragmentation and the near-collapse of sustainable land management [6,7]. Initially, the study of ecological risk primarily focused on the impact of pollution sources on human health and the environment [8]. However, as research has progressed, constructing ecological risk evaluation models based on landscape patterns has gradually become feasible. These models can comprehensively consider the characteristics of landscape structure and type, and can be integrated with land use simulations. Thus, they provide a more comprehensive and precise perspective for ecological risk assessment [9]. Land use simulation and prediction can effectively explore future land use patterns, thereby revealing potential conflicts between ecological preservation and human activities [10]. By adjusting land use patterns and formulating corresponding land use plans, we can optimize land utilization and reduce the pressure exerted by human activities on land resources, thus mitigating ecological risks [11,12]. Therefore, optimizing future land use and rationally controlling ecological risks have become critical research priorities for sustainable land development.

Completion of the above research requires the synthesis of two parts: the first part involves setting up a multi-scenario model in the process of land use simulation, including an NS, an ES, and a PS. The NS refers to the transformation between land types by following the rules of land type conversion after considering the relationship between society, ecology, economy, and land without policy constraints [13,14]. The ES aims to guarantee the highest economic value for regional development, and usually increases the likelihood of converting anthropogenic land uses, such as construction land, into other land categories, while simultaneously reducing the possibility of transferring ecological land to man-made land [15,16]. The PS aims to maintain the stability of the ecosystem, and achieves this goal by increasing the probability of shifting construction land and cultivated land to other land types, or decreasing the probability of shifting ecological land, such as woodland, to artificial land [17,18]. Some studies often do not take the restriction of conversion zones as a hard constraint after setting up the scenarios, resulting in simulation results that may overestimate the ecological risk of future land use changes and fail to accurately reflect the ecological security pattern under policy intervention.

The other part involves setting up restricted conversion zones. Relevant studies have shown that the inclusion of restriction zones in the land use simulation process can effectively maintain the ecological function of the land [19,20]. Therefore, in order to realize the goal of land planning, it is necessary to extract specific areas according to actual needs and ensure that the land use types of these areas remain unchanged in the simulation process. Currently, the extraction of restricted zones is divided into two categories. The first is the extraction of restricted conversion zones by the direct identification method. For example, the Yangtze River is designated as a restricted conversion zone so that it is not converted to other land use types [21]. Water bodies and wetlands are also designated as restricted zones to protect them from encroachment by other land types [22]. Additionally, all nature reserves and reservoirs are set as restricted conversion areas [23,24]. However, this direct identification method only protects intuitive areas such as water and nature reserves, a process which is highly subjective and makes it difficult to comprehensively

address complex ecological problems. It may also lead to the continuous deterioration of ecological conditions. The second category involves conducting a multi-dimensional comprehensive evaluation to extract restricted zones. For example, combining the importance of ecosystem services with ESs can be used to evaluate the suitability of construction land, with unsuitable areas serving as constraints to limit the conversion and redistribution of various pieces of land [25]. Another approach is to integrate the ecological protection red line, cultivated land, and urban development suitability as constraints on ecological space, thereby restricting the transfer to construction land [26]. The above multi-dimensional considerations for extracting restricted conversion areas break away from the single protection of ecosystem functions to some extent. This approach can effectively reduce ecosystem sensitivity and enhance the stability and resilience of the ecosystem. However, the effectiveness of ecological restoration cannot be clearly assessed solely from the results of land use simulation.

The above analysis shows that, although the importance of multi-scenario models and restricted conversion zones has been fully considered in land use simulation projections, the results of these simulations are still insufficient to reflect whether the ecosystem has been improved. The existing land use simulation results can only reveal the transformations across land use, but cannot directly reflect whether the ecological condition has been improved. The core of this problem lies in the fact that most current studies are limited to the simulation of land use changes, but neglect in-depth investigation of the ecosystem status. Therefore, after comprehensively extracting restricted zones by a multi-dimensional approach and incorporating them into the constraints of land use simulation, finding a suitable method to explore changes in ecological conditions is not only an urgent need for current research, but also a key direction for future research.

Of course, reliable predictive models are indispensable to realize the above analysis. The theory of cellular automata (CA) was proposed by John von Neumann in the 1940s. Initially, CA were used as mathematical models mainly to simulate complex phenomena such as physics, chemistry, and living systems. The study of land use models began to introduce the concept of CA, especially for modeling urbanization processes and landscape evolution [27]. The CA-based land use simulation method was proposed and used to simulate the urban expansion process, which opened up the application of land use CA modeling [28]. The mainstream integrated CA-based models are as follows: the FLUS model is a land use change simulation model developed based on the theory of CA. It has been improved and extended on the basis of traditional CA, and the total probability of each land use type conversion on each image element is calculated by combining the suitability probability, neighborhood effect, conversion cost, and inertia coefficient, so as to realize the land use change simulation with high accuracy [29]. The PLUS model mines the driving factors of land expansion through the random forest algorithm, and combines the multiple types of random seeds and the threshold-decreasing mechanism to dynamically simulate patch generation; the simulation results have high accuracy and similar landscape patterns [30]. The PLUS model was chosen in this study for three reasons. First, based on its advancement, the stochastic deep forest algorithm is used to mine the rules, which can efficiently and accurately derive the conversion rules. The second is based on its applicability: the PLUS model constructs CA based on automatic generation of patches, which can adapt to spatial heterogeneity and improve the simulation effect of land use change. Third, the PLUS model is highly compatible with the objective of this study: the ecological risk in this study is calculated based on the landscape pattern index, and the results obtained by choosing this model better simulate the patch formation in the landscape.

In view of this, this study further explores the ecological risk of the Dianchi basin based on land use simulation. The study is mainly carried out in the following three aspects: First, the ecological defense zone is extracted as the restriction zone for land use simulation by integrating the ecological function importance (EFI) and ecological sensitivity (ESE). Second, three scenarios—namely, NS, ES, and PS—are set to simulate for 2030 and compare the land use situation under the constraints of the ecological defense zone. Third, an ecological risk evaluation is conducted for 2030. Finally, the ecological risk evaluation is carried out, and the ecosystem state change characteristics under the constraints of the ecological defense zone are compared. Through the above studies, we aim to establish a scientific foundation for the optimization of land use patterns and the sustainable management of ecosystems going forward.

2. Study Area

The Dianchi basin is located in southwestern China (Figure 1), where the sixth-largest freshwater lake, known as the Pearl of the Chinese Plateau, is situated [31]. The basin is narrow in the north and south, and broad in the east and west, surrounded by mountains [32]. The geographic location of the basin is between 24°28′~25°27′ N and 102°29′~103°00′ E. The altitude ranges from 1864 to 2789 m, and the terrain is rich in geomorphology. The natural conditions are relatively complex. Cultivated land and woodland are the main land use types in the region, and the distribution of construction land is relatively concentrated, mainly in the junction of Wuhua District, Panlong District, Guandu District, and Xishan District. Although the abundant water resources and vegetation give the region a relatively low ecological risk value, the basin has a total population exceeding 4.06 million, which accounts for approximately 64% of the population of Kunming. Moreover, with the increasing intensity of human activities in recent years, the ecological risk in certain areas has significantly increased, creating challenges for the protection of its ecological environment. Therefore, identifying ecological defense zones within the Dianchi basin and evaluating the effects of land use alterations on ecological risk are of considerable importance for research.

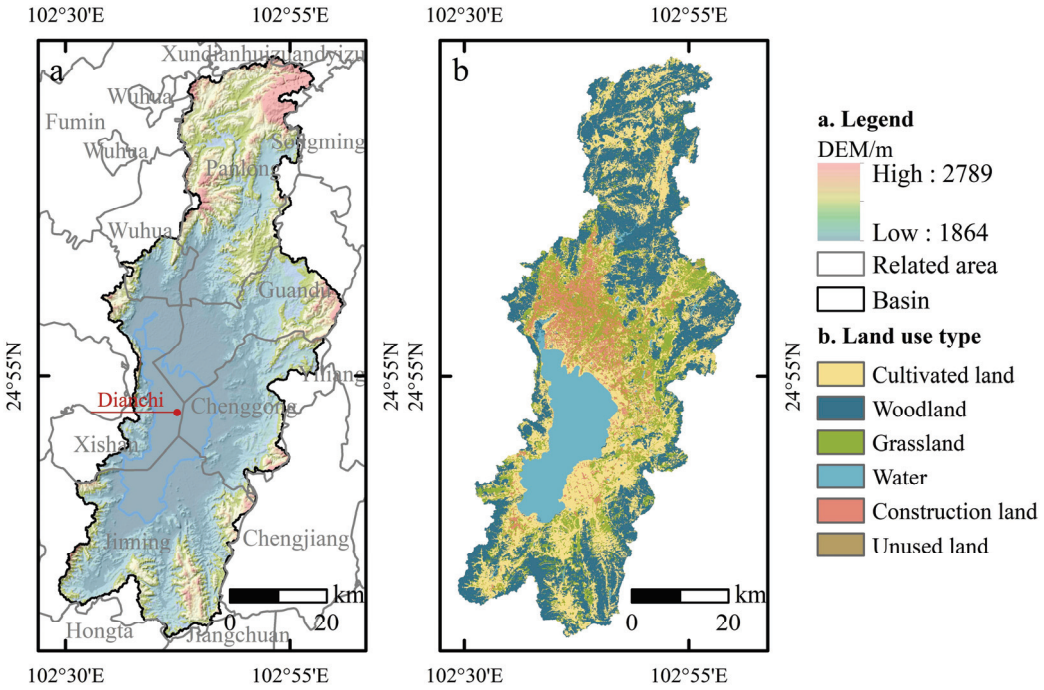


Figure 1. An overview of the Dianchi basin.

3. Materials and Methods

3.1. Data

The main data types used were data for modeling land use and data for ecological risk assessment (Table 1). These data were selected for three main purposes. First, the historical land use data and drivers selected based on previous studies were used as the basis for simulating land use for 2030. Second, corresponding data were selected to evaluate EFI and ESE. The resulting ecological defense zone were then used as a restricted conversion zone for the 2030 land use simulation. Lastly, the simulated land use data for 2030 were used as the basis for ecological risk evaluation.

Table 1. Data required for the study.

Data/Year	Data Source	Description	Data Type/Resolution
Land use data/2000, 2010, 2020	Publicly available datasets at Wuhan University [33]	For 2030 land use modeling and ecological risk assessment	Raster/30 m
Distance to road Distance to town	National Geographic Information Resources Catalog Service System (https://www.webmap.cn) accessed on 1 April 2024	For land use modeling for 2030	Vector
Population density/2000, 2010, 2020	WorldPop (https://www.worldpop.org/) accessed on 1 April 2024		Raster/1 km
Night light/2000, 2010, 2020	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) accessed on 1 April 2024		
Elevation Slope	Geospatial Data Cloud (http://www.gscloud.cn) accessed on 1 April 2024	For land use modeling and EFI and ESE evaluation for 2030	Raster/90 m
Average annual temperature/2000, 2010, 2020	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (http://www.resdc.cn) accessed on 1 April 2024		
Annual precipitation	Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn/home) accessed on 1 April 2024		Raster/1 km
Evaporation/2000, 2010, 2020	Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn/home) accessed on 1 April 2024	For ecological importance and sensitivity assessment	
Soil	Harmonized World Soil Database (https://gaez.fao.org/pages/hwsd) accessed on 1 April 2024		

3.2. Simulation and Evaluation Methods

3.2.1. Evaluation of EFI and ESE

According to the "Guidelines for the Delineation of Ecological Red Lines" (GDERI) issued by the Ministry of Natural Resources of China, and following the principles of data accessibility and validity, water source protection, soil and water conservation, and biodiversity were selected as indicators for the evaluation of EFI. Additionally, soil and water erosion and rock desertification were selected as indicators for the evaluation of ESE. The EFI aims to identify areas that are important for ecological sustainable development, while the evaluation of ESE is used to identify the problems facing the ecological environment [34,35]. The specific classification process is as follows:

Indicator calculation: First, based on relevant data and scientific methods, the values of each indicator are calculated. The specific evaluation indicators and formulas are shown in Table 2.

Table 2. Construction of index system of EFI and ESE.

	Index	Formula	Description
EFI	Water source protection	$PAWC = 54.509 - 0.132sand\% - 0.003(sand\%)^2 - 0.055silt\% - 0.006(silt\%)^2 - 0.738clay\% + 0.007(clay\%)^2 - 2.688OM\% + 0.501(OM\%)^2$ $W_i = Y_i - L_i$ $Y_i = F_{pre} - ET_i$ $L_i = \min(X_i \times F_{pre}, Y_i)$	The average annual precipitation, evapotranspiration, root depth, and effective water content of plants were imported into the InVEST model to calculate the water yield. The formula for calculating the importance of water source protection ecological function was taken from [36].
	Soil and water conservation	$R_i = 0.0668 \times F_{pre}^{1.6266}$ $K_i = (-0.01383 + 0.51575K_{EPIC}) \times 0.1317$ $K_{EPIC} = \left\{0.2 + 0.3exp\left[-0.0256ms\left(1 - \frac{msilt}{100}\right)\right]\right\} \times \left[\frac{m_{silt}}{(m_c + m_{silt})}\right]^{0.3} \times \left\{1 - \frac{0.25orgC}{[orgC + exp(3.72 - 2.95orgC)]}\right\} \times \left\{1 - 0.7\left(1 - \frac{m_s}{100}\right) / \left\{\left(1 - \frac{m_s}{100}\right) + exp\left[-5.51 + 2.2.9\left(1 - \frac{m_s}{100}\right)\right]\right\}\right\}$	The formula for calculating the erosive power of average annual rainfall was taken from [37], and the formula for calculating soil erodibility was taken from [38]. These formulas, along with other relevant data, were imported into the InVEST model for calculation. Finally, the results of the EFI of soil and water conservation were obtained.
	Biodiversity	$S_i = NPP_{mean} \times F_{pre} \times F_{tem} \times (1 - F_{alt})$	This part can be calculated by referring to the formula in the GDERI.
ESE	Soil and water erosion	$T_i = \sqrt[4]{R_i \times K_i \times LS_i \times C_i}$ $C_l = (NDVI - NDVI_{soil}) / (NDVI_{veg-} NDVI_{soil})$	
	Rock desertification	$M_i = \sqrt[3]{D_i \times P_i \times C_i}$	

Note: *PAWC* is the plant-available water content; sand%, silt%, and clay% are the proportions of soil sand, silt, and clay, respectively; and *OM* is the soil organic matter content. W_i is the water yield, Y_i is the water production, L_i is the surface runoff, F_{pre} is the average annual rainfall, ET_i is the evapotranspiration, R_i is the average annual rainfall erosive power, and X_i is the surface runoff coefficient. K_{EPIC} is the pre-amended soil erodibility, and K_i is the post-amended soil erodibility. m_c, m_{silt}, m_s, and orgC are the percentage contents of clay, silt, sand, and organic carbon, respectively. NPP_{mean} is the average multi-year net primary productivity of vegetation, F_{tem} is the average annual temperature, and F_{alt} is the slope factor; R_i is the rainfall erodibility, LS_i is the slope length and gradient, C_i is the surface vegetation cover, $NDVI_{veg}$ is the information contributed by a fully vegetated surface, and $NDVI_{soil}$ is the information contributed by an unvegetated surface. D_i is the percentage of the area of regional carbonate outcrops, and P_i is the slope of the terrain. Data for which no formulas are listed were obtained directly.

Classification method: The results are classified using the natural breaks method, which divides the region into five levels: general importance, importance, medium importance, high importance, and extreme importance.

3.2.2. PLUS Model

The PLUS model [39] is a high-precision spatial model for simulating future land use change, with the core objective of predicting the dynamic evolution of land types under different policy-related, natural, and socio-economic drivers. It consists of two components: the Land Expansion Analysis Strategy (LEAS)-based model and the CARS model based on multi-class stochastic patch seeds. The former is able to analyze the driving factors for the expansion of different land types by mining historical land use data, and to quantify the influence weights of each factor on land expansion. The latter is able to simulate the competition and conversion between different land types and generate a model closer to reality by combining the "Adaptive Inertia Mechanism" and the "Patch Generation Algorithm". In addition, the PLUS model supports different constraints (e.g., prohibited waters, nature reserves) and policy scenarios (e.g., PS), making it highly applicable to this study.

In terms of rule and parameter settings, the LEAS module uses random sampling, with the number of decision trees, sampling rate, and number of features used for training the random forest set to the model's default values of 20, 0.01, and 5, respectively. In

the CARS module, the neighborhood size, threshold reduction decay coefficient, and expansion coefficient are set to the model's default values of 3, 0.2, and 0.1, respectively. The neighborhood weights set for arable land, woodland, grassland, water bodies, built-up land, and unused land are 0.2815, 0.5747, 0.9888, 0.0001, 0.0492, and 0.6553, respectively. The transition matrix is shown in Table 3, where 0 indicates that the land use type cannot be converted to another land use type, and 1 indicates that conversion can occur. The relevant calculation formulas can be found in [40].

Table 3. Multiple scenario land use transition matrices.

	Land Use	Cultivated Land	Woodland	Grassland	Water	Construction Land	Unused Land
NS	Cultivated land	1	1	1	0	0	0
	Woodland	1	1	1	1	0	1
	Grassland	1	1	1	1	1	1
	Water	0	0	0	1	1	1
	Construction land	0	0	0	0	1	1
	Unused land	1	1	1	1	1	1
ES	Cultivated land	1	0	0	0	1	1
	Woodland	0	1	0	0	0	0
	Grassland	0	1	1	0	0	0
	Water	0	0	0	0	0	0
	Construction land	0	1	0	1	1	0
	Unused land	1	1	1	1	1	1
PS	Cultivated land	1	0	1	0	1	0
	Woodland	1	1	1	0	1	0
	Grassland	1	1	1	1	1	1
	Water	1	0	1	1	1	1
	Construction land	1	1	1	1	1	1
	Unused land	0	0	0	0	0	1

Therefore, the model was chosen to simulate land use in the Dianchi Basin for the year 2030. To validate the model's accuracy, the CARS module was employed to predict the 2020 land use, utilizing land use data from 2000 and 2010 as the baseline. The predicted results were compared with the actual 2020 land use pattern for accuracy assessment. It revealed an overall accuracy of 0.8109 and a Figure of Merit (FoM) of 4.4336, demonstrating high predictive performance. The main steps of the operation were as follows: Firstly, data were selected as the driving factors. Secondly, the extracted ecological defense zone was restricted from land type conversion. Lastly, the probability of conversion of land use types was adjusted several times to select the most appropriate probability for setting up the NS, ES, and PS to simulate the land use for 2030.

3.2.3. Ecological Risk Evaluation

Based on relevant studies and considering the actual situation of the study area, it was finally divided into 2373 blocks with a grid size of 1.2 km × 1.2 km. Afterward, the landscape disturbance index (E_i), landscape vulnerability index (Q_i), and landscape loss index (R_i) were selected to construct the ecological risk value. Specific formulas can be found in the literature [41–43]. Taking 2000 as the baseline, the values were classified into five grades using the natural breaks method: lower (0~0.0582), low (0.0582~0.0717), medium (0.0717~0.0905), high (0.0905~0.1246), and higher (0.1246~1).

4. Results

4.1. Extraction of Restricted Conversion Areas in Dianchi Basin

4.1.1. Spatial Patterns of EFI and ESE

To safeguard the integrity and sustainability of the ecosystem, the distribution pattern of EFI and ESE was identified (Figure 2). The distribution pattern is as follows: medium-importance areas for water source protection are distributed in lakes and reservoirs with sufficient water sources; highly important areas are distributed in some grassland areas in the northern part of the Dianchi basin; medium-importance areas are centrally distributed near construction sites; and important and general areas are distributed in a staggered pattern throughout the entire basin. The distribution of extremely important and highly important areas for soil and water conservation is highly consistent, mainly concentrated in high-altitude areas with high vegetation cover. Important areas surround the generally important areas, which are mainly distributed in areas with low altitude and gentle terrain. The extremely important, highly important, and medium-importance areas for biodiversity are concentrated in the northern part of the Dianchi basin, with sporadic medium-importance areas distributed around the basin. Important areas are distributed in a belt-like pattern around the medium and lower parts of the basin. Generally important areas are mainly located around the Dianchi basin and in the northern part of the area with concentrated construction, which is a region with frequent human activities and a low degree of vegetation cover, posing a certain threat to biodiversity.

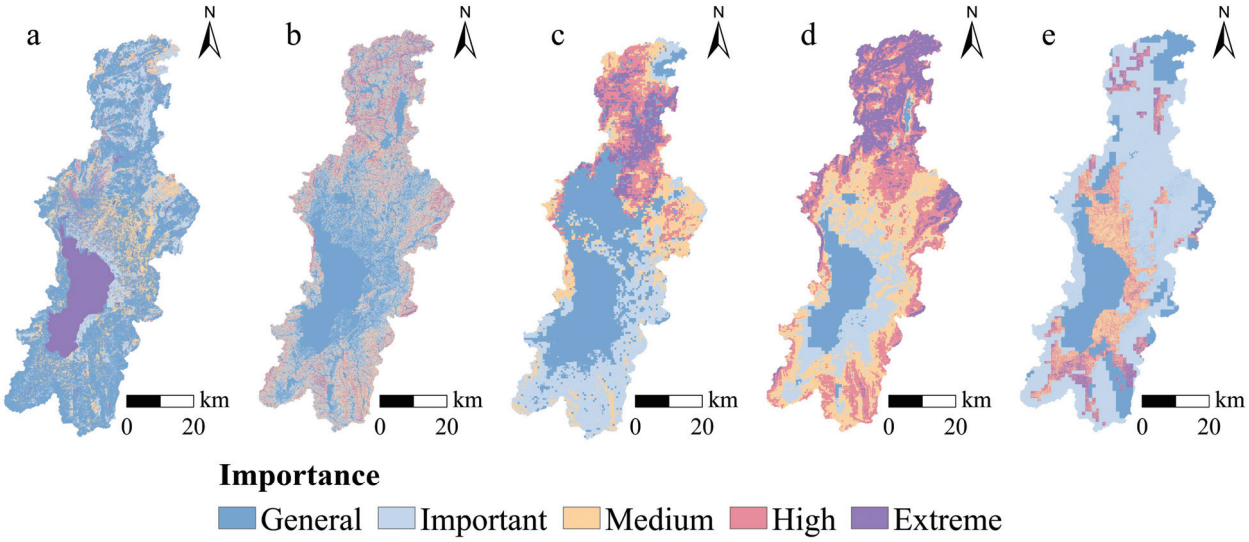


Figure 2. Distribution of EFI and ESE in Dianchi basin. Note: (**a**–**e**) represent, respectively, water source protection, soil and water conservation, biodiversity, soil and water erosion, and rock desertification.

The ESE pattern of the Dianchi basin is as follows: the extremely important areas for soil and water erosion are distributed in the upper and middle parts of the basin; the highly important areas are distributed around the extremely important areas; the moderately important areas, characterized as transition zones, are distributed between the highly important areas and the important areas; and the generally important areas are located in the waters of lakes and reservoirs. The extremely important areas for rocky desertification are scattered throughout the basin in small patches; the highly important areas are sporadically distributed within the moderately important areas; the important areas are distributed in a continuous pattern throughout the entire basin; and the generally

important areas are predominantly situated around the lakes and in the surroundings of the basin. Overall, the pattern in the Dianchi basin shows obvious spatial differences, and the superposition of extremely important areas can effectively identify the key ecological zone in the Dianchi basin.

4.1.2. Identification of Ecological Defense Zone

According to the GDERI, the core scenic areas of scenic spots, national parks, nature reserves, and primary protection zones of drinking water sources are included in the prohibited development zone. These areas include the Kunming World Horticultural Expo, Dianchi, and the National Tourism Resort (as scenic spots); the Yunnan Qipanshan National Forest Park and the Kunming Financial National Forest Park (as forest parks); Jinning Meishucun Nature Reserve (as a nature reserve); and the Songhuaba Reservoir, Dianchi, Caohai, and the Chaihe Reservoir (as primary protection zones of drinking water sources). Adhering to the principle of "should be included as much as possible", the prohibited development zones, extremely important zones in terms of EFI and ESE, were spatially superimposed. Surrounding areas with a map area of less than 1 km^2 were eliminated, and the remaining areas were included in the prevention zone (Figure 3). It was then imported into the PLUS model as restricted zone.

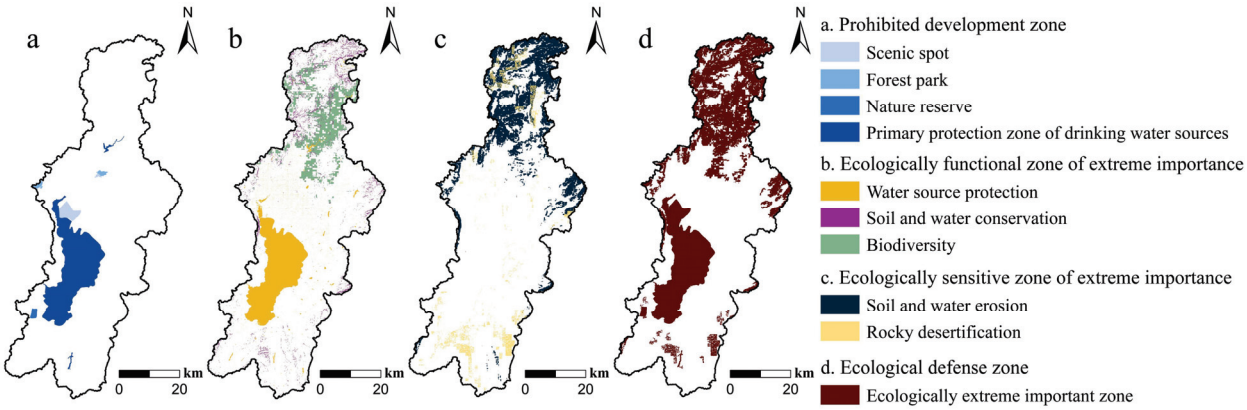


Figure 3. The ecological defense zone of the Dianchi basin.

4.2. Land Use Change Under the Constraint of the Ecological Defense Zone in the Dianchi Basin

4.2.1. Multi-Scenario Simulation of Land Use for 2030

In this study, based on the land use data and driver data from 2020, three development scenarios were designed for simulation by adjusting the neighborhood weights, transfer moments matrix, and land demand. These scenarios include the NS, ES, and PS. The ecological defense zone was then added to each scenario to constrain the conversion of land use types. Each scenario compared land use changes with and without ecological defense zones (Figure 4). Local details were selected for analysis, and it was found that the land use distribution patterns with and without the ecological defense zone were roughly the same. However, the changes in each category in the NS and ES were insignificant, while the area of construction land in the PS was significantly reduced compared to the other two scenarios. Localization analysis revealed differences in detail. In regions I and II, the area of cultivated land was larger in the ES than in the NS, and construction land was more compact in the NS than in the ES. In contrast, construction land was relatively fragmented in the PS. The enhanced protection of ecological land under the PS constrained the expansion of human-interference land categories, such as larger areas of construction land, making it difficult for these areas to merge into larger patches.

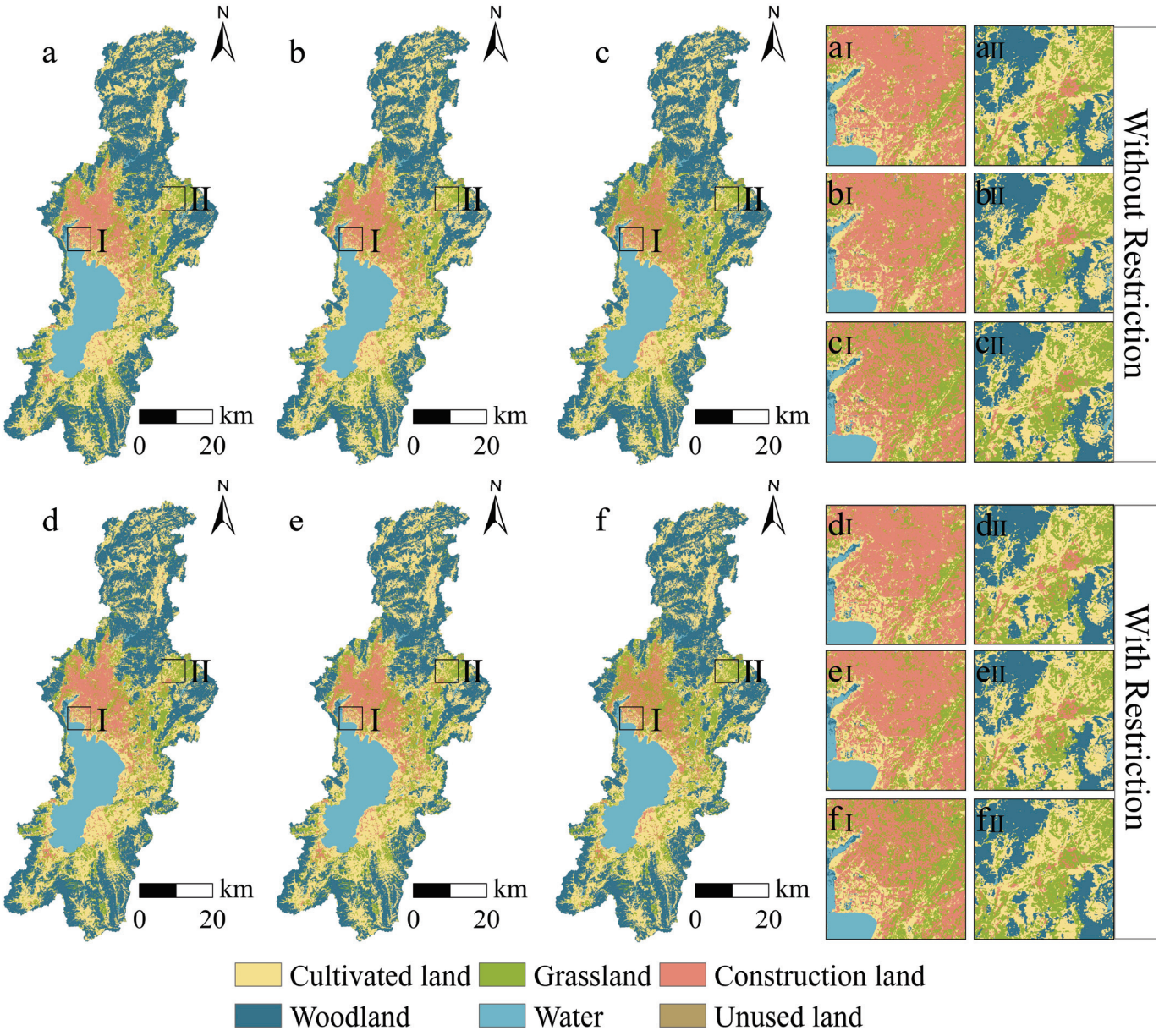


Figure 4. Land use patterns under multiple scenarios in the Dianchi basin for 2030. Note: (**a**–**f**) represent NS, ES, PS, NS (with restricted zone), ES (with restricted zone), and PS (with restricted zone), respectively, and I and II are localized detail comparisons.

As shown in Figure 5, under the NS, the area of water increased slightly, transforming from grassland after the addition of the ecological defense zone, while the rest of the land categories remained unchanged. In the ES, after the inclusion of the ecological defense zone, the area of woodland exceeded that of cultivated land and became the most extensive. Accordingly, the area of natural landscapes, such as grassland and water, increased slightly, while the area of cultivated land decreased. In the PS, after incorporating the ecological defense zone, the area of woodland and grassland increased significantly, while the area of construction land decreased significantly. Overall, in the ES, the difference in the area of cultivated land and woodland was not significant. The rest of the scenarios showed that the area of woodland was the largest, followed by cultivated land, grassland, water, construction land, and unused land. The area of construction land was the highest under the ES, at 289.32 km^2, and the lowest under the PS, at 220.82 km^2. In short, the land

use distribution was influenced by the ecological defense zone. Extracting the zone as a restricted conversion zone effectively inhibited the erosion of natural landscapes by man-made landscapes. Compared with the multi-scenario simulation, the introduction of the ecological defense zone optimized land use allocation and provided a feasible solution to alleviate the conflict between land protection and human development.

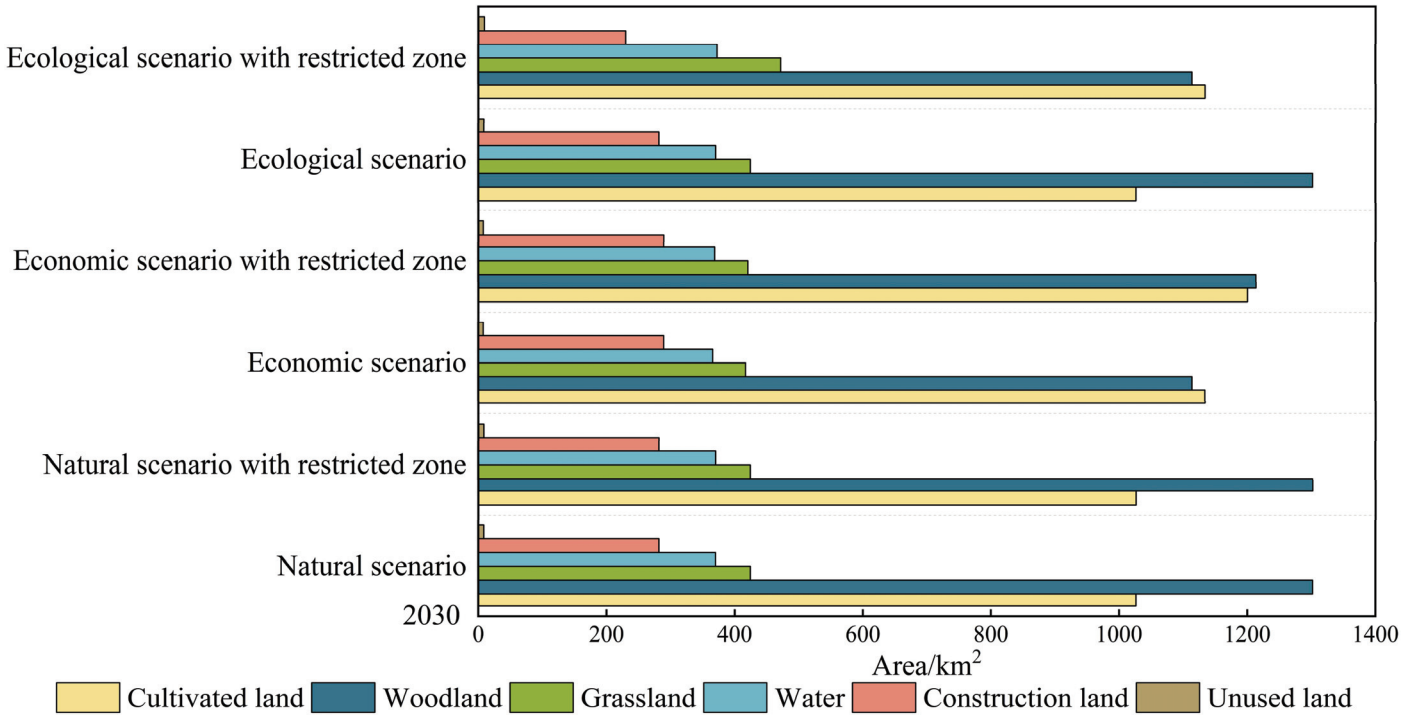


Figure 5. Land use area in the Dianchi basin under multiple scenarios for 2030.

4.2.2. Land Use Changes Between 2020 and 2030

The trend of changes in each land use type in the Dianchi basin from 2020 to 2030 is shown in Figure 6. According to the scenarios alone, cultivated land and construction land see the greatest increase under the ES, with the area of construction land increasing the most significantly, by 75.13 km^2. Under the PS, woodland, water, and unused land experience the greatest increase, with woodland increasing by 50.25 km^2. Grassland shows a decreasing trend in all scenarios, with the largest decrease occurring in the ES, at 73.26 km^2. After the addition of the ecological defense zone, grassland and water increase in the NS compared to the ecological defense zone scenario, while the rest of the land categories remain unchanged. Under the ES, except for construction land and unused land, the remaining land categories change significantly. Under the PS, all land categories change, except for cultivated land. Overall, compared to 2020, ecological land under the ES and the PS increases significantly under the ecological defense zone constraints, compared to scenarios with no constraints.

4.3. Analysis of Ecological Risk Changes Under the Ecological Defense Zone in the Dianchi Basin

4.3.1. Ecological Risk Evaluation Under Multiple Scenarios for 2030

Under different scenarios for 2030, regardless of whether the ecological defense zone is established or not, the results of land use simulation can only indicate the area changes for each category, and do not directly show improvements in ecological conditions. Ecological risk evaluation, based on land use data, can intuitively reflect the pressure exerted on the ecosystem by human activities and natural factors, as shown in Figures 7 and 8. A

vertical comparison reveals that the overall ecological risk of the Dianchi basin for 2030 is at a low level, with varying risk situations under different scenarios. The ecological risk under the PS is lower than that under the NS, and is also lower than that under the ES. This is reflected in the areas with higher risk: 117.45 km^2, 213.47 km^2, and 261.42 km^2, respectively. The distribution pattern of ecological risks in the Dianchi basin is generally similar, with higher risks concentrated at the northern junction of the lake. High risks are distributed around these areas, and a small number of them are scattered in the medium and lower parts of the Dianchi basin. Low risks and lower risks are distributed throughout the Dianchi basin, in the northern part of the basin, and along the edges.

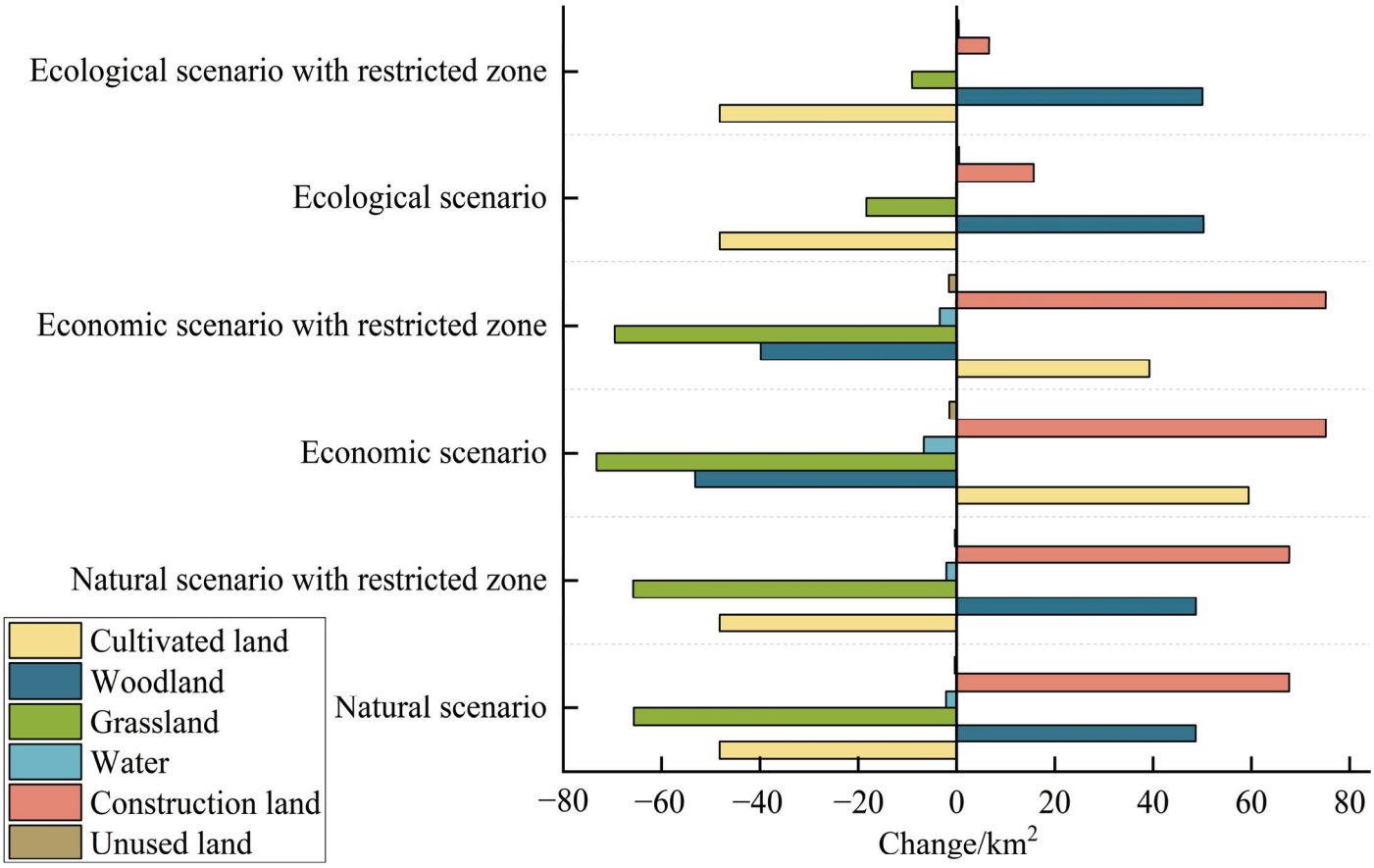


Figure 6. Changes in land use area under multiple scenarios in the Dianchi basin, 2020–2030.

In the horizontal comparison, the ecosystem condition within the ecological defense zone is significantly better than that in scenarios without an ecological defense zone, particularly regarding changes in higher-risk areas. In the NS, the percentage of higher-risk areas without an ecological defense zone (6.25%) is significantly higher than that within the ecological defense zone (3.77%). The higher-risk areas in the Wuhua District and Xishan District are significantly reduced when compared to areas that include the ecological defense zone. In the PS, the higher-risk area without an ecological defense zone accounts for 0.63% more than that with an ecological defense zone. The higher risk at the junction of Guandu, Panlong, Wuhua, and Xishan districts shows a contraction when compared to the condition without ecological defense zone constraints. The difference in the area of high risk with and without an ecological defense zone is minimal (only 0.03% higher), and the higher risk at the junction of Wuhua District and Xishan District is mitigated by the presence of an ecological defense zone. The above results demonstrate

that the establishment of an ecological defense zone has a significant effect on reducing ecological risks and protecting ecosystems.

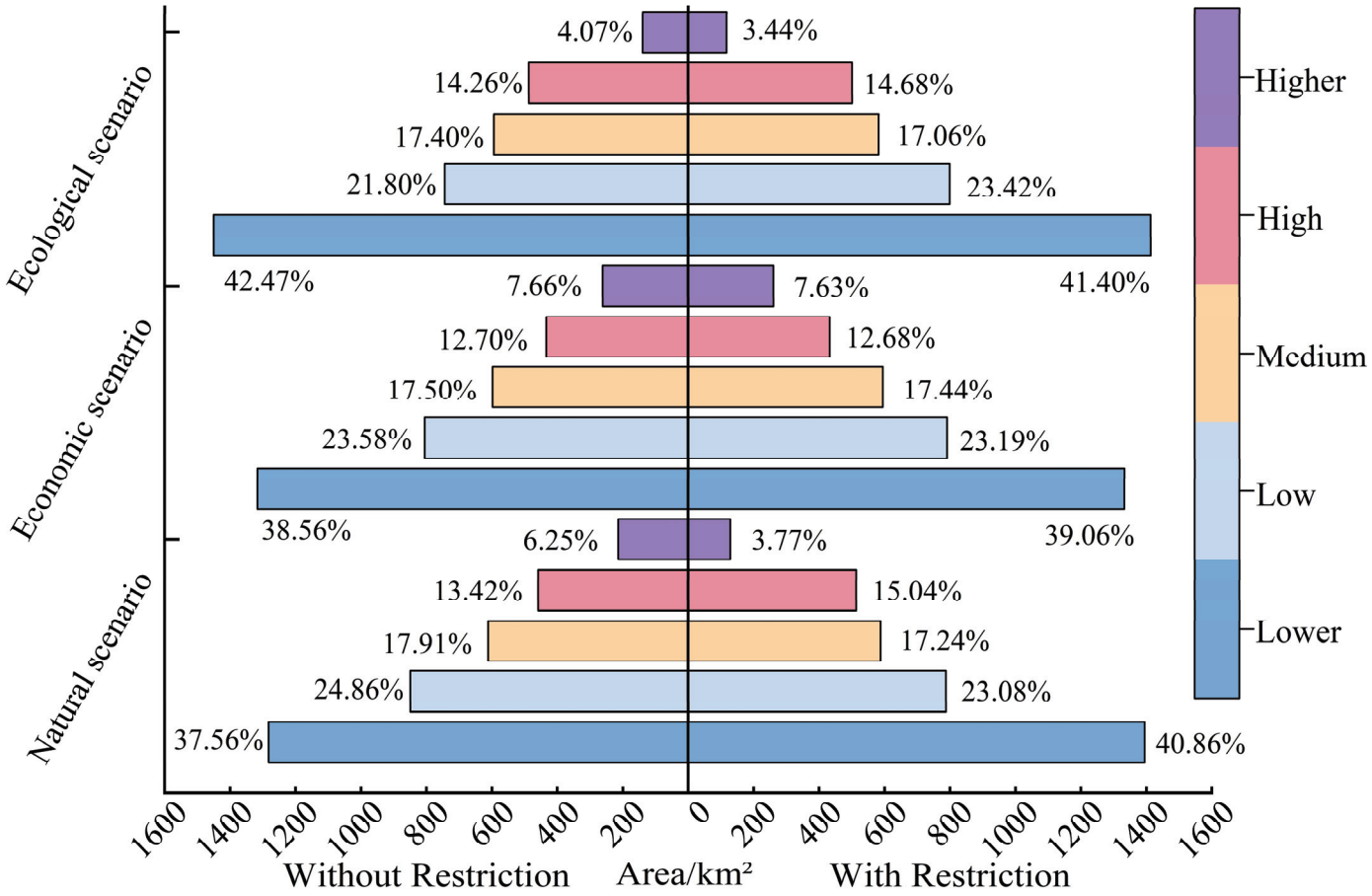


Figure 7. Area and percentage of ecological risk classes under multiple scenarios in Dianchi basin for 2030.

4.3.2. Ecological Risk Changes Between 2020 and 2030

A comparison of the study's end results with the projections indicates which model is most effective in improving ecological risk (Figure 9). Compared to 2020, changes in ecological risk levels for 2030 under different scenarios primarily occur between neighboring levels, and the proportion of area where the ecological risk level remains unchanged is consistently the highest. Without the constraint of an ecological defense zone, only the PS has more areas with decreasing ecological risk levels than increasing levels. Under the constraints of an ecological defense zone, only the ES has more areas where the ecological risk level increases than decreases.

Specifically, in the NS, the area with reduced ecological risk levels in the northern part of Dianchi Lake significantly expands under the condition of ecological defense zone constraints, and the percentage of area with reduced ecological risk rises from 1.11% to 7.02%. In the ES, the area with an elevated ecological risk rating is always more than the area with a reduced ecological risk rating. Compared with the condition without ecological defense zone constraints, the proportion of area with reduced ecological risk increases by 0.23%, mainly distributed in the northern part of the Dianchi basin. Under the PS, the area with reduced ecological risk levels in the northern part of the Dianchi basin shrinks, while the area with reduced risk levels in the medium and lower parts of the basin shows an expansion trend. The percentage of area with reduced ecological risk rank expands from

7.99% to 8.33%; the area with an elevated rank slightly increases from 2.53% to 2.57%. These results indicate that, considering the connection between predicted and historical data, the establishment of ecological defense zones has a significant effect on reducing ecological risks and improving ecosystem conditions, especially in the NS and PS. Ecological defense zone are able to effectively contribute to a reduction in ecological risk grades over a large area.

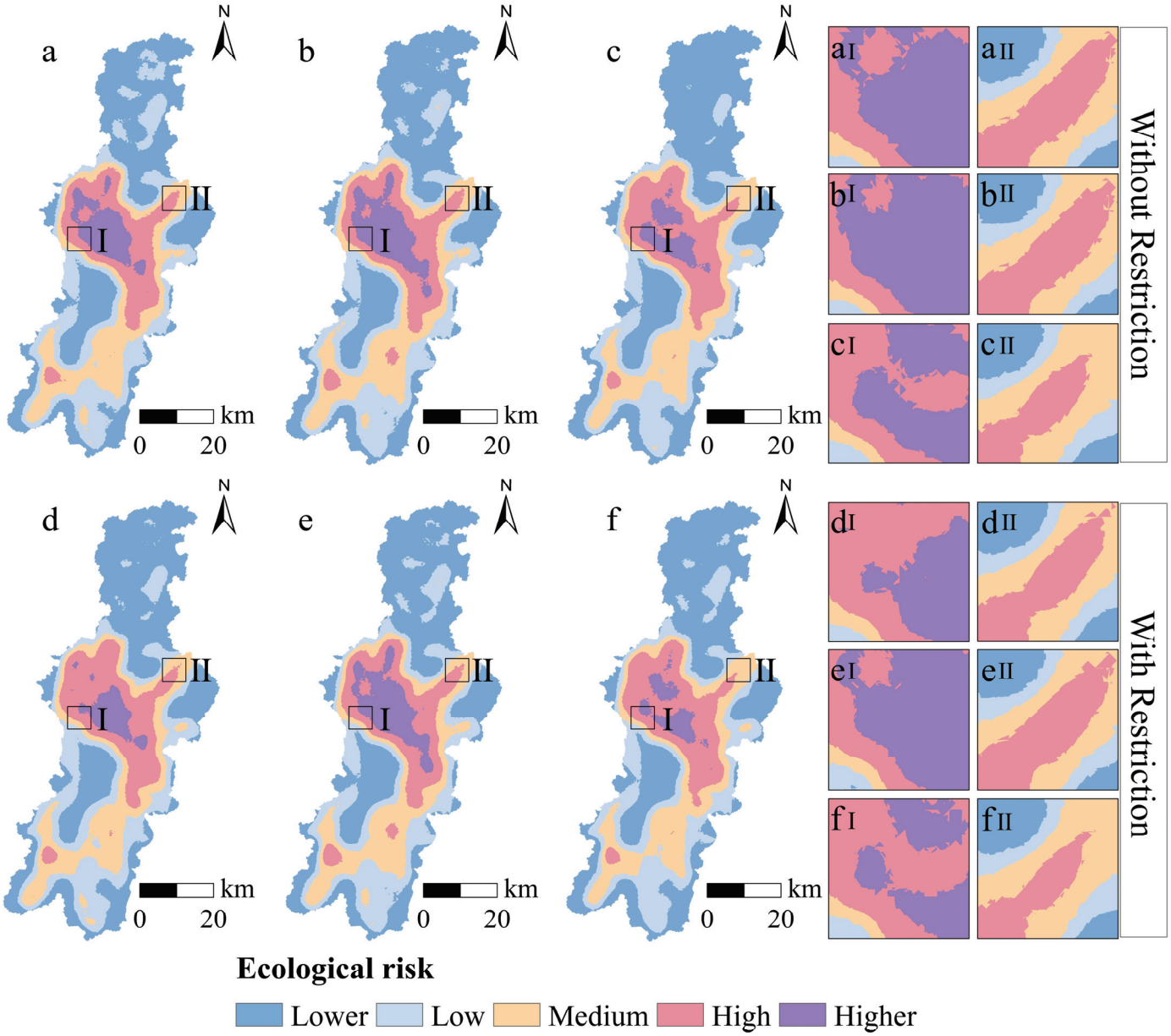


Figure 8. Ecological risk evaluation under multiple scenarios for Dianchi basin for 2030. Note: (**a**–**f**) represent NS, ES, PS, NS (with restricted zone), ES (with restricted zone), and PS (with restricted zone), respectively, and I and II are localized detail comparisons.

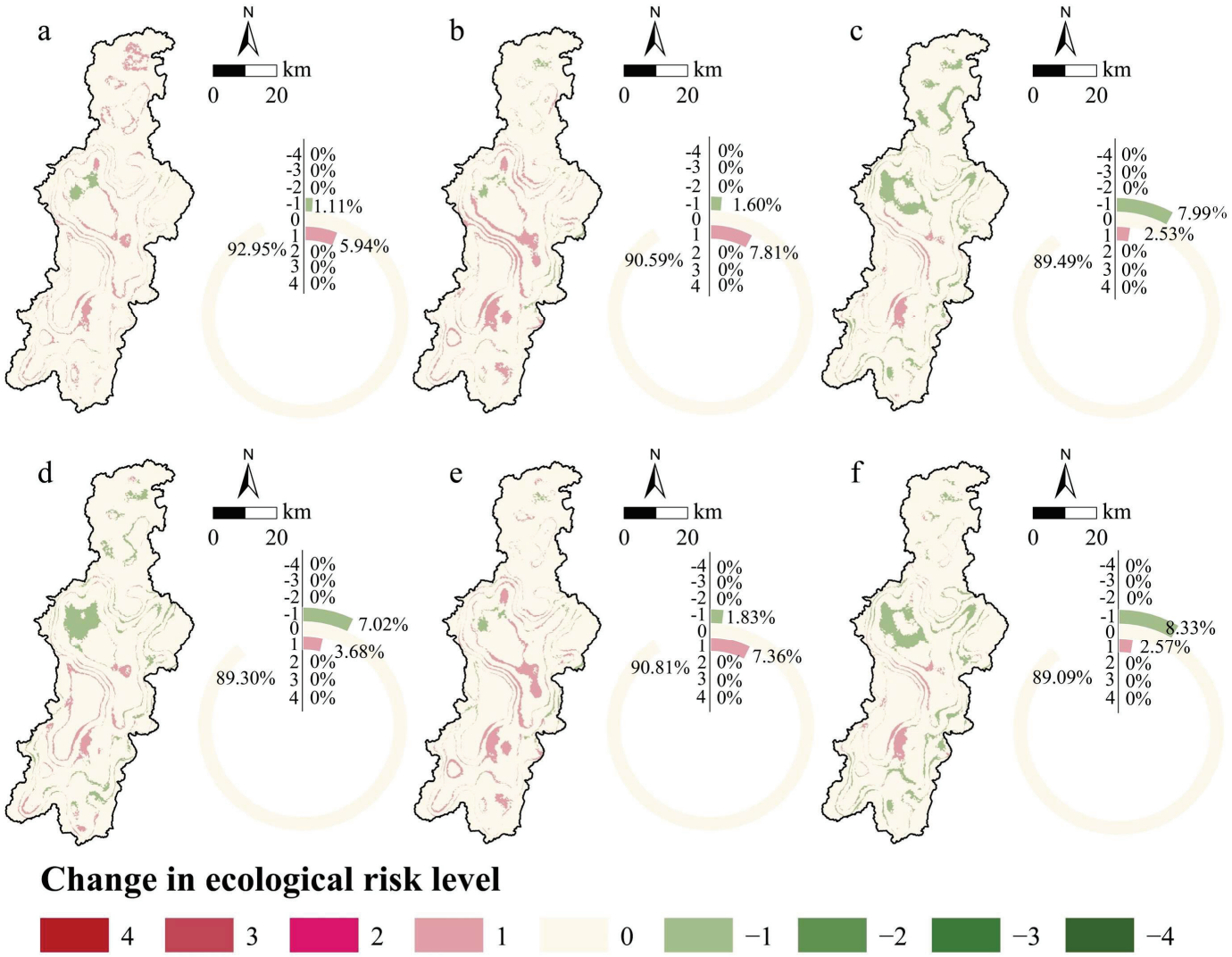


Figure 9. Changes in the ecological risk level under multiple scenarios in the Dianchi basin, 2020–2030. Note: (**a**–**f**) represent NS, ES, PS, NS (with restricted zone), ES (with restricted zone), and PS (with restricted zone), respectively, and I and II are the localized detail comparisons. The number 1 indicates an increase in ecological risk by one level, −1 indicates a decrease in ecological risk by one level.

5. Discussion

5.1. Significance of Ecological Defense Zone for Future Land Layout Optimization

The ecological defense zone serves as a constraint for land use, and the relevant literature was combined to establish the land use scenarios for 2030 [44–46]. By comparing the NS, ES, and PS both with and without the ecological defense zone, a significant difference in land use area was observed. The ecological defense zone extracted in this study not only restricts the conversion of land use types, but also takes into account the constraining effects of prohibited development, EFI, and ESE on land use change. On the one hand, it protects the ecological land areas with higher elevation and maintains the stability of ecologically valuable areas. On the other hand, it safeguards water areas and reduces the damage caused by human activities to water quality and the environment. It can be seen that the ecological defense zone can coordinates the development of economy, society, and ecology. By maintaining the EFI and protecting the vulnerability of ecosystems, it not only

prevents ecosystem destruction due to land development, but also provides a scientific spatial layout scheme for ecological restoration and natural recovery.

Some findings of this study are highly consistent with the conclusions of existing research, further confirming the pivotal role of the ecological priority strategy in optimizing land resource allocation and mitigating ecological risks. For instance, compared to 2020, the area of construction land increases under both scenarios, with or without the restriction of an ecological defense zone, and cultivated land and woodland remain the predominant land use types in the study area [47]. Under the ES, the area of cultivated land and construction land increases further. However, due to the lack of effective ecological constraints, overexploitation and irrational land use patterns exacerbate the ecological pressure in the region, making the risk of ecological degradation more severe than in the NS [11]. In contrast, the PS achieves synergistic growth of woodland, water, and construction land through scientific planning and a strategy of ecological prioritization. Despite the increase in construction land compared to 2020, ecological risk is effectively regulated, and the regional ecological quality is the best among the three scenarios [48].

5.2. Implications of Ecological Risk Assessment for Future Sustainable Management of Ecological Ecosystems

Previous scholars have analyzed land use changes to assess improvements in regional ecological status [49–51]. The theoretical basis is that there is a linear correspondence between land use type and ecosystem status. However, in this study, we found that relying solely on the conversion of land use types in statistical results could not fully reflect the complex state of regional ecosystems. This was particularly true after the introduction of ecological risk assessment, as the two approaches yielded different conclusions.

Our results show that with the superimposed ecological defense zone, the area of ecological land (woodland, waters, etc.) under both the ES and the PS increased significantly from 2020 to 2030, compared to scenarios without ecological defense zones. Only the grassland (+0.10 km^2) and water (-0.10 km^2) under the NS showed small changes. Empirically, a significant increase in the area of ecological land with the inclusion of the ecological defense zone should directly correspond to an overall improvement in the quality of the ecosystem. However, after evaluating the ecological risk, it was found that under the NS, the ecological risk was most significantly improved after the addition of ecological control zones compared to the other scenarios, with the area of reduced ecological risk increasing by 5.91%. This was different from the ecosystem improvement results obtained from the land use analysis. This indicates that it is too one-sided to conclude the ecosystem status solely from the trend of land use change. Ecological risk is considered to be related to the adverse effects of land use layout and ecological dynamic processes [52]. Therefore, ecological risk evaluation was added in this study, which can more accurately explore the ecosystem status behind land use.

The heterogeneity of the assessment results stems from the limitations of traditional research models: firstly, they ignore the non-linear impacts of the spatial configuration of land use on ecological processes, such as the hidden risks of landscape fragmentation and landscape loss; secondly, they fail to take into account the synergistic and antagonistic effects generated by different combinations of land types, such as the biodiversity maintenance function of the cultivated land–woodland intertwined zone; thirdly, they lack dynamic considerations of ecosystem resilience. This study innovatively constructs an integrated framework of "ecological defense zone, land use, and risk identification". By introducing the landscape pattern index, the risk status of the study area is effectively

delineated, and these areas can often be developed with different development strategies depending on the level of risk.

5.3. Management Strategies for Ecological Vulnerability and Ecological Risks in Urban-Type Lake Basin Environments

As a typical urban lake, Dianchi Lake's water environment exhibits close linkage between ecological vulnerability and ecological risk. Ecological vulnerability refers to an ecosystem's high sensitivity to external disturbances and its relatively weak recovery capacity [53]. Dianchi Lake is heavily affected by factors such as urban domestic sewage and industrial wastewater discharge, making its water quality highly susceptible to degradation. Once damaged, restoring it to its original state often requires a long time and substantial effort. The connection between ecological vulnerability and ecological risk is evident. Ecological risk denotes the probability of harm to ecosystems [54], including threats like biodiversity loss and water quality deterioration. Lakes with higher ecological vulnerability tend to face greater ecological risks. For instance, due to its ecological fragility, Dianchi Lake is prone to eutrophication when heavy rainfall washes large quantities of pollutants into the lake—a clear manifestation of ecological risk.

From a landscape pattern perspective, ecological risk is primarily reflected in landscape fragmentation and disturbance [55]. Issues such as sewage inflow and excessive land development within the basin have severely damaged the natural landscape, reducing connectivity between patches and thereby elevating ecological risk. Ecologically, Dianchi Lake's severe eutrophication correlates with its low biodiversity (see Figure 2c). Once a "Pearl of the Plateau", Dianchi's low-lying topography, combined with sustained wastewater discharge from Kunming and overdevelopment, has compromised its ecosystem integrity. At its worst, the water quality degraded to Class V, ranking it among China's most polluted freshwater lakes. According to Yunnan Province's monthly water quality reports for plateau lakes, Dianchi's water quality remains highly unstable and heavily polluted. While Caohai's water quality has reached Class V, the outer lake remains below Class V.

To mitigate these ecological risks, the Chinese government has introduced policies in recent years. In 2018, the Opinions of the Central Committee of the Communist Party of China and the State Council on Strengthening Ecological Environmental Protection and Resolutely Fighting the Battle of Pollution Prevention and Control explicitly advocated for the intensification of environmental management, emphasizing the holistic concept of "mountains, rivers, forests, farmlands, lakes, and grasslands as a life community". In 2019, Yunnan's Implementation Plan for the Battle of Nine Plateau Lakes Governance prioritized protection to ensure ecological quality "only improves, never deteriorates", shifting from "lake-specific" to "basin-wide" governance. The 2021 Opinions on the "Lake Revolution" Campaign called for a comprehensive overhaul of governance concepts, measures, and mechanisms, underscoring Yunnan's resolve. The basin features stunning landscapes and is a key tourist hub in Yunnan. Its unique geography and strategic position make it vital for Yunnan's ecological civilization construction and regional ecological security. Government policies have effectively curbed risks from eutrophication.

5.4. Limitations

Of course, there are limitations to this research. Within the PLUS model's parameter configuration, the conversion rule from grassland to construction land significantly influenced the final simulation results. Adjusting the parameters several times revealed that this phenomenon may be closely related to the spatial heterogeneity of the study

area. Both types of land in the northern region of Dianchi are highly spatially neighboring, which led to the mutual reinforcement of the conversion probabilities of the two land classes in the neighborhood effect calculation of the CA. This amplified the sensitivity of the grassland conversion parameter to the simulation results. To address this, future studies need to further optimize the neighborhood weighting algorithm or introduce a spatial heterogeneity calibration module into the model framework to reduce the excessive interference of specific land class distributions on simulation results.

6. Conclusions

This study integrates various ecological conditions to determine the restricted conversion zones for land use change in the Dianchi basin. It conducts multi-scenario simulations of land use in the basin for 2030 and, based on these, performs ecological risk evaluations. The study compares the trends of change with and without ecological defense zones, to identify the most suitable land planning mode for the Dianchi basin and to provide theoretical support for its ecological rehabilitation and sustainable development. The main conclusions are as follows: (1) Except for water source conservation, the rest of the generally important zones include the Dianchi area. The extremely important zones for water source conservation, soil and water conservation, and biodiversity evaluation were overlaid to identify the most critical areas for ecosystem function. The mountainous areas with higher elevations exhibit the highest sensitivity to soil and water erosion, while the overall sensitivity to rocky desertification in the basin is lower. (2) The land use types in the Dianchi basin for 2030 are dominated by cultivated land and woodland, and the distribution of ecological risks under different scenarios is similar to the historical distribution. Compared to the NS and ES, the PS shows a decreasing trend in ecological risk, which is more conducive to alleviating the ecological risk of the basin and aligns better with the needs of ecological management. (3) With the addition of ecological defense zones as constraints, ecological risks in all scenarios show an improving trend. The NS shows greater improvement than the PS, which, in turn, shows greater improvement than the ES. The most significant improvement is observed in the northern part of Dianchi lake. In summary, adding an ecological prevention zone as a constraint in the PS offers greater advantages in the efficient allocation of land resources, and highlights their scientific and prospective importance in optimizing the ecological environment, which is particularly evident in ecological risk evaluations.

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Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

NS	Natural scenario
ES	Economic scenario
PS	Ecological scenario
EFI	Ecological function importance
ESE	Ecological sensitivity
GDERI	Guidelines for the Delineation of Ecological Red Lines

References

1. Wu, J.; Han, P.; Zhai, J.; Zhang, Q. Innovative Perspectives on Ecological Assessment in the Agro-Pastoral Ecotone of Inner Mongolia: An Integrated Evaluation and Forecast of Landscape and Ecological Risks and Drivers. *Land* **2024**, *13*, 1849. [CrossRef]
2. Solomon, K.R.; Baker, D.B.; Richards, R.P.; Dixon, K.R.; Klaine, S.J.; La Point, T.W.; Kendall, R.J.; Weisskopf, C.P.; Giddings, J.M.; Giesy, J.P.; et al. Ecological risk assessment of atrazine in North American surface waters. *Environ. Toxicol. Chem.* **1996**, *15*, 31–76. [CrossRef]
3. Abdullah, S.; Adnan, M.S.G.; Barua, D.; Murshed, M.M.; Kabir, Z.; Chowdhury, M.B.H.; Hassan, Q.K.; Dewan, A. Urban green and blue space changes: A spatiotemporal evaluation of impacts on ecosystem service value in Bangladesh. *Ecol. Inform.* **2022**, *70*, 101730. [CrossRef]
4. Cervelli, E.; Pindozzi, S.; Sacchi, M.; Capolupo, A.; Cialdea, D.; Rigillo, M.; Boccia, L. Supporting land use change assessment through Ecosystem Services and Wildlife Indexes. *Land Use Policy* **2017**, *65*, 249–265. [CrossRef]
5. Guo, J.; Shen, B.; Li, H.; Wang, Y.; Tuvshintogtokh, I.; Niu, J.; Potter, M.A.; Li, F.Y. Past dynamics and future prediction of the impacts of land use cover change and climate change on landscape ecological risk across the Mongolian plateau. *J. Environ. Manag.* **2024**, *355*, 120365. [CrossRef]
6. Rahman, M.; Islam, M.M.; Kim, H.-J.; Sadiq, S.; Alam, M.; Siddiqua, T.; Mamun, M.A.; Gazi, M.A.H.; Raju, M.R.; Chen, N.; et al. Assessing the Influence of Land Cover and Climate Change Impacts on Runoff Patterns Using CA-ANN Model and CMIP6 Data. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 401. [CrossRef]
7. Fulford, R.S.; Russell, M.; Myers, M.; Malish, M.; Delmaine, A. Models help set ecosystem service baselines for restoration assessment. *J. Environ. Manag.* **2022**, *317*, 115411. [CrossRef]
8. Jing, Z.; Weihua, F.; Peijun, S.; Li, Z. Modeling the impacts of land use change on hydrological processes in fast urbanizing region—A case study of the Buji watershed in Shenzhen City, China. *J. Nat. Resour.* **2009**, *24*, 1560–1572.
9. Karimian, H.; Zou, W.; Chen, Y.; Xia, J.; Wang, Z. Landscape ecological risk assessment and driving factor analysis in Dongjiang river watershed. *Chemosphere* **2022**, *307*, 135835. [CrossRef]
10. Wu, J.; Luo, J.; Zhang, H.; Qin, S.; Yu, M. Projections of land use change and habitat quality assessment by coupling climate change and development patterns. *Sci. Total Environ.* **2022**, *847*, 157491. [CrossRef]
11. Neyret, M.; Peter, S.; Le Provost, G.; Boch, S.; Boesing, A.L.; Bullock, J.M.; Hölzel, N.; Klaus, V.H.; Kleinebecker, T.; Krauss, J.; et al. Landscape management strategies for multifunctionality and social equity. *Nat. Sustain.* **2023**, *6*, 391–403. [CrossRef]
12. Cao, M.; Tian, Y.; Wu, K.; Chen, M.; Chen, Y.; Hu, X.; Sun, Z.; Zuo, L.; Lin, J.; Luo, L.; et al. Future land-use change and its impact on terrestrial ecosystem carbon pool evolution along the Silk Road under SDG scenarios. *Sci. Bull.* **2023**, *68*, 740–749. [CrossRef] [PubMed]
13. Sui, L.; Yan, Z.; Li, K.; Wang, C.; Shi, Y.; Du, Y. Prediction of ecological security network in Northeast China based on landscape ecological risk. *Ecol. Indic.* **2024**, *160*, 111783. [CrossRef]
14. Li, C.; Qin, F.; Liu, Z.; Pan, Z.; Gao, D.; Han, Z. Multi-scenario assessment of landscape ecological risk in the transitional zone between the warm temperate zone and the northern subtropical zone. *Front. Ecol. Evol.* **2024**, *12*, 1471164. [CrossRef]
15. You, C.; Qu, H.; Zhang, S.; Guo, L. Assessment of Uncertainties in Ecological Risk Based on the Prediction of Land Use Change and Ecosystem Service Evolution. *Land* **2024**, *13*, 535. [CrossRef]
16. Huang, J.; Wang, Y. Ventilation potential simulation based on multiple scenarios of land-use changes catering for urban planning goals in the metropolitan area. *J. Clean. Prod.* **2024**, *483*, 144301. [CrossRef]

17. Xu, D.; Yu, C.; Lin, W.; Yao, J.; Zhou, W. Spatiotemporal Evolution and Prediction of Land Use and Carbon Stock in Shanghai. *Land* **2024**, *13*, 267. [CrossRef]
18. Xin, X.; Zhou, J.; Johnson, V.C.; Shi, J.; Tan, M.L.; Zhang, F. Multi-scenario land use change simulation and spatial-temporal evolution of carbon storage in the Yangtze River Delta region based on the PLUS-InVEST model. *PLoS ONE* **2025**, *20*, e0316255. [CrossRef]
19. Nie, W.; Xu, B.; Yang, F.; Shi, Y.; Liu, B.; Wu, R.; Lin, W.; Pei, H.; Bao, Z. Simulating future land use by coupling ecological security patterns and multiple scenarios. *Sci. Total Environ.* **2023**, *859*, 160262. [CrossRef]
20. Li, Y.; Ma, Q.; Song, Y.; Han, H. Bringing conservation priorities into urban growth simulation: An integrated model and applied case study of Hangzhou, China. *Resour. Conserv. Recycl.* **2019**, *140*, 324–337. [CrossRef]
21. Gao, L.; Tao, F.; Liu, R.; Wang, Z.; Leng, H.; Zhou, T. Multi-scenario simulation and ecological risk analysis of land use based on the PLUS model: A case study of Nanjing. *Sustain. Cities Soc.* **2022**, *85*, 104055. [CrossRef]
22. Kang, L.; Yang, X.; Gao, X.; Zhang, J.; Zhou, J.; Hu, Y.; Chi, H. Landscape ecological risk evaluation and prediction under a wetland conservation scenario in the Sanjiang Plain based on land use/cover change. *Ecol. Indic.* **2024**, *162*, 112053. [CrossRef]
23. Hu, S.; Chen, L.; Li, L.; Zhang, T.; Yuan, L.; Cheng, L.; Wang, J.; Wen, M. Simulation of Land Use Change and Ecosystem Service Value Dynamics under Ecological Constraints in Anhui Province, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 4228. [CrossRef] [PubMed]
24. Qi, B.; Yu, M.; Li, Y. Multi-Scenario Prediction of Land-Use Changes and Ecosystem Service Values in the Lhasa River Basin Based on the FLUS-Markov Model. *Land* **2024**, *13*, 597. [CrossRef]
25. Song, X.; Zhang, Z.; Wang, Z.; Liu, Y. Development vs. conservation in limited urban sprawl: An integrated framework for resolving the urban boundary dilemma in China. *J. Geogr. Sci.* **2024**, *34*, 1371–1393. [CrossRef]
26. Luan, C.; Liu, R.; Sun, J.; Su, S.; Shen, Z. An Improved Future Land-Use Simulation Model with Dynamically Nested Ecological Spatial Constraints. *Remote Sens.* **2023**, *15*, 2921. [CrossRef]
27. Tong, X.; Feng, Y. A review of assessment methods for cellular automata models of land-use change and urban growth. *Int. J. Geogr. Inf. Sci.* **2019**, *34*, 866–898. [CrossRef]
28. Clarke, K.C.; Gaydos, L.J. Loose-coupling a cellular automaton model and GIS: Long-term urban growth prediction for San Francisco and Washington/Baltimore. *Int. J. Geogr. Inf. Sci.* **1998**, *12*, 699–714. [CrossRef]
29. Liu, X.; Liang, X.; Li, X.; Xu, X.; Ou, J.; Chen, Y.; Li, S.; Wang, S.; Pei, F. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. *Landsc. Urban Plan.* **2017**, *168*, 94–116. [CrossRef]
30. Yao, Y.; Jiang, Y.; Sun, Z.; Li, L.; Chen, D.; Xiong, K.; Dong, A.; Cheng, T.; Zhang, H.; Liang, X.; et al. Applicability and sensitivity analysis of vector cellular automata model for land cover change. *Comput. Environ. Urban Syst.* **2024**, *109*, 102090. [CrossRef]
31. Wang, Q.; Xiao, X.; Yao, A.; Hillman, A.L.; Jiang, Z.; Wang, R.; Yang, X. Unraveling the early human impacts on the ecosystem of Dianchi Lake: A 20,000-year diatom record from the southeastern Tibetan Plateau. *Quat. Sci. Rev.* **2024**, *337*, 108813. [CrossRef]
32. Cai, F.; Tang, B.-H.; Sima, O.; Chen, G.; Zhang, Z. Fine Extraction of Plateau Wetlands Based on a Combination of Object-Oriented Machine Learning and Ecological Rules: A Case Study of Dianchi Basin. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2024**, *17*, 5364–5377. [CrossRef]
33. Yang, J.; Huang, X. The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth Syst. Sci. Data* **2021**, *13*, 3907–3925. [CrossRef]
34. Yu, P.; Feng, M.; Liu, B.; Bai, S.; Gu, S.; Chen, Y. Demarcation and administration of watershed ecological protection red line considering the ecological security pattern—A case of the Qilu Lake watershed, Yunnan Province. *J. Lake Sci.* **2020**, *32*, 89–99.
35. Wang, Z.; Li, W.; Li, Y.; Qin, C.; Lv, C.; Liu, Y. The "Three Lines One Permit" policy: An integrated environmental regulation in China. *Resour. Conserv. Recycl.* **2020**, *163*, 105101. [CrossRef]
36. Shen, M.; Liu, Y.; Zheng, H.; Chen, J. Evaluation of Water Source Conservation Service Value and Its Spatial Transfer in Yangtze River Basin. *J. Yangtze River Sci. Res. Inst.* **2024**, *41*, 14–22.
37. Zhang, W.; Fu, J. Rainfall erosivity estimation under different rainfall amount. *Resour. Sci.* **2003**, *25*, 35–41.
38. Williams, J.R.; Jones, C.A.; Dyke, P.T. A Modeling Approach to Determining the Relationship Between Erosion and Soil Productivity. *Trans. ASAE* **1984**, *27*, 0129–0144. [CrossRef]
39. Liang, X.; Guan, Q.; Clarke, K.C.; Liu, S.; Wang, B.; Yao, Y. Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: A case study in Wuhan, China. *Comput. Environ. Urban Syst.* **2021**, *85*, 101569. [CrossRef]
40. Wang, Z.; Zhong, A.; Li, Q. Optimization of Land Use Structure Based on the Coupling of GMOP and PLUS Models: A Case Study of Lvliang City, China. *Land* **2024**, *13*, 1335. [CrossRef]
41. Yang, S.; Jin, Z. Impact of road network expansion on landscape ecological risk and soil erosion sensitivity on the Luochuan Tableland of the Chinese Loess Plateau. *Reg. Environ. Change* **2024**, *24*, 37. [CrossRef]

42. Bhardwaj, P.; Yu, Y.; Cui, W.; Liu, S.; Yu, T.; Song, Y. Evolutionary analysis of landscape ecological risk in Baili Rhododendron National Forest Park. *PLoS ONE* **2025**, *20*, e0317851. [CrossRef]
43. Yaermaimaiti, A.; Li, X.; Ge, X.; Liu, C. Analysis of landscape pattern and ecological risk change characteristics in Bosten Lake basin based on optimal scale. *Ecol. Indic.* **2024**, *163*, 112120. [CrossRef]
44. Hou, X.; Song, B.; Zhang, X.; Wang, X.; Li, D. Multi-scenario Simulation and Spatial-temporal Analysis of LUCC in China's Coastal Zone Based on Coupled SD-FLUS Model. *Chin. Geogr. Sci.* **2024**, *34*, 579–598. [CrossRef]
45. Mutale, B.; Qiang, F. Modeling future land use and land cover under different scenarios using patch-generating land use simulation model. A case study of Ndola district. *Front. Environ. Sci.* **2024**, *12*, 1362666. [CrossRef]
46. Koko, A.F.; Han, Z.; Wu, Y.; Zhang, S.; Ding, N.; Luo, J. Spatiotemporal Analysis and Prediction of Urban Land Use/Land Cover Changes Using a Cellular Automata and Novel Patch-Generating Land Use Simulation Model: A Study of Zhejiang Province, China. *Land* **2023**, *12*, 1525. [CrossRef]
47. Chen, S.; Yao, S. Identifying the drivers of land expansion and evaluating multi-scenario simulation of land use: A case study of Mashan County, China. *Ecol. Inform.* **2023**, *77*, 102201. [CrossRef]
48. Gan, L.; Halik, Ü.; Shi, L.; Welp, M. Ecological risk assessment and multi-scenario dynamic prediction of the arid oasis cities in northwest China from 1990 to 2030. *Stoch. Environ. Res. Risk Assess.* **2023**, *37*, 3099–3115. [CrossRef]
49. Wang, Y.; Wang, J.; Hao, B.; Zhang, S.; Ding, J.; He, B. Multi-Scenario Simulation of Future Land Use in the Beijiang River Basin Under Multidimensional Ecological Constraints. *Sustainability* **2024**, *16*, 10910. [CrossRef]
50. Gong, J.; Du, H.; Sun, Y.; Zhan, Y. Simulation and prediction of land use in urban agglomerations based on the PLUS model: A case study of the Pearl River Delta, China. *Front. Environ. Sci.* **2023**, *11*, 1306187. [CrossRef]
51. Ma, X.; Li, J.; Li, G. Simulation and multi-scenario prediction of land-use change in the Gansu section of the Yellow River Basin, China. *Front. Environ. Sci.* **2024**, *12*, 1403248. [CrossRef]
52. Zhang, Z.; Yu, H.; He, N.; Jin, G. Future land use simulation model-based landscape ecological risk prediction under the localized shared socioeconomic pathways in the Xiangjiang River Basin, China. *Environ. Sci. Pollut. Res.* **2024**, *31*, 22774–22789. [CrossRef] [PubMed]
53. Han, X.; Pan, B.; Pan, Z.; Xu, N.; Wu, J.; Sun, W.; Hou, B.; Dong, Y. A clustering approach based on high-resolution ecological vulnerability index reveals spatial patterns of per- and polyfluoroalkyl substances pollution in lakes on the Tibetan Plateau. *Water Res.* **2025**, *279*, 123461. [CrossRef] [PubMed]
54. Shamuxi, A.; Han, B.; Jin, X.; Wusimanjiang, P.; Abudukerimu, A.; Chen, Q.; Zhou, H.; Gong, M. Spatial pattern and driving mechanisms of dryland landscape ecological risk: Insights from an integrated geographic detector and machine learning model. *Ecol. Indic.* **2025**, *172*, 113305. [CrossRef]
55. Yan, J.; Li, J.; Yao, X.; Li, Q.; Zheng, Z.; Li, G.; Qi, G.; Ma, W.; Song, M.; Gao, P. Ecological security pattern construction based on landscape ecological risk assessment in the Yellow River basin. *Front. Environ. Sci.* **2025**, *13*, 1514599. [CrossRef]

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A GIS-Based Approach to Land Take Monitoring and Actual Land Use Analysis

Peter Lamovec [1,*], Katarina Kuk [1], Barbara Černič [1], Tomaž Černe [2] and Ines Lupše [3,*]

[1] Geodetic Institute of Slovenia, Jamova cesta 2, 1000 Ljubljana, Slovenia; katarinakuk@gis.si (K.K.); barbara.cernic@gis.si (B.Č.)
[2] IGEA d.o.o., Podpeška cesta 1, 1351 Brezovica pri Ljubljani, Slovenia; tomaz.cerne@igea.si
[3] Ministry of Natural Resources and Spatial Planning, Spatial Planning and Construction Directorate, Dunajska cesta 48, 1000 Ljubljana, Slovenia
* Correspondence: peter.lamovec@gis.si (P.L.); ines.lupse@gov.si (I.L.)

Abstract: In September 2023, the European Commission approved a proposal for a Directive on Soil Monitoring and Resilience, representing a significant step forward in the EU's efforts toward more sustainable land use management. The proposal mandates the monitoring of land take and soil sealing indicators but does not specify the method for determining their values. Instead, it allows for the use of scientific literature or other publicly available methods. This study presents a methodology based on GIS analyses for monitoring artificial land and the land take indicator. A quantitative analysis of two municipalities in the Podravska region in Slovenia is complemented by a qualitative assessment of detailed actual land use in these municipalities. The results show that the annual land take rate in the period 2019–2022 amounted to 881.96 m^2/year·km^2 in the municipality of Maribor and 731.31 m^2/year·km^2 in the municipality of Kungota. If current trends continue, the extent of (semi-)natural land will continue to decline, which is considered unsustainable. Further analysis reveals that the expansion of artificial land in these areas is mainly due to the development of new residential land, accounting for 60.8% of newly converted land in the municipality of Maribor and 50.2% in the municipality of Kungota during the period under review. As the results point to unsustainable land management, the study is aimed at policymakers and public authorities, highlighting the urgent need to limit the conversion of (semi-)natural land and to initiate land restoration measures as compensation for new land take. It may also be of interest to scientists and researchers developing methodologies for monitoring artificial land and refining land take indicators.

Keywords: land take; land use; spatial planning; artificialization; artificial land; circular spatial management

1. Introduction

All human activities require space. Economic growth and the increase in gross domestic product drive the demand for spatial development. Industrial production and service activities, such as trade and tourism, require extensive areas for their operations. The same applies to infrastructure for the transportation of people and goods, which is being allocated increasing amounts of space. Population growth and rising living standards demand substantial space for housing with adequate infrastructure. Furthermore, the green transition requires space for the production of electricity from renewable sources. According to the European Environment Agency (EEA), between 2000 and 2018, the current

EU Member States developed 12,966 square kilometres of new land, averaging 720 square kilometres per year [1]. However, such activities compete with the need for space for primary activities, particularly agricultural and forestry production, as well as the need to preserve good water quality and maintain natural ecosystems.

Spatial development has historically—and to some extent still today—been implemented according to the principles of the linear economic model. The linear economic model is based on the assumption that resources are unlimited, easily available, and accessible, and that their extraction is inexpensive [2]. Likewise, spatial development under the linear model assumes the unlimited availability of land for artificialization and, consequently, easy access to new land. This approach leads to the expansion of artificial land and increased environmental burdens.

The finite nature of land as a natural resource, the environmental impacts of artificialization, and the high societal costs of acquiring and managing artificial land mean that this approach is no longer viable. Conflicts of interest are already significant and will continue to grow. The trend of increasing resource and land use conflicts with the need to preserve land for agriculture and forestry, as well as for natural ecosystems and water conservation.

In response to this situation, European strategies are increasingly prioritizing the concept of a circular economy, which focuses on environmental protection and the conservation of natural resources while simultaneously supporting economic growth [3]. It promotes the idea that material goods should never become waste but should be renewed and reused, thereby reducing resource consumption and environmental burdens while enabling nature to regenerate.

The European Commission has so far prepared five key documents addressing the limitation of land take, which are relevant to this article:

- The Roadmap to a Resource-Efficient Europe (European Commission, 2011) [4];
- The Seventh Environment Action Programme of the European Union until 2020 (Official Journal of the European Union, L 354/171, 2013) [5];
- The EU Soil Strategy for 2030 (European Commission, 2021) [6];
- The Eighth Environment Action Programme of the European Union until 2030 (Official Journal of the European Union, L 114/22, 2022) [7];
- The Proposal for a Directive on Soil Monitoring and Resilience (European Commission, 2023) [8].

Through those documents, the European Union has progressively developed a comprehensive policy framework to address artificialization and soil degradation, with the aim of achieving no net land take (NNLT) by 2050. Beginning with the Roadmap to a Resource-Efficient Europe [4], which introduced the NNLT objective, successive documents—including the Seventh [5] and Eighth Environment Action Programmes [7], the EU Soil Strategy for 2030 [6], and the Proposal for a Directive on Soil Monitoring and Resilience [8]—have emphasized sustainable land use, the restoration of degraded areas and the integration of land use considerations into broader environmental and economic planning. These policies promote the prevention of new artificialization, reusing previously artificialized land, the monitoring land take and the establishment soil health indicators. Together, they provide a foundation for coordinated action across EU Member States to preserve ecosystem services and ensure long-term land sustainability. As a result, the EU has developed a coherent and evolving EU policy framework that safeguards soil functions, supports sustainable land use, and advances the objective of no net land take by the middle of this century.

1.1. Data Sources at European Level

The Copernicus Programme offers remote sensing data from the CORINE Land Cover and the High-Resolution Layers (HR Layers) for EEA39 [1,9,10]. HR Layers serve as input data for CLCplus Backbone, Urban Atlas and similar products.

The Corine Land Cover (CLC) dataset is used to monitor land cover changes across Europe. It is also used by the European Environment Agency (EEA) to measure and report on land take and net land take processes for Europe (EEA39 and EU28) [1,9,10]. Data are provided for every 6 years of the acquisition period, as well as for the entire period from 2000 to 2018 [1]. A key limitation of the CLC dataset in measuring land take is its resolution—it cannot detect changes smaller than 5 hectares. As a result, only land take changes covering a minimum of 5 ha are mapped and calculated [9,10]. This also accounts for the significant discrepancy between land take values derived from CLC data and those from national sources, as the CLC tends to underestimate land take [11].

The CLCplus Backbone dataset is more detailed land cover inventory dataset, comprising 11 basic thematic land cover classes (with spatial resolution raster of 10 meters). Data are available for the 2018 and 2021 reference years [12]. In connection with the European soil protection and monitoring policy, it includes data on sealed artificial surfaces—data on all impervious and sealed surfaces [13]. The CLCplus Backbone is currently being used to support the implementation of the EU's Nature Restoration Regulation [12].

The resolution of the Urban Atlas dataset is higher than that of the CLC (0.25 ha for urban classes and 1 ha for rural classes), yet its territorial coverage is limited. It offers comparable land cover and land use data for Functional Urban Regions (FUA) of large cities and its commuting zones in Europe and the UK [9,14,15], covering approximately 23% of the territory of the EU-27 and the UK and 75% of the population [14].

The Urban Atlas provides three different datasets:

- Detailed land cover and land use information for selected FUAs in Europe (for the reference years 2006, 2012 and 2018);
- Building height data for core urban areas in selected cities in Europe (for the reference year 2012);
- Street tree layer for each FUA (for the reference years 2012 and 2018) [16].

1.2. Data Sources of European Countries

European countries primarily use national, regional and municipal data sources to monitor land take. These data are generally more detailed than those available at the European level [9], and consequently, they tend to yield higher values for land take and artificial areas.

In several European countries, land take monitoring is based on cadastral data. France uses the municipal land register, which relies on the compulsory declaration of any construction activity [9,17]. In Germany, land take monitoring is based on the Real Estate Cadastre from the Official Real Estate Cadastre Information System, while in the Walloon Region of Belgium it relies on land registry data [17].

Other European countries or regions combine European CLC data with their own data, for example, Austria, Italy, and the Île-de-France region [17–19].

Until 2022, Austria monitored land take using the digital cadastral map [18,19]. Between 2021 and 2023, a new method was developed to monitor land take and land sealing [18,19]. The new method combines various up-to-date government and remote sensing data that are available throughout Austria, including: (1) building data (digital landscape model); (2) an accurate representation of the public road network; (3) data on agricultural land; (4) data on forest land; (5) current land use (digital landscape model); (5) land cover

from orthophotos; (6) aggregated land use data from the states and municipalities; (7) the Address, Building, and Housing Register (AGWR); and (8) remote sensing data from the Copernicus Programme [19].

Italy uses Sentinel data from the European Copernicus Programme, Very High Resolution (VHR) satellite and aerial imagery and a national land consumption map [18].

The Île-de-France region has implemented a more comprehensive monitoring based on a combination of legal data (planning permissions), satellite monitoring (CLC), and other sources (agricultural census) [17].

This overview of data sources used by European countries shows that newly developed methodologies for monitoring and reporting land take rely on more data and are therefore more complex.

1.3. Circular Spatial Management in Slovenia: A Path Toward Sustainable Land Use

In Slovenia, the Strategic Plan for Circular Spatial Management 2024–2030 [20] was prepared to tackle the problem of unsustainable land use. The Strategic Plan is a professional framework developed as part of a broader project led by the Ministry of Natural Resources and Spatial Planning (MNVP) to support the implementation of an NNLT policy in Slovenia. This concept emphasizes the efficient and repeated use of already existing land and building stock. The plan defines three key thematic pillars: (1) the principles of circular spatial management, (2) measures to achieve the strategic goal of reducing net land take by 25% by 2030 and reaching no net land take by 2050, and (3) indicators for monitoring progress.

The principles of circular spatial management are based on the land use hierarchy recommended by the European Commission in the EU Soil Strategy for 2030 [5]. The core principle is to avoid new land take wherever possible. When choosing a location for a particular activity, priority is given to building renovation and replacement construction, provided that these require minimal consumption of natural resources. If such options are not feasible, preference is given to locations within existing urban areas—especially degraded ("brownfield") sites—over undeveloped ("greenfield") land.

The measures aim to gradually reduce the annual growth of artificial land, with a central focus of the reuse of already built-up areas and promoting internal development within settlements. The plan outlines six categories of measures to support the transition:

1. Spatial information infrastructure involves the establishment of comprehensive databases on building land, degraded areas and land take; linking legal land use data with the real estate cadastre; implementing a joint spatial intervention monitoring system; mandating the use of Building Information Modelling (BIM); and creating a registry of rental contracts and green space inventories for major cities;
2. Spatial planning measures involve integrating circular principles into spatial planning guidelines, defining settlement and permanently protected agricultural zones, analyzing the potential of urban centres, drafting thematic action programmes (for housing, the economy, tourism, renewable energy), and preparing guidelines for soil unsealing;
3. Land policy measures include the legal and cadastral restructuring of land parcels (land consolidation), the preparation of land supply plans on municipality level, the activation of degraded urban areas through contractual development, the establishment of land banks and the legal foundations for proactive land policy;
4. Empowerment and promotion measures foresee the creation of an office or agency for circular spatial management, the establishment of expert working groups, training programmes for professionals and municipalities, and a dedicated web por-

tal featuring information, good practices, and educational content on circular spatial management;

5. Regulatory measures include the establishment of a special, public management system for business zones, with investment incentives conditional on compliance with circular spatial principles, and amendments to housing regulations aimed at revitalizing both the public and private rental markets and the existing housing stock;
6. Economic and financial measures propose increased taxation of unused real estate, tax relief for rental income, reform of compensation fees for land use changes from agricultural to building land, and the establishment of a Circular Spatial Management Fund as a financial mechanism to support projects aligned with these principles.

The monitoring framework includes indicators such as net land take, the area and number of functionally degraded sites, the share of building permits issued on grasslands, arable land and permanent crops, and the number of vacant dwellings. Baseline values, target benchmarks, data sources and methodologies for each indicator are clearly defined.

Overall, the document introduces proposals for institutional, legal, informational and financial foundations to enable a transition to sustainable, data-driven and inclusive spatial governance in line with the goals of no net land take and the preservation of high-quality land. As part of the development of the Strategic Plan for Circular Spatial Management 2024–2030 [20], an analysis of the state of artificial land in Slovenia was also conducted (Figure 1).

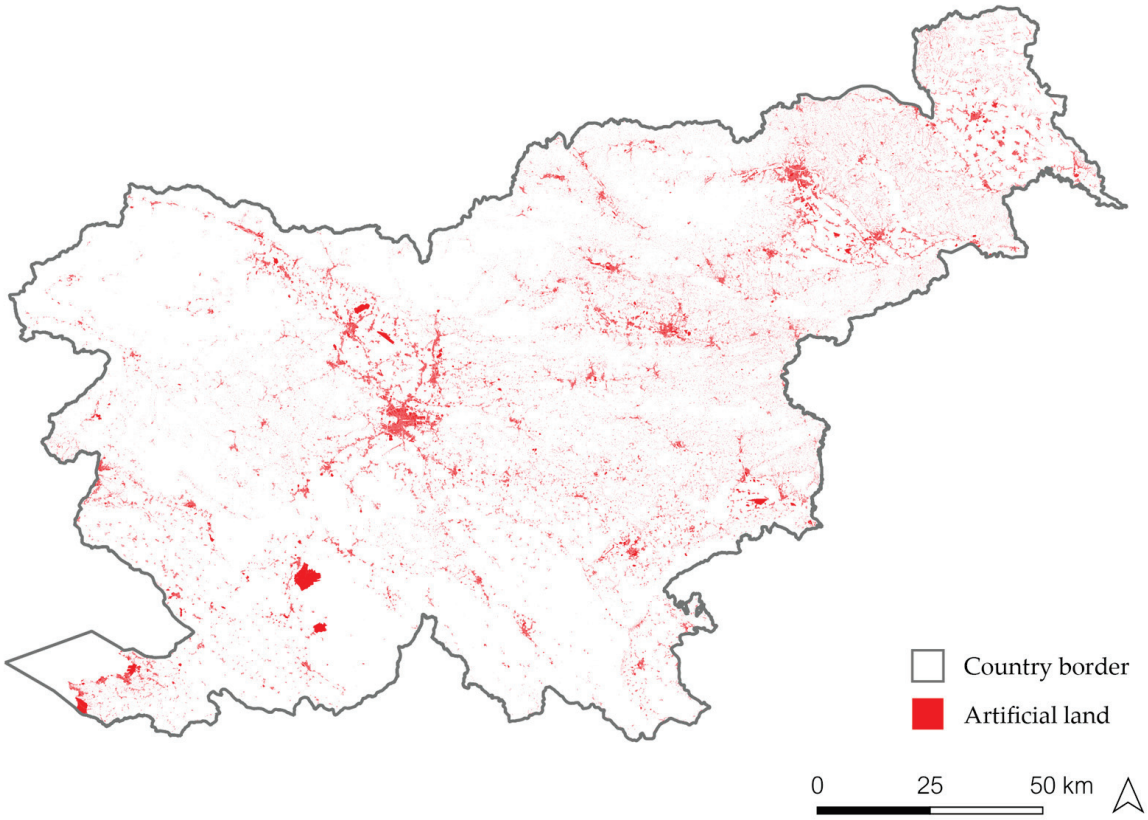


Figure 1. Artificial land in Slovenia according to data from March 2023 (Source: actual land use of settled land—MNVP; actual land use for public road and railway infrastructure—DRSI).

The red areas in the figure above represent artificial land in Slovenia, as defined by the Spatial Management Act (ZUreP-3) [21], based on data available in March 2023. The total area of artificial land amounts to 115,523 hectares, which corresponds to 5.70% of

Slovenia's territory. Unfortunately, this artificial land layer does not currently support trend analysis, as it is based on a one-time dataset. The layer comprises data from the Registry of Actual Land Use of Settled Land and the Registry of Actual Land Use for Public Road and Railway Infrastructure. The first dataset is still pending formal confirmation and is not yet maintained systematically. The second dataset, which pertains to public road and railway infrastructure, is continuously updated; however, it currently does not include information on associated land for all public municipal roads. Considering these limitations, which are discussed in more detail in Section 2.2, the percentage should be regarded as an estimate rather than an exact figure. Nevertheless, despite these limitations, it provides a representative reflection of the artificial land at the national level.

1.4. Problem Definition and Study Objective

The study addresses two main problems. The first concerns the measures needed to slow the continuous increase in artificialized land. The EU requires Member States to define practices and measures that ensure sustainable soil and land management. The land take hierarchy should be integrated into spatial planning according to the principles of circular space management, considering the order of spatial interventions. First, additional artificialization should be avoided wherever possible. Second, previously artificialized land should be reused. Third, new artificialization should only take place where land is in a less favourable condition. Fourth, mitigation and compensation measures should be applied for any new artificialized land to offset the loss of ecosystem services [6].

Germany, the Belgian regions, France, Luxembourg and Austria are among the five pioneering countries that have been actively engaged in the implementation of the NNLT objective [22]. Slovenia has also taken steps to address this issue by developing the concept of circular spatial management. This concept is based on the principles of the circular economy, adapted and applied to spatial management [20]. While many European countries have already defined the objective of reducing artificializations in their regulations, they often lag behind in designing concrete measures to achieve it [9,17]. To address this gap, the concept of circular spatial management developed in Slovenia also includes practical solutions aimed at reducing and ultimately halting the artificialization of new land [20].

The second problem concerns how to monitor the expansion of artificial land. Statistics on the land take by country are available through international reporting systems based on the Corine Land Cover accounting layer [23]. However, monitoring this expansion process within an individual country in a way that ensures the comparability of results across countries remains a challenge [24]. To enable effective land take monitoring at the EU level, it is essential to standardize terminology across all Member States to ensure consistent definitions of key terms and indicators. Additionally, reliable and harmonized data are essential for accurately monitoring the expansion of artificial land.

Marquard et al. [24] identified a lack of harmonized terminology in the EU and noted that previous studies had already emphasized the need for a clear conceptualization of the terms land consumption and land take [25–27], as well as for compatible monitoring and reporting, which affect the credibility of quantitative targets [25,28]. Based on the extensive research already conducted on this problem, the present article does not propose new solutions to that challenge. Instead, it presents methodology for conducting a land take analysis, complemented by a qualitative assessment in two test areas. The results provide insights into newly artificialized land and its driving forces.

2. Materials and Methods

The following section presents the study areas, data availability, data sources and methodology.

2.1. Location of the Study Areas

The study focuses on the Municipality of Maribor and the Municipality of Kungota. The study area was defined through a three-step process, transitioning from a broader scale to specific locations for detailed analysis, as illustrated in Figure 2.

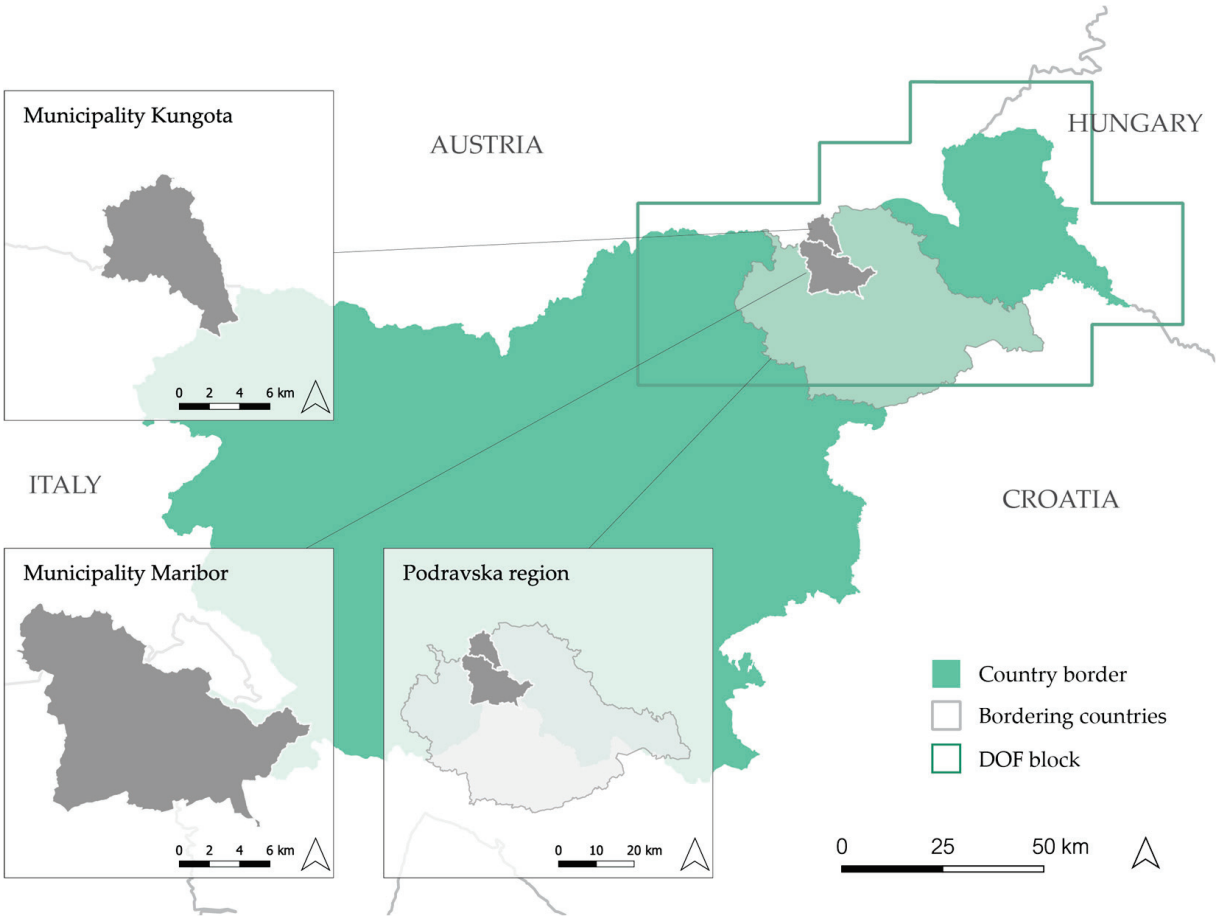


Figure 2. Study area—The Municipality of Maribor and the Municipality of Kungota in the Podravska region (Slovenia).

The two final study areas were determined through three steps:

- The first step involved selecting an area based on the division of Slovenia into blocks covered by aerial imagery captured in the same year. A block from the northwest part of Slovenia was chosen, as it is covered by digital orthophoto imagery (DOF) for both 2019 and 2022.
- In the second step, the selected block was further refined using administrative boundaries. Within this block, the Podravska region was identified as the most suitable for analysis due to its diverse landscape, which includes both urban and rural characteristics.
- Since the entire Podravska region was too large for a detailed analysis, the third step involved selecting two study municipalities with distinct characteristics:
    a. Maribor, an urban municipality, representing a complex artificial environment with diverse spatial development patterns;

b. Kungota, a rural municipality, allowing for the analysis of artificialization in rural environment.

The two study areas serve to validate the methodology for identifying newly artificialized land in diverse environments, as presented in Section 2.3.

2.2. The Problems of Data Availability

The data that can be used to assess land take in Slovenia are currently the data on the actual land use of agricultural and forest land, managed and maintained by the Ministry of Agriculture, Forestry and Food (MKGP). The vector layer is based on the manual identification and interpretation of aerial photographs (DOF) for the relevant time period, approximately every 3 years for each part of Slovenia, and represents the only dataset in Slovenia that provides a continuous time series from which land use trends can be determined. Although the data are primary intended for the implementation of agricultural policy and not for monitoring the expansion of artificial land, the vector layer also contains polygons representing artificial land, which are used to calculate the land take indicator [29]. Due to its primary purpose, the data more closely reflect land cover than actual land function. Nevertheless, it remains the only nationwide dataset with a multi-year time series suitable for tracking land use dynamics throughout the years. As a result, estimates of artificial land expansion based on this dataset are indicative rather than precise. However, with detailed data processing (such as that conducted for the municipalities of Maribor and Kungota) reliable insights into the expansion of artificial land can still be obtained.

In Slovenia, a new register of building land is currently being established, marking an important step toward the official monitoring of land take. The register includes data on artificial land in accordance with the definition in the Spatial Management Act (ZUreP-3) [21]. These data are compiled from two sources: the Registry of Actual Land Use of Settled Land (established by the Ministry of Natural Resources and Spatial Planning—MNVP) and the Registry of Actual Land Use for Public Road and Railway Infrastructure (established by the Slovenian Infrastructure Agency—DRSI). This information is intended to enable accurate monitoring of the expansion of artificial land in relation to the detailed land use.

The register of building land will be developed in several phases. Currently, the first phase—the mass capture on settled land covering the period 2017–2021—has already been completed and this data are already publicly available. However, the dataset is not yet maintained systematically, so comparisons between years are not possible. As on settled land also remain subject to confirmation by the municipalities and landowners. The MNVP is providing municipalities with financial and technical assistance to set up the register by the end of 2026 [30].

At the time of the analysis presented in this paper, the data on public road and railway infrastructure did not yet include data on the associated land of all public municipal roads. As of March 2023—the reference date for the artificial land data presented in this article at the national level—data were still missing for 46 of Slovenia's 212 municipalities.

2.3. Data Sources

The analysis of the land take status was conducted using open spatial data, as presented in Table 1. The primary data source for the analysis is the actual land use layer of agricultural and forest land from the Ministry of Agriculture, Forestry and Food (MKGP). In addition to this, several auxiliary data sources were utilized, including the actual land use of settled land layer (MNVP), the actual use of building parts from the real estate

cadastre (e.g., apartments, offices) (GURS), the land use layer of public road and railway infrastructure (DRSI), roads and railways from consolidated cadastre of economic public infrastructure (GURS), and digital orthophoto imagery (GURS).

Table 1. Data sources.

Data	Source	Purpose of Use
Actual land use of agricultural and forest land	Ministry of Agriculture, Forestry and Food (MKGP).	Monitoring of artificial land in 2019 and 2022 for land take calculation between the two years
Actual land use of settled land	Ministry of Natural Resources and Spatial Planning (MNVP)	Assigning actual land use to newly artificialized land (land take)
Actual use of building parts—real estate cadastre	Surveying and mapping authority of the Republic of Slovenia (GURS)	Assigning actual land use to newly artificialized land (land take)
Actual land use for public road and railway infrastructure	Slovenian Infrastructure Agency (DRSI)	Assigning actual land use to newly artificialized land (land take)
Roads and railways from consolidated cadastre of economic public infrastructure (ZKGJI)	Surveying and mapping authority of the Republic of Slovenia (GURS)	Assigning actual land use to newly artificialized land (land take)
Orthophoto	Surveying and mapping authority of the Republic of Slovenia (GURS)	Visual interpretation and manual verification of land use changes.

2.4. Data Processing and Methods

The data processing consisted of two components: land take monitoring and identification of land take drivers. Both were carried out using the Geographic Information System (GIS) methods in QGIS version 3.34.13. Land take monitoring was conducted to extract newly artificialized land within two study areas. The actual land use layers from the MKGP were initially clipped to the Podravska region. Then, the selection tool was used to extract artificial land for the years 2019 and 2022. In continuation, the intersection tool was used to overlay artificial land layers for the years 2019 and 2022. This overlay allowed for the creation of a difference layer, which identifies land take (newly artificialized land) within the observed period (2019–2022).

The analysis of overlay results revealed that some polygons do not represent newly artificialized land but are instead a result of the following:

- Interpreter inconsistency in two consecutive captures;
- Misclassification of actual use.

In both cases mentioned above, the inappropriate polygons are the result of human error. Based on these findings, the GIS procedure for land take monitoring was defined as presented by a flowchart in Figure 3.

The process continued with the identification of land take drivers following the land take monitoring. This identification was based on the following data: building parts (GURS), settled land (MNVP), and roads and railways (GURS and DRSI). Using these data, areas identified as newly artificialized were assigned detailed actual land use, which also helped to indicate the underlying drivers of land take.

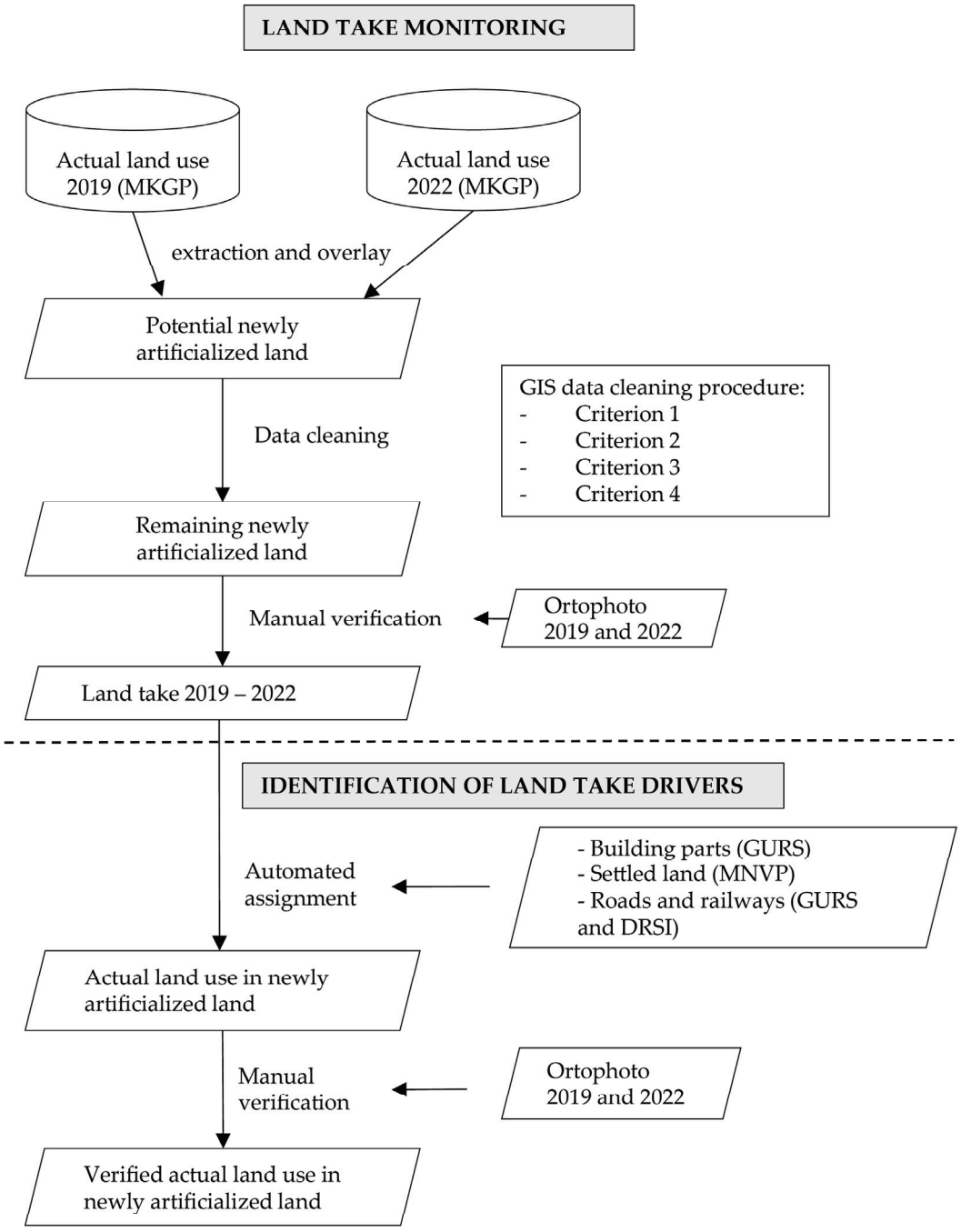


Figure 3. Flowchart of the proposed procedure.

The land take results for both test areas (with partial results also for the entire Podravska region) are presented in hectares and number of polygons in Section 3.1. Comparing the surface area in hectares with the number of polygons allows for an assessment of how much area was excluded from the land take dataset—either through the GIS-based data cleaning procedure or manual verification. Since land take expressed in hectares does not allow for a meaningful comparison of annual land take rates across spatial units of different sizes, an aspect particularly relevant in this study, land take is additionally presented in $m^2/year \cdot km^2$ in Section 4.

The following two subsections provide a detailed description of the individual steps of the proposed procedure.

2.4.1. GIS Procedure for Data Cleaning

The first step after extraction of potential newly artificialized land was data cleaning based on four criteria, which determined the polygons to be excluded:

- Criterion 1: Polygon area smaller than 25 m^2.
- Criterion 2: Polygons with a P/A ratio greater than 1.5.
- Criterion 3: Polygon width smaller than 3 m.
- Criterion 4: Sharp polygons with a circle to polygon area ratio greater than 3.

Each of the four criteria is described in more detail below.

- Removal of polygons smaller than 25 m^2

To ensure the accuracy of the analysis and reduce the impact of small, irrelevant polygons that could lead to the incorrect interpretations of results, a filtering process was applied to the dataset based on polygon surface area. According to the specifications of the MKGP dataset, a minimum artificial land area of 25 m^2 was defined. Any polygons with an area below this threshold were excluded from further analysis.

As a result, the final dataset contained only polygons meeting or exceeding the 25 m^2 threshold, allowing for a more relevant analysis of artificial land while minimizing the impact of potential inaccuracies in the original dataset.

- Removal of "slivers" based on perimeter-to-area ratio (P/A)

To further refine the dataset, a method for removing polygons based on the ratio between perimeter and area was applied. The objective of this method was to identify and eliminate elongated and narrow polygons that did not correspond to actual artificial land. The ratio was determined using the following formula: ratio = perimeter/area.

The obtained values were analyzed to identify significant deviations from expected ratios for real artificial land. The threshold for polygon removal was set at a ratio of 1.5, as this was the point where irregular polygons started to emerge while still preserving relevant polygons for further analysis. Through this process, elongated and irregular polygons, likely resulting from data inconsistencies or land use capture errors, were removed, thereby improving the overall quality of the final dataset.

- Removal of "slivers" based on polygon width.

This automated method calculates internal points within polygons that allow for the measurement of polygon width. To remove polygons that do not meet the criteria for actual artificial land, a standard minimum width had to be established, ensuring that the threshold was too narrow to represent road surfaces. Based on the analysis, this threshold was set at 3 m.

The final selection of polygons for removal was based on attribute values; all polygons where the total width was less than 3 m were eliminated from the dataset. By applying this method, elongated and narrow polygons, most likely resulting from data capture errors or misinterpretations of land use, were effectively removed, improving the dataset's overall accuracy and reliability.

- Removal of polygons with sharp edges.

This automated method identifies polygons with sharp or elongated shapes, which often result from data capture errors or incorrect land use classification. The approach is based on calculating the ratio between the area of the minimum enclosing circle and the polygon's actual area.

The ratio between the circle's area and the polygon's area was computed using the following formula:

$$\text{Ratio} = \text{circle area}/\text{polygon area}$$

Polygons with exceptionally high ratio values (greater than 3) were removed, as they indicate that the circle's area is significantly larger than the polygon's area. This suggests the presence of highly elongated or sharp-edged shapes, which do not meet the criteria for real artificial land and are likely data anomalies.

However, after the cleaning up the polygons, a quick review of the remaining polygons was conducted. It was found that a significant number of polygons still exhibited unusual shapes. Consequently, the polygons retained according to four criteria were manually reviewed and cleaned. The result was a cleaned set of polygons representing land take over a three-year period (2019–2022). Detailed actual land use was then attributed to the land take polygons to identify which activities are the largest consumers of natural and semi-natural land.

2.4.2. Manual Verification and Assignment of Land Use for Newly Artificialized Land

Manual verification was carried out twice, as shown in Figure 3. The first time, it was performed after the extraction of newly artificialized land from the input data and the GIS data cleaning procedure using four criteria. The second manual verification took place after the automated assignment. The first manual verification checked the accuracy of identifying newly artificialized land, while the second focused on verifying the accuracy of assigning actual land use to these newly artificialized land. In both manual verifications, orthophotos for the observed period were used as the reference layer.

Manual verification in both parts of the procedure—land take monitoring and identification of land take drivers—as well as the assignment itself, was conducted only for the Municipality of Maribor and the Municipality of Kungota, excluding the broader Podravska Region. These smaller study areas allowed for a manual verification and an in-depth examination of borderline cases.

The following is a description of the part of the procedure in which the assignment of actual land use was carried out. The assignment of detailed actual land use for newly artificialized land (2019–2022) on two study areas was conducted using an automated method.

Automated Assignment Method:

- If a polygon contains data on the actual use of building parts from the Real Estate Cadastre (GURS), the land use is assigned based on this data, as it reflects the most up-to-date situation.
- If the polygon lacks real estate cadastre data but is either fully or partially covered by a settled land polygon (MNVP), or lies within 2.5 m of one, land use is assigned based on settled land data. In such cases, polygons assigned land use based on proximity are subject to manual verification.
- If the polygon lacks data from the real estate cadastre (GURS) and settled land (MNVP), but overlaps with data on actual land use for public road and railway infrastructure (DRSI) and/or roads and railways from consolidated cadastre of economic public infrastructure (GURS), the land use is assigned as road and parking areas.

Additional manual verification of the accuracy of the assigned actual land use was conducted for the following groups of polygons:

- Large surface polygons;
- Polygons assigned land use based on proximity to settled land polygon (MNVP);

- Polygons assigned land use based on public road and railway infrastructure (DRSI).

3. Results

As a result of the methodology presented in the previous chapter, land take data was obtained for both study areas and partial land take data for the Podravska Region (Section 3.1). The second output, which is the result of a subsequent process, is the data on actual land use, reflecting the reduction in the amount of (semi-)natural land (Section 3.2).

3.1. Land Take in the Study Areas

Table 2 shows the land take in hectares and the number of polygons. Both values are also presented as a percentage of potential land take. First, the potential land take is shown (Row 3 in Table 2). The entire Podravska Region was not included in the further analysis. This is followed by the remaining land take (Row 5 in Table 2) and the final land take (Row 7 in Table 2). Rows 4 and 6 represent the intermediate reduction in land take during the GIS data cleaning procedure and manual verification.

Table 2. Land take (2019–2022) based on GIS procedure for data cleaning and manual verification (Podravska Region, Municipality of Maribor and Municipality of Kungota).

Land Take	Podravska Region		Municipality of Maribor		Municipality of Kungota	
	Area (Share)	**No. of Polygons (Share)**	**Area (Share)**	**No. of Polygons (Share)**	**Area (Share)**	**No. of Polygons (Share)**
POTENTIAL LAND TAKE	559.25 ha (100%)	53,544 (100%)	52.64 ha (100%)	3,799 (100%)	17.25 ha (100%)	2,156 (100%)
Land take excluded by GIS procedure	64.40 ha (11.5%)	41,234 (77.0%)	3.15 ha (6.0%)	2,906 (76.5%)	0.80 ha (4.6%)	1385 (64.2%)
REMAINING LAND TAKE	494.85 ha (88.5%)	12,310 (23.0%)	49.49 ha (94.0%)	893 (23.5%)	16.45 ha (95.4%)	771 (35.8%)
Land take excluded after manual verification	/	/	10.46 ha (21.1%)	335 (37.5%)	5.70 ha (34.6%)	467 (60.6%)
LAND TAKE 2019–2022	/	/	39.03 ha (78.9%)	558 (62.5%)	10.75 ha (65.4%)	304 (39.4%)

Table 2 shows a decrease in the number of polygons that were cleaned using the four criteria mentioned in Section 2.4.1. The four criteria cleaned up the majority of the inappropriate polygons. A total of 76.5% of all input polygons were excluded in the Municipality of Maribor and 64.2% in the Municipality of Kungota. If instead of polygons, the area in hectares is considered, the percentage decreases to (6.0%) or (4.6%), which means that polygons with very small areas were removed. After the GIS data cleaning procedure, 49.49 ha remained in the case of Maribor and 16.45 ha in the case of Kungota, which were reduced by manual verification to the final land take of 39.03 ha and 10.75 ha, respectively. These final land take results correspond to the newly artificialized land developed between 2019 and 2022 and are shown in red in Figure 4. Previously artificialized land (up to 2019) is shown in grey.

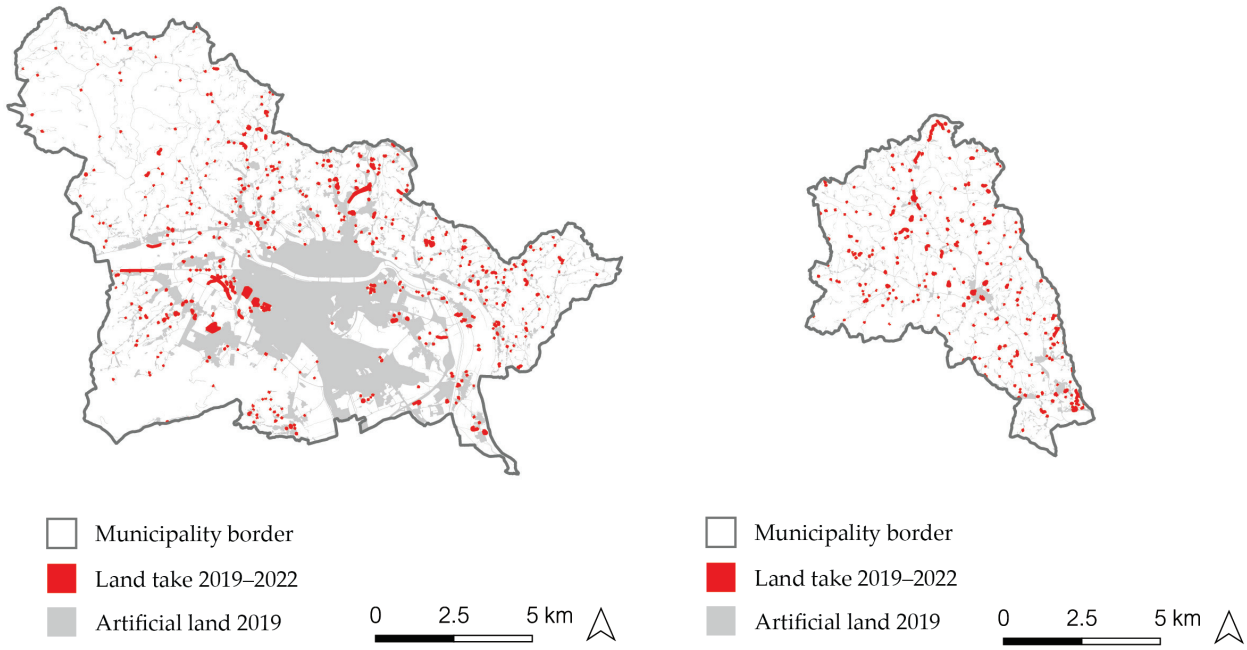


Figure 4. Land take between 2019 and 2022 in the Municipality of Maribor (**left**) and the Municipality of Kungota (**right**).

Aside from the main town of both municipalities (Maribor and Kungota), as well as some other villages with compact artificial land (larger grey areas in Figure 4), Figure 4 illustrates a high dispersion of artificial land by 2019 (shown in grey). The red areas indicate the continuation of this artificialization trend between 2019 and 2022. A detailed land use change analysis for this newly artificialized land is presented in the next chapter. It is important to note that many small polygons (depicted as red dots in Figure 4) are outlined with a bold border on the map for better visibility. Their natural size is relatively small and usually corresponds to small building plots.

Both study areas are relatively small, with areas of 148 km^2 (Maribor) and 49 km^2 (Kungota). Therefore, land take data in m^2/year·km^2 are also presented in the discussion section, to provide a clear understanding of the natural and seminatural areas transformed into artificial areas during the studied period.

3.2. Land Use Change Analysis

The land use change analysis was carried out on the cleaned polygons for both study areas (Municipality Kungota and Municipality Maribor), which were assigned an attribute of detailed actual land use, as explained in Section 2.4.2.

The largest share of newly artificialized land between 2019 and 2022 in both study areas corresponds to residential areas, accounting for 60.8% in Maribor and 50.2% in Kungota (Figure 5). In Maribor, a substantial share (20.4%) of land take is attributed to road infrastructure. Agricultural infrastructure represents 6.4%, industry 4.6%, and sport and recreation 3.1% of land take. The presence of other land use appears in smaller proportions. In Kungota, a significant share (23%) corresponds to the expansion of agricultural infrastructure, often associated with the development of supplementary tourism and hospitality activities. Roads represent 9.7%, sport and recreation 9.4%, and tourism and hospitality 7.4% of land take.

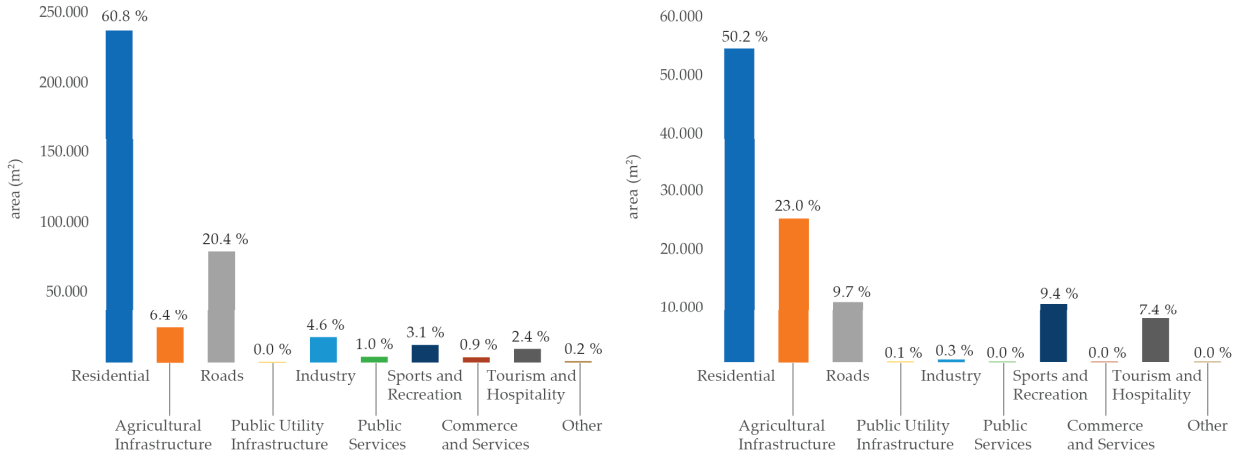


Figure 5. Land take drivers (%) in the Municipality of Maribor (**left**) and Kungota (**right**)—2019–2022.

On the basis of a land take map (Figure 4) and the results of the additional land use change analysis (Figure 5), it can be confirmed that the majority of new land take occurs as an expansion of existing residential areas, while a smaller part represents the expansion of land take in the form of dispersed construction. This is probably a consequence of the fact that development in Slovenia is already fundamentally highly fragmented with large number of small settlements [31].

4. Discussion

The following discussion interprets the key findings of the study and places them in a broader context. As announced in Section 3.1, land take data expressed in m^2/year·km^2 are also presented in this section (Table 3). The last two rows (Rows 6 and 7) in Table 3 contain land take data for both study areas, derived from our own research (labelled as "original research" in Table 3) and recalculated into m^2/year·km^2. Row 5, by contrast, presents land take for the entire territory of Slovenia, based on external sources. It should be noted that comparing land take between the two study areas and Slovenia—although all values are expressed in m^2/year·km^2—is not entirely meaningful, as the results are based on different input data and methodologies.

Table 3. Land take in Slovenia determined using CLC data and national data (MKGP) for selected time periods (external sources), and land take data for the Municipality of Maribor and the Municipality of Kungota determined using national data (MKGP) for the period 2019–2022 (obtained through the present study).

Data Source	**Corine Land Cover**	**National Data (MKGP)**		
Subject of observation	**Land take**	**Land take**	**Land take**	**Land take**
Period of observation	**2012–2018**	**2012–2019**	**2015–2022**	**2019–2022**
Measurement unit	**m^2/year·km^2**	**m^2/year·km^2**	**m^2/year·km^2**	**m^2/year·km^2**
Slovenia (external sources)	52.78 [1]	279.50 [29]	310.79 [20]	
Municipality Maribor (original research)				881.96
Municipality Kungota (original research)				731.31

The land take estimates for the whole of Slovenia in Table 3 were obtained from studies conducted by other authors [1,20,29]. These data are shown once based on Corine Land Cover (CLC) dataset [1] and again based on national data provided by the Ministry of Agriculture, Forestry and Food (MKGP) [20,29]. Land take for the entire country, based on national MKGP data, is presented for two time periods: from 2012–2019, with a value of 279.50 m^2/year·km^2 [29], and 2015–2022, with a value of 310.79 m^2/year·km^2 [20]. These values provided by national data provide some evidence that between the two periods considered, there was an acceleration in the consumption of natural and semi-natural land. However, due to the partial overlap between the periods considered, minor methodological changes, and especially the continuously improving quality of input data used by the MKGP for determining actual land use, the trend of increasing land take cannot be fully confirmed based on a comparison of these two periods, nor was this the objective of the present study. Additionally, land take for the entire territory of Slovenia based on CLC is presented [1] and shows that this data source does not allow for accurate identification of newly artificialized land, as the result is significantly underestimated.

The same national MKGP data as for the whole of Slovenia were also used to determine land take in both study areas for the time period 2019–2022. A comparison of land take between the two study areas and the national average shows that land take at the national level is significantly lower than in either study area. This lower value at the national scale is primarily due to the extensive mountainous regions in the north and northwest of Slovenia, as well as the large forested areas in the south—regions that are among the least densely populated in the country. In contrast, neither of the two study areas contains large expanses of very sparsely populated land. On the contrary, according to data from the Statistical Office of the Republic of Slovenia (SURS), the Municipality of Maribor is the second most densely populated municipality in the country, while the Municipality of Kungota ranked 81st out of 212 municipalities in 2022 [32]. Despite the large difference in population density between the two municipalities (766.2 inhabitants/km^2 in Maribor and 100.4 inhabitants/km^2 in Kungota in 2022) [32], land take values are relatively comparable. This is largely due to the prevalence of multi-apartment residential construction in the Municipality of Maribor (particularly in the city of Maribor) on the one hand, and the predominance of single-family housing in the Municipality of Kungota on the other. According to the results of this study, land take amounted to 881.96 m^2/year km^2 in the Municipality of Maribor and 731.31 m^2/year km^2 in the Municipality of Kungota.

Given that the analysis of land take drivers showed that the majority of newly artificialized land stemmed from residential development, the elevated levels of land take observed in both study areas can largely be explained by the concurrent increase in settlement density. According to official data from the Statistical Office of the Republic of Slovenia, population density between 2019 and 2022 increased by 6.3 inhabitants/km^2 in the Municipality of Maribor and by 4.4 inhabitants/km^2 in the Municipality of Kungota [32]. This observation raises an important policy question: to what extent can the demand for new residential development be met within existing urban areas? While not all needs can be satisfied in this manner, a significant portion of housing demand could plausibly be addressed through the densification and revitalization of already urbanized areas. Realizing this potential, however, requires the systematic implementation of measures outlined in the Strategic Plan for Circular Spatial Management 2024–2030 [20], as discussed in Section 1.3 of this study. Among the plan's priority actions are two key interventions: (1) the renovation of buildings and public spaces in urban centres, aimed at reversing the ongoing depopulation of inner-city areas, and (2) the development of public rental housing in line with the principles of circular land management. The latter is particularly relevant in the case of

Maribor (as second largest city of Slovenia [33], a centre of international importance and an important scientific and educational (a university), healthcare (university medical centre), cultural (national theatre, museums), judicial, sports and employment centre of the eastern part of the country, and one of the priority areas for housing development according to the Spatial Development Strategy of Slovenia 2050 [34]), where housing demand continues to significantly exceed available supply [33].

5. Conclusions

The trend shows that the amount of artificial land in Slovenia (and more broadly across Europe) continues to grow. Effectively addressing this issue requires both reliable monitoring using appropriate indicators and the development of targeted measures that support a transition toward more sustainable, circular and spatially efficient land management. The present article presents a precise methodology for accurately determining land take using national-level input data. The targeted measures aimed at reducing the annual increase in artificial land are briefly presented in Section 1.3.

The problem of artificialization, monitored through the land take indicator, remains one of the key spatial and environmental challenges in contemporary spatial planning. The study highlighted the discrepancy between land take estimates derived from different data sources and methods, which hinders the reliable monitoring of the process and the comparability of land take across countries. While CLC data at the European level are less precise, their value lies primarily in enabling the observation of broader land use trends across Europe. In the case of Slovenia, the land take indicator derived from CLC data measures 52.78 $m^2/year \cdot km^2$ for the period 2012–2018, while the indicator based on national data reports a significantly higher value of 279.50 $m^2/year \cdot km^2$ for the period 2012–2019. However, national indicator values are not always directly comparable across countries. Key differences arise from differences in input data types and their accuracy, and differences in data processing methods.

To reliably monitor the growth of artificial land at the national level and to meet future EU requirements, ensuring the comparability of land take indicators across countries is essential. The annexes to the proposed Soil Monitoring Law state that the methodologies chosen for assessing land take shall be either available in scientific literature or publicly accessible [8]. In this context, the land take methodology presented for the two case study areas demonstrates an approach to identifying land take under conditions where a dedicated and systematically maintained layer of artificial land is not yet established. Although the methodology provides solutions adapted to the current availability and quality of input data in Slovenia, it could (with appropriate modifications) also prove applicable in other countries or regions. It should be noted, however, that the effectiveness of the proposed methodology largely relies on manual verification, which is time-consuming and limits its scalability to larger areas. For this reason, enhancing the methodology through increased automation would be a meaningful step toward improving its practical applicability. An advantage of the methodology is the inclusion of a qualitative assessment of actual land use on newly articulated land to identify the drivers of land take. The data obtained from this analysis can support data-driven decision—making by policymakers in implementing the NNLT policy.

Achieving reliable results also depends on the availability of high-quality input data, specifically designed for monitoring the land take indicator. As highlighted in Section 2.2, this study also revealed issuesrelated to data availability. The analysiswas conducted using data from the Ministry of Agriculture, Forestry and Food (MKGP), which collects information on the actual land use of agricultural and forest land, including data on

artificial land. However, these data were not originally intended for land take monitoring. To address this limitation, additional sources (such as data on building parts, settled land, roads and railways) were integrated to identify the land use of newly artificialized land. This highlightsthe need for establishing a dedicated register of building land. Such data would enable accurate monitoring of the expansion of artificial land in relation to detailed land use. However, in order to serve its intended purpose of representing key information for tracking land take trends, the register of building land must include comprehensive information on all artificial land and be systematically maintained.

Assuming that national land take increased between the two analyzed periods (although this cannot be confirmed with certainty due to differences in input data and methodologies), we propose the following recommendations, which are also set out in the EU Soil Strategy for 2030. These include limiting land take through circular land use, establishing effective land monitoring, and continuing both new research and innovation efforts as well as public engagement [6].

The latter is of particular importance in the Slovenian context, which is characterized by mostly historically conditioned dispersed settlement patterns. Such patterns are unsustainable, as they contribute to the increased consumption of natural and seminatural land, and promote land take. For these reasons, it is crucial to prioritise the internal development of settlements and the renewal of functionally degraded sites prior to initiating new spatial interventions on undeveloped land [21]. In addition, raising public awareness about the long-term negative impacts of dispersed settlement and encouraging more sustainable spatial development practices are essential.

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

Abbreviations

The following abbreviations are used in this manuscript:

CLC	Corine Land Cover
DRSI	Slovenian Infrastructure Agency
DOF	Digital Orthophoto
EU	European Union
GIS	Geographic Information System
GURS	Surveying and Mapping Authority of the Republic of Slovenia
MKGP	Ministry of Agriculture, Forestry and Food
MNVP	Ministry of Natural Resources and Spatial Planning
NNLT	No Net Land Take

References

1. European Environment Agency (EEA). Land Take and Net Land Take. Analysis and Data. Available online: https://www.eea.europa.eu/en/analysis/maps-and-charts/land-take-statistics-dashboards (accessed on 31 March 2025).

2. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; de Vries, W.; de Witt, C.A.; et al. Planetary boundaries: Guiding human development on a changing planet. *Science* **2015**, *347*, 6223. [CrossRef] [PubMed]
3. Korhonen, J.; Honkasalo, A.; Seppälä, J. Circular Economy: The Concept and its Limitations. *Ecol. Econ.* **2018**, *143*, 37–46. [CrossRef]
4. European Commission (2011): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Roadmap to a Resource Efficient Europe. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0571 (accessed on 31 March 2025).
5. The Seventh Environment Action Programme of the European Union Until 2020 (Official Journal of the European Union, L 354/171, 2013). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013D1386 (accessed on 2 April 2025).
6. European Commission (2021): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: The EU Soil Strategy for 2030. Reaping the Benefits of Healthy Soil for People, Food, Nature and Climate. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0699 (accessed on 31 March 2025).
7. The Eighth Environment Action Programme of the European Union Until 2030 (Official Journal of the European Union, L 114/22, 2022). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022D0591 (accessed on 2 April 2025).
8. European Commission (2023): Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52023PC0416 (accessed on 3 April 2025).
9. Gensheimer, M.; Rossignol, M.; van Herwijnen, M.; Desjardins, X.; Devos, T.; Leclercq, A. *Policy Brief. No Net Land Take Trajectories. Policies and Practices Across Europe*; ESPON EGTS: Luxembourg, 2024; p. 20. Available online: https://www.espon.eu/sites/default/files/2024-12/no-net-land-take-trajectories_policy-brief.pdf (accessed on 12 March 2025).
10. The Alpine Convention. Land Take in the Alpine Region: The Data Perspective. *Summary.* Available online: https://www.alpconv.org/fileadmin/user_upload/Organisation/TWB/SPSD/CDR_ACTS_IP_S3_1a_Land_Take_Data_Summary.pdf (accessed on 12 March 2025).
11. Fina, S.; Hamacher, H.; Rönsch, J.; Scholz, B. *Land Use Monitoring and Land Take in International Comparison: Methods and Data. Final Report*; Umweltbundesamt: Dessau-Roßlau, Germany, 2023; p. 52. Available online: https://www.umweltbundesamt.de/en/publikationen/land-use-monitoring-land-take-in-international (accessed on 12 March 2025).
12. LCplus Backbone 2021 (Raster 10 m), Europe, 3-Yearly. Available online: https://land.copernicus.eu/en/products/clc-backbone/clc-backbone-2021 (accessed on 20 May 2025).
13. LCplus Backbone 2021 (Raster 10 m), Europe, 3-Yearly. Product User Manual. Available online: https://land.copernicus.eu/en/technical-library/product-user-manual-clc-backbone-2021/@@download/file (accessed on 20 May 2025).
14. European Environmnet Agency: Net Land Take in Cities and Commuting Zones in Europe. Available online: https://www.eea.europa.eu/en/analysis/indicators/net-land-take-in-cities (accessed on 12 March 2025).
15. Urban Atlas. Available online: https://www.eea.europa.eu/en/datahub/datahubitem-view/e006507d-15c8-49e6-959c-53b61facd873 (accessed on 12 March 2025).
16. Urban Atlas. Available online: https://land.copernicus.eu/en/products/urban-atlas (accessed on 20 May 2025).
17. D'Ascanio, R.; Desjardins, T.X.; Devos, T.; Dupont, V.; Estèbe, P.; Leclercq, A.; Palazzo, A.L.; Roose, T.A.; Sadowy, K.; Siedentop, S.; et al. *No Net Land Take—Policies and Practices in European Regions. Main Administrative, Economic, Political or Social Challenger to Implement No Net Land Take (NNLT). Final Report*; ESPON EGTC: Luxembourg, 2024; p. 88. Available online: https://www.espon.eu/sites/default/files/2024-06/no-net-land-take-policies-and-practices-in-european-regions-final-report.pdf (accessed on 12 March 2025).
18. The Alpine Convention. Land Saving Targets in Alpine Countries: Status Quo and Challenges. Available online: https://www.alpconv.org/fileadmin/user_upload/Organisation/TWB/SPSD/CDR_ACTS_IP_SP1_3_Land_Saving_Targets.pdf (accessed on 12 March 2025).
19. Environment Agency Austria. Umweltbundesamt. Flächenanspruchname. Available online: https://www.umweltbundesamt.at/umweltthemen/boden/flaecheninanspruchnahme/datengrundlage/fragen-und-antworten-zur-neuen-methodik (accessed on 12 March 2025).
20. Portal GEO Slovenija. Sotočje Prostorskih Informacij. EUKN Policy Lab—Krožno Gospodarjenje S Prostorom—GRADIVO. Available online: https://www.geo-slovenija.si/blog/eukn-policy-lab-krozno-gospodarjenje-s-prostorom-gradivo (accessed on 12 March 2025).

21. Spatial Management Act. Zakon O Urejanju Prostora (ZUreP-3). Available online: https://pisrs.si/pregledPredpisa?id=ZAKO8249 (accessed on 6 April 2025).
22. Lacoere, P.; Decoville, A.; Delattre, R.; Melot, R.; Grimski, D.; Schamann, M.; Halleux, J.-M. National introduction of no net land take: A comparative study of five pioneering countries seeking to limit their land consumption. *Town Plan. Rev.* **2024**, *96*, 4. [CrossRef]
23. European Environment Agency (EEA). Corine Land Cover Accounting Layer. Available online: https://www.eea.europa.eu/en/datahub/datahubitem-view/a55d9224-a326-4cb1-9b9c-3a324520341a (accessed on 7 April 2025).
24. Marquard, E.; Bartke, S.; Gifreu i Font, J.; Humer, A.; Jonkman, A.; Jürgenson, E.; Marot, N.; Poelmans, L.; Repe, B.; Rybski, R.; et al. Land consumption and land take: Enhancing conceptual clarity for evaluating spatial governance in the EU context. *Sustainability* **2020**, *12*, 8269. [CrossRef]
25. Decoville, A.; Schneider, M. Can the 2050 zero land take objective of the EU be reliably monitored? A comparative study. *J. Land Use Sci.* **2016**, *11*, 331–349. [CrossRef]
26. Desrousseaux, M.; Schmitt, B.; Billet, P.; Béchet, B.; Le Bissonnais, Y.; Ruas, A. Artificialised land and land take: What policies will limit its expansion and/or reduce its impacts? In *International Yearbook of Soil Law and Policy 2018*, 1st ed.; Ginzky, H., Dooley, E., Heuser, I.L., Kasimbazi, E., Markus, T., Qin, T., Eds.; Springer Nature: Cham, Switzerland, 2019; pp. 149–165.
27. Nicolau, R.; David, J.; Caetano, M.; Pereira, J.M.C. Ratio of Land Consumption Rate to Population Growth Rate-Analysis of Dierent Formulations Applied to Mainland Portugal. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 10. [CrossRef]
28. BIO by Deloitte. *Study Supporting Potential Land and Soil Targets Under the 2015 Land Communication; Report Prepared for the European Commission, DG Environment in Collaboration with AMEC, IVM and WU*; Publications Office of the European Union: Luxembourg, 2014; p. 464.
29. Slovenian Environment Agency. Environmental Indicators in Slovenia. Land Take. Soil and Land Take. Land Take. Available online: https://kazalci.arso.gov.si/en/content/land-take-0 (accessed on 6 April 2025).
30. Spatial Information System of Republic of Slovenia. The Register of a Building Land. Available online: https://pis.eprostor.gov.si/en/pis/evidenca-stavbnih-zemljisc.html?changeLang=true (accessed on 6 April 2025).
31. Bizjak, I.; Cotič, B.; Gantar, D.; Gulič, A.; Koblar, S.; Kozamernik, J.; Mušič, B.; Mujkić, S.; Nikšič, M.; Sendi, R.; et al. *Poročilo o prostorskem razvoju 2021 [Spatial Development Report 2021]*; Ministrstvo za okolje in prostor, Direktorat za prostor, graditev in stanovanja: Ljubljana, Slovenia, 2021; p. 117. Available online: https://www.gov.si/assets/ministrstva/MNVP/Dokumenti/Prostorski-razvoj/porocilo_prostorski_razvoj_2021.pdf (accessed on 6 April 2025).
32. Statistical Office of the Republic of Slovenia. SISTAT Database. Available online: https://pxweb.stat.si/SiStat/en (accessed on 6 June 2025).
33. Surveying and Mapping Authority of the Republic of Slovenia. Report on the Slovenian Real Estate Market for the Year 2022. March 2023. Available online: https://www.e-prostor.gov.si/podrocja/trg-in-vrednosti-nepremicnin/trg-nepremicnin/?acitem=1967-2268 (accessed on 5 June 2025).
34. Bartol, B.; Humerca Šolar, L.; Lupše, I.; Miklavčič, T.; Torbica, J. *Spatial Development Strategy of Slovenia 2050*; Ministry of Natural Resources and Spatial Planning: Ljubljana, Slovenia, 2024; p. 99. Available online: https://www.gov.si/assets/ministrstva/MNVP/Dokumenti/Prostorski-razvoj/SPRS/Strategija-prostorskega-razvoja_2050_v-angleskem-jeziku.pdf (accessed on 7 June 2025).

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Structural Evolution of the Coastal Landscape in Klaipėda Region, Lithuania: 125 Years of Political and Sociocultural Transformations

Thomas Gloaguen [1,2,*], Sébastien Gadal [2], Jūratė Kamičaitytė [1] and Kęstutis Zaleckis [1,3]

[1] Cultural and Spatial Environment Research Group, Faculty of Civil Engineering and Architecture, Kaunas University of Technology, LT-51367 Kaunas, Lithuania; jurate.kamicaityte@ktu.lt (J.K.); kestutis.zaleckis@ktu.lt (K.Z.)
[2] UMR 7300 ESPACE, CNRS, Aix Marseille Université, Université Côte-d'Azur, Avignon Université, 84029 Avignon, France; sebastien.gadal@univ-amu.fr
[3] NEB Research Center, Vilnius Academy of Arts, LT-01124 Vilnius, Lithuania
* Correspondence: thomas.gloaguen@ktu.lt

Abstract: The coastal region of Klaipėda (Lithuania) has experienced major political, economic, social, and cultural transformations since the 20th century. Landscapes as evolving expressions of land use and land cover patterns offer a valuable lens to analyse these changes. This study examines the evolution of physical landscape structures across the pre-Soviet, Soviet, and post-Soviet periods, using historical maps and open-access geospatial data. An ontological approach, combined with morphological and configurational metrics, reveals four major and relatively persistent landscape structures: hydrological systems (sea, lagoon, rivers), forest cover, farming intensity (from extensive grassland use to intensive arable farming), and semi-natural environments. Their structural evolution reflects broader cultural factors, such as contrasting land use traditions between former Prussian and Russian territories. The study also highlights the impact of Soviet collectivisation, marked by irrigation networks, agricultural intensification, and forest expansion. The post-Soviet period is characterised by widespread farmland abandonment and fragmentation, revealing new spatial dynamics and challenges in land reappropriation. Landscape transformations are predominantly structured around agricultural dynamics. Although the analysis was limited by the incomplete availability of data for this specific land use class, the centrality of agriculture in shaping territorial organisation is evident and reinforces the strong rural identity associated with the landscape.

Keywords: spatial system; landscape structures; spatiotemporal modelling; territorial dynamics; geospatial ontologies; Lithuania; pre-Soviet; Soviet; post-Soviet

1. Introduction

The Lithuanian coastal region provides a compelling example of territorial transformations shaped by successive geopolitical, economic, social, and cultural changes since the beginning of the 20th century.

Since the third partition of the Polish–Lithuanian Commonwealth in 1795, the region has been politically divided between the Kingdom of Prussia, which controlled the southwestern part of the coastal zone, and the Russian Empire, which extended its influence into the northeastern territories. This political division was mirrored with ethno-cultural distinctions: "Mažoji Lietuva" (Lithuania Minor), under Prussian rule, in contrast to "Žemaitija"

(Samogitia), incorporated into the Russian Empire. These differences were manifest in language use, religious affiliation, ethnic composition, and land tenure systems. Agrarian reforms promoting private land ownership and family farming, for instance, were implemented earlier and more systematically in the Prussian part, whereas the Russian-controlled areas retained more traditional and communal arrangements until the Stolypin reforms of 1906 [1–3].

During the interwar period, the 1923 annexation of the former Prussian territory enabled newly independent Lithuania to unify its coastal region. From 1944 onwards, with the incorporation of the country into the Soviet Union, the coastal zone acquired major geostrategic importance as the Union's external border. This position led to the region's heavy militarisation and territorial closure, accompanied by profound socioeconomic transformations, including the collectivisation of agriculture, the expansion of heavy industry, and intense internal migration within the Soviet bloc [1,4,5].

The collapse of the Soviet Union in 1991 marked a radical political and economic shift, as Lithuania transitioned to market liberalisation and integrated into the European Union in 2004. Since then, despite ongoing demographic decline, the coastal region has become increasingly dynamic. Urbanisation, metropolisation, and investments in port and tourism infrastructure reflect the broader process of coastalisation, which is restructuring the functions and uses of the Lithuanian coastal region [1,5–9].

In this regard, the land use and land cover (LULC) functions both as a manifestation of these spatial transformations, reflecting the evolving socio-economic and environmental functions assigned to different territories. A distinction is made between land cover, defined as "the observed physical cover on the earth's surface", and land use, which refers to "the total of arrangements, activities, and inputs that people undertake in a certain land cover type to produce, change, or maintain it" [10]. This distinction highlights the interaction between natural systems and human society.

Within spatial systems, land use and land cover interact with the structures of spatial organisation, whether these are spontaneous or the result of regulations. Moreover, they maintain close relationships with other geographical objects, including networks or built-up environments [11,12].

Geographical analysis has historically focused on the study of landscapes, understood as the outcome of interactions between societies and their natural environment.

Landscapes can be approached from two interrelated perspectives: on the one hand, they are the visible expression of geographical space, shaped by land use and land cover dynamics; on the other hand, they are the product of symbolic, identity-related, and representational dimensions projected by individuals and communities onto space [13–16].

In the 20th century, geographic studies often related culture to society's capacity to organise and manage its environment—a vision at times marked by a deterministic reading of spatial systems. While this conception has evolved, it underscores the intrinsic connections between spatial transformations and sociocultural processes [14,17]. As such, landscape, when analysed through land use and land cover dynamics, is a significant indicator of changes within spatial systems.

The study of landscape dynamics within the conceptual framework of spatial systems proves particularly relevant in the case of the Baltic Sea Region, as its regionalisation is subject to debate. While scholars have highlighted the considerable variability in its spatial definition, its emergence from political rather than historical or cultural foundations, and the economic and demographic heterogeneity among the countries, few studies have truly focused on the territoriality of the Baltic space and the intrinsic relations between societies and their spatial environments at the core of the regionalisation concept [18–21].

This study, therefore, aims to contribute to a broader understanding of territoriality in the Baltic region by exploring shared spatialisation processes across its different parts over the long term. Specifically, it seeks to identify and characterise the physical structures of Lithuania's coastal landscape over the past 125 years, a period marked by particularly rapid, significant, and multifaceted political, economic, and social transformations. These structures are examined through morphological and configurational metrics applied to land use and land cover classes derived from historical maps and open-access geospatial data.

Relatively few studies at the Baltic regional scale have employed historical cartographic sources due to a triple uncertainty related to data production, transformation, and application of maps [22–24]. These materials are often incomplete and feature heterogeneous classification schemes, rarely accompanied by sufficiently precise definitions to allow for seamless data integration [25,26]. However, they remain essential for capturing the long-term complexity and persistence of spatial systems shaped by successive Prussian, Russian, Soviet, and post-Soviet influences. They are particularly valuable for investigating long-term transformations, as they provide rare, spatially explicit records that enable researchers to trace continuity and change across multiple political and socio-economic regimes [23,24].

This methodological approach draws on recent hybrid ontological frameworks developed for the analysis of landscape structures through land use and land cover classifications. Landscape metrics are employed as analytical primitives—basic descriptors associated with core landscape concepts such as fragmentation, connectivity, or spatial heterogeneity. This perspective allows researchers to go beyond the descriptive limitations of land use and land cover categories and contributes to a redefinition of landscape semantics in both structural and functional terms [27].

This approach addresses the issues faced by Geographic Information Systems (GIS), developed in the 1960s and 1970s, which were quickly confronted with a semantic gap between the complexity of geographical reality and the cognitive conceptualisation of spatial objects. This gap stems from the challenge of formalising complex spatial entities through representations based on spatial boundaries, relationships, temporal and spatial scales, and semantic descriptions [28].

Land use and land cover classifications, designed to formalise existing knowledge about the spatial dynamics of landscapes, can exhibit several limitations. While numerous classification schemes exist, often tailored to national or regional requirements, this diversity reflects a range of conceptual, legal, and practical approaches to land categorisation. Just as landscapes are shaped by cultural representations, land use and land cover classes stem from a subjective conceptualisation of geographic reality. These semantic challenges become even more critical as geospatial information is increasingly used by non-expert audiences. These classification still face several challenges, particularly concerning the completeness, quality, and reliability of the source data, as well as their spatial and temporal resolution [25,27,29,30].

The use of landscape metrics has become widespread since the emergence of landscape ecology in the 1980s, which focused on the relations between spatial structure, ecological functions, and landscape dynamics [31]. However, they are not exclusive and can be complemented or contrasted by alternative methodologies. In coastal contexts, for instance, the quantification of shoreline change is often conducted through statistical analysis of remote sensing, mapped, or measured data. Although effective, these techniques typically have a limited spatial scope, focusing primarily on the immediate coastline [32,33]. More broadly, landscape characterisation can be achieved using remote sensing techniques, in-

cluding automated or supervised classification of land use and land cover changes: in Lithuania, such methods are widely applied due to the standardisation of satellite data in both acquisition and image processing. These studies have significantly contributed to understanding spatial dynamics related to major socio-political transitions, particularly the shift from the Soviet to the post-Soviet period. The focus is often on changes in forestry and agriculture, two sectors most affected by this transformation [5,8,34–43]. Additionally, multi-criteria analysis provides an integrative framework for evaluating landscape evolution by incorporating social, environmental, and economic dimensions through a set of defined indicators [44]. Finally, participatory methods, based on interviews, surveys, and mental mapping, allow for the exploration of social representations of landscapes and their cultural and identity-based values [15,16].

Following the presentation of the selected metrics, each landscape structure is described individually in terms of its physical characteristics and spatial distribution. This analysis is then contextualised by the major political, economic, and social shifts documented in the scientific literature on the region.

2. Spatial Modelling Approaches for Landscape Structural Analysis

Figure 1 illustrates the methodological approach for modelling the landscape structures of the Lithuanian coastal region, which is further detailed in the following sub-sections through data collection, the application of morphological, configurational, and holistic landscape metrics, and machine-learning multivariate clustering.

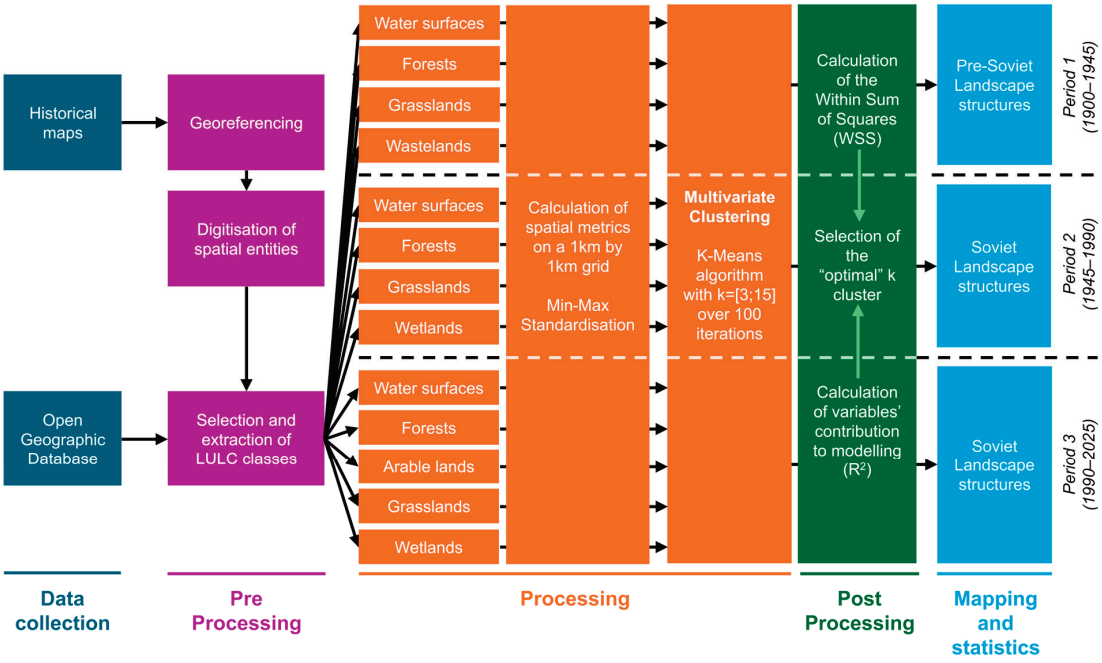


Figure 1. Methodological diagram of the different processing methods used to model landscape structures in the Lithuanian coastal region over 125 years.

The historical analysis is conducted over three distinct periods: the pre-Soviet period (from the beginning of the 20th century until 1945), the Soviet period (from 1945 to 1990), and the post-Soviet period (since 1990).

This choice is justified by the availability of the data needed for the study; the coherence of the historical bifurcations selected, i.e., the political, economic, social, and cultural transformations that are sufficiently significant to produce measurable territorial effects;

and the duration of each period (lasting spatial dynamics resulting from major societal bifurcations often emerge only many years later, reflecting the delayed impact of political, economic, and social transformations on territories) [45].

2.1. Data Collection

Land use and land cover data were derived from historical maps and open-access geographic databases (Figure 1). Historical maps were used exclusively for the pre-Soviet and Soviet periods due to their temporal archival value. The main challenge for the pre-Soviet period lies in sourcing data that are both available and consistent in terms of spatial resolution, geographic information, and production dates, particularly between the two areas formerly under the control of the Kingdom of Prussia and the Russian Empire.

For the Prussian-controlled area, six sheets from the "Karte des Deutschen Reiches" series—dated 1914, 1916, 1917, and 1920—were utilised. This series, produced between 1870 and 1944, offers a monochrome (black and white) resolution of 1:100,000. These maps were complemented by four sheets from the "Karte des Westlichen Russlands" series—dated 1897, 1915, and 1920—produced between 1892 and 1921, which share similar spatial resolution and colour characteristics (an excerpt is shown in Figure 2).

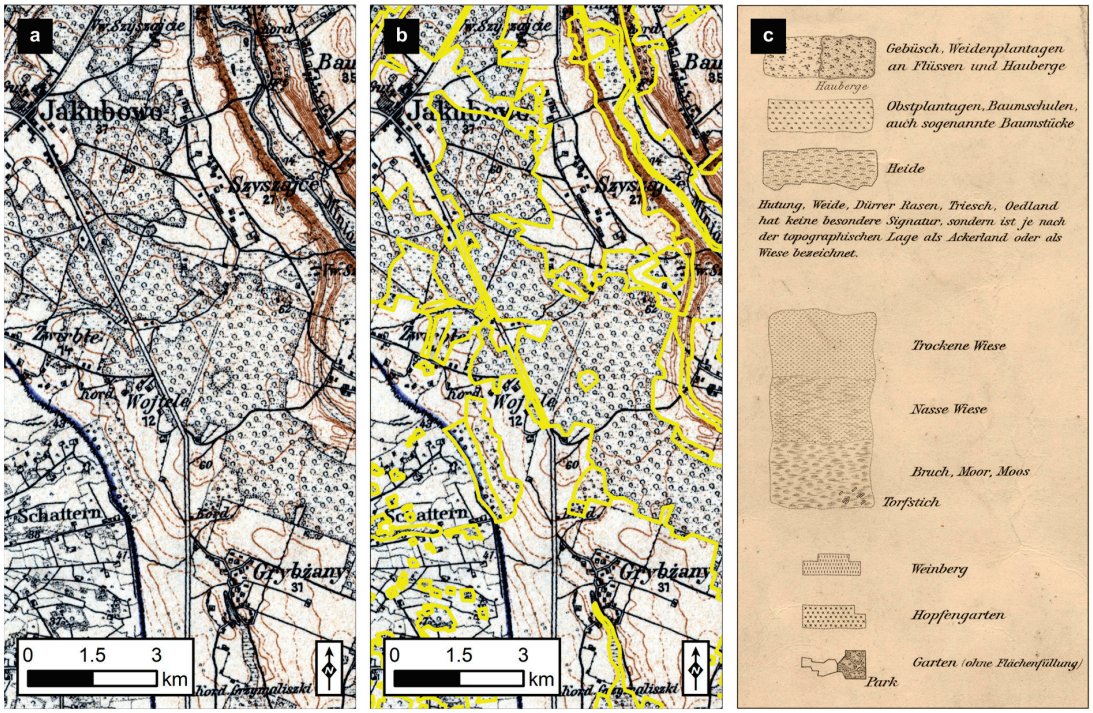


Figure 2. Preprocessing of historical maps for modelling landscape structures: (**a**) extract of the "Schattern–Korciany" sheet (1914) from the 1:100,000 Karte des Deutsche Reiches series after georeferencing, (**b**) digitisation process of spatial features relating to land use and land cover, and (**c**) extract of the nomenclature [46] for identifying land use and land cover classes.

Georeferencing of these historical maps was performed using a set of control points evenly distributed across each sheet, based on identifiable physical features (e.g., road intersections, specific infrastructures, etc.) visible on both the historical maps and modern satellite imagery. A spline transformation method was employed for the georeferencing processing with an average margin of error below 10 m.

For the Soviet period (1945–1990), Soviet military topographic maps were used. Specifically, the 1985 series comprising 24 colour sheets at a spatial resolution of 1:50,000, already georeferenced, was employed.

Given the significant variability in scan resolutions (ranging from 100 to 600 dpi), manual digitisation was preferred for extracting spatial entities related to land use and land cover. Each digitised vector feature was classified according to the legend-defined nomenclature (Figure 2). The cartographic sources were produced in diverse historical, institutional, and geopolitical contexts, which present a challenge for the cartographic exploitation of the data [22–24]. The nature and hierarchy of the geographical objects represented reflect these contexts and consequently shape the definition of the LULC classes that can be reconstructed from them [46,47]. These data are subject to the interpretation of the operator responsible for digitisation, particularly concerning the visibility of pixels delineating spatial entities related to land use and land cover, the reliability and selection of geographical information represented on the maps, and the assignment of land use and land cover classes to these entities following the established nomenclature [22]. For instance, Soviet military maps often depicted certain features using symbology corresponding simultaneously to multiple land use and land cover classes (Appendix A). In such cases, hybrid classes were created to integrate both dimensions of information.

For the post-Soviet period, the analysis is based on ESA WorldCover data, available at a resolution of 10 m by 10 m [48]. In contrast to historical cartography, this data was produced with the specific purpose of observing land use and land cover.

For each of the three study periods, a preprocessing step involved selecting land use and land cover classes for landscape modelling (Figure 1). This operation led to the identification of classes that were common across all data sources, such as forested areas, water bodies, and grasslands, as well as classes that were specific to sources, including wetlands and wastelands, for example, whose presence was deemed significant in the study area. Artificial surfaces were deliberately excluded from the analysis due to the heterogeneity of their cartographic representation: historical maps primarily depict buildings, whereas more recent sources include zonings that encompass buildings, transport infrastructure, and other man-made structures. A list of the land used and land cover classes, their reclassification, and exclusions is provided in the Appendix A.

2.2. Morphological and Configurational Metrics by Land Use and Land Cover Class to Identify Physical Landscape Structures

Six morphological and configurational metrics—density, shape, size and orientation, spatial cohesion, spatial dispersion, and spatial continuity—are calculated for each digitised entity within the land use and land cover (LULC) classes across the three study periods (Figure 1). These metrics serve to identify and characterise the physical structures of the landscape. To ensure comparability across LULC classes, each index is standardised using min–max normalisation and rescaled to a 0–100 range.

The metrics selected in this study are drawn from disciplines traditionally familiar with landscape analysis, such as ecology, geography, or urban planning, and are frequently applied to a wide variety of contexts: natural, rural, and urban. For example, the shape index, commonly used to describe the circularity or elongation of forest patches or agricultural parcels, can also be applied to urban fabric to characterise urban morphology. This reflects the index's interdisciplinary applicability and relevance across scales and landscape types. In this sense, the metrics not only support quantitative assessment of landscape structures but also resonate with more classical, typological approaches used in architecture and urban design, such as distinctions of compact vs. dispersed forms, spatial

coherence, etc. The objective was to select non-redundant metrics that together provide a comprehensive view of morphological, configurational, and functional aspects.

2.2.1. Density Metric

The first metric quantifies the density of each LULC class within the grid tiles. It is calculated as the ratio between the area occupied by a given class and the total area of the corresponding tile. This index serves to identify areas of high concentration (approaching 100) or dispersion (approaching 0) of specific LULC classes.

2.2.2. Shape Metric

The second metric evaluates the shape of each entity by comparing it to a circular form. Drawing on Gibbs' work on urban morphology [49], the index is computed by comparing the area of the entity to that of its minimum enclosing circle (Equation (1)):

$$C = \frac{100 \times S_E}{\pi \times \left(\frac{d}{2}\right)^2} \quad (1)$$

S_E: total surface area of the entity.
d: diameter of the circle circumscribing the entity.

Values of the index approaching 0 indicate more elongated shapes, while values nearing 100 correspond to more circular forms. For each tile in the grid, the mean circularity is computed based on the entities it contains. The metric helps distinguish land cover features based on morphological characteristics, for example, differentiating lakes, which tend to be compact or circular, from rivers, which typically display elongated and sinuous shapes.

2.2.3. Size and Orientation Metrics

The third index captures both the size and orientation of features. For each digitised entity within a given LULC class, a standard ellipse is computed based on the spatial distribution of its vertices. The ellipse represents the spatial extent and direction trend of the feature, derived from the standard deviations of the x and y coordinates relative to the feature's mean centre (Equation (2)) [50].

$$\sigma_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2},\ \sigma_y = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \overline{y})^2} \quad (2)$$

x_i, y_i: coordinates of the entity's vertices.
$\overline{x}$, $\overline{y}$: centre of gravity (average of vertices' coordinates).

Values close to 0 indicate the minimal spatial extent, whereas values approaching 100 represent the maximal extent.

Orientation is determined by the angle of rotation of the standard ellipse relative to the vertical (south–north) axis (Equation (3)) [50]. In the study, an entity oriented towards the east corresponds to a score of 25; towards the south, 50; west, 75; and north, 100. This metric captures the predominant directional alignment of spatial features. The average size and orientation are calculated for each grid tile, considering the features it intersects.

$$\theta = \frac{1}{2} tan^{-1}\left(\frac{2 \times cov(x,y)}{\sigma_x^2 - \sigma_y^2}\right) \quad (3)$$

x, y: coordinates of the entity's vertices.

A comparison of sizes and orientations of features, particularly within agricultural forestry parcels, can offer valuable insights into territorial planning policy strategies, land management models, or the dynamics of landscape transformation such as fragmentation.

In addition, the variances of the standard deviations along the x and y axes, as well as the angles of rotation of the ellipses, are calculated to assess the degree of heterogeneity or homogeneity in the sizes and orientations of features across space. A variance index close to 0 reflects a high degree of uniformity in the sizes and orientations of spatial features, whereas a value near 100 indicates strong heterogeneity. Such variability may stem from natural constraints (e.g., topography, hydrography) or human activities (e.g., agricultural practices, urban development).

2.2.4. Spatial Cohesion Metric

The fourth metric quantifies the spatial cohesion of features within each LULC class. It is calculated from the ratio between the perimeter and surface area of the digitised features (Equation (4)), a common indicator of geometric complexity [51]. This ratio ranges between 0 (highly fragmented, irregular features) and 100 (compact, cohesive features). The average value of this index is calculated for each grid tile, based on the features it contains.

$$K = 1 - \left(\frac{P_E}{S_E} \right) \tag{4}$$

P_E: perimeter of the entity.
S_E: total surface area of the entity.

2.2.5. Spatial Dispersion Metric

The fifth metric evaluates the spatial dispersion of features within each LULC class. It is based on the ratio between the number of features present in each grid tile and the distance to the nearest neighbour. This index is used to characterise the degree of concentration or dispersion of features, considering both their number and their spatial distribution.

In contrast to the density index, which simply quantifies the number of entities relative to the area they occupy, the dispersion index focuses on the count of entities and integrates the proximity between entities, specifically through the distance to the nearest neighbour.

A low average distance between neighbours, coupled with a high number of entities, indicated a high spatial concentration (near 0). Conversely, a high distance between entities suggests significant dispersion (nearly 100). Since the calculation depends on the number of entities per grid tile, the grid resolution can significantly influence the results of the spatial dispersion metric.

2.2.6. Spatial Continuity Metric

The sixth metric quantifies the degree of spatial continuity among entities of the same LULC class within the analysis grid. A tile is considered continuous if it contains at least one entity of the designated class, and if one of its eight neighbouring tiles (first-order Moore neighbourhood) also contains an entity of the same class [52]. The presence of an entity in each adjacent tile signifies the maximal continuity (100).

This index is useful for identifying connected spatial structures, such as ecological corridors, and for detecting large-scale landscape patterns, especially at the territorial scale.

However, it is important to note that the value of the index is highly sensitive to the tile size, which may influence the interpretation of the results at different spatial scales.

2.3. Holistic Metrics to Assess Landscape Structures

Two additional metrics—entropy and relief—are computed at the scale of the entire study area for each of the three periods. In contrast to the previous metrics, the entropy index considers the complete set of LULC classes, while the relief index is derived independently of LULC classifications.

2.3.1. Entropy Metric

The entropy metric (Shannon index) quantifies the diversity of LULC classes within each grid tile. It is calculated based on the proportional surface area occupied by each LULC class in the tile [53]. A low entropy value indicates the dominance of a single LULC class (low diversity), whereas a high value reflects a more balanced distribution among multiple classes (high diversity). An index value of 0 denotes complete homogeneity, where only one class is present.

In this analysis, the proportions used in the entropy calculation correspond to the ratio of the area of the class occupied by each class to the total area of the tile. Importantly, all theoretically possible classes are included in the calculation, even those not represented in a given tile, to ensure comparability across tiles by accounting for the full potential structure of the landscape.

2.3.2. Relief Metric

The relief index is derived from the mean elevation of pixels measuring approximately 30 m by 30 m, based on 30 m SRTM (Shuttle Radar Topography Mission) elevation data for each intersecting grid tile [54].

This index remains constant across the three periods studied, as topographic variation is assumed to be negligible at the territorial scale between periods and limited to specific development projects, such as port extension or coastal infrastructure, for example. The relief index is the only metric that was not standardised to a 0–100 scale, as it retains its original values in metres. This is due to the use of the same elevation dataset across all three study periods, ensuring consistency in topographic representation.

Relief is considered a stable contextual variable that helps to interpret its spatial dynamics in the landscape. In the Baltic Eastern region, particularly in Lithuania, the relief is notably flat and exhibits low variability, which can characterise certain landscape structures. Its inclusion enables the identification of patterns potentially shaped by elevation, without being influenced by marginal anthropogenic modifications.

2.4. Machine Learning-Based Multivariate Clustering of Landscape Structures

The metrics are calculated on a 1 km-by-1 km grid, a spatial resolution suitable for capturing local and territorial landscape dynamics. Landscape structural modelling is performed using a multivariate clustering approach based on the k-means machine learning algorithm, with the previously computed morphological and configurational metrics serving as explanatory variables (Figure 1). The objective is to group the grid tiles into homogeneous landscape structures (clusters) that minimise intra-cluster variance while maximising inter-cluster variance. An initial estimate of the optimal number of clusters (k) is obtained using the within-cluster sum of squares (WSS), a common metric for assessing cluster compactness [55]. However, in this case, WSS values declined monotonically, rendering the elbow method inconclusive for identifying a clear inflexion point (Figure 3).

To reinforce this cluster selection process, the average contribution of the variables to clustering (R^2 coefficient) is computed across 100 iterations (given the sensitivity of the k-means algorithm to initial cluster centroid placement) for k values ranging from 3 and 15. Clustering beyond 15 classes is not considered, as higher granularity diminishes the interpretability of results (identification of the main landscape structures). As expected, R^2 increases with the number of clusters, while the WSS decreases. To reconcile these two opposing trends, both curves are standardised and intersected to determine an optimal balance point between intra-cluster cohesion and inter-cluster separation (Figure 3).

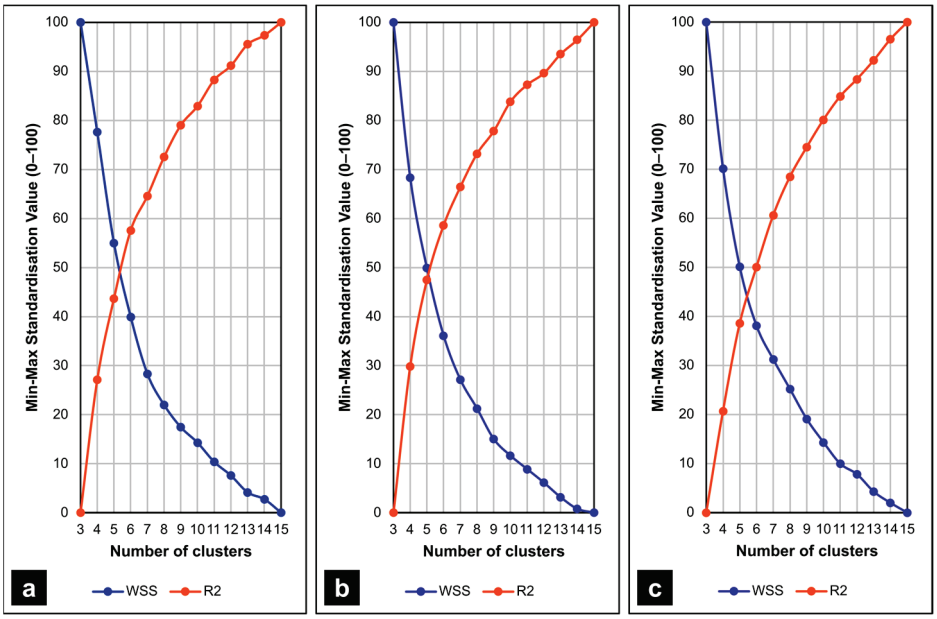


Figure 3. Trends in the standardised (min–max) within-cluster sum of squares (WSS) and the average contributions of the variables to clustering (R^2 coefficient) for 3 to 15 clusters over the (**a**) pre-Soviet, (**b**) Soviet, and (**c**) post-Soviet periods.

For each of the three periods of study—pre-Soviet, Soviet, and post-Soviet—this method consistently identified five distinct landscape structural clusters. The iteration yielding the highest average R^2 value, reflecting the optimal explanatory power of the input variables (metrics), was selected for the final analysis.

3. A Diachronic Spatial Analysis of Physical Landscape Structures

The modelling of physical structures of the coastal landscape is presented separately for each study period, due to the variations in LULC classes and differences in data resolution between sources. For each period, the mean metric values (scaled from 0 to 100) for each LULC class are used to characterise the clusters in terms of land use and land cover composition, patch morphology and spatial configuration, as well as entropy and relief-related metrics. The spatial distribution of the clusters is also considered. Each cluster corresponds to a physical landscape structure specific to the given period.

3.1. Typology of Pre-Soviet Landscape (1870–1920)

The modelling of pre-Soviet landscape structures is based on the main LULC classes present in the study area, i.e., water surfaces, forests, meadows, and wastelands. Marginal classes, such as nurseries or sandy areas, were excluded from the analysis due to their low spatial representativeness (Appendix A). The maximum average contribution of the

indexes to the modelling was 0.51, reflecting a moderate ability to discriminate between landscape structures based on the variables selected.

3.1.1. Pre-Soviet Hydrological Environments

This landscape structure includes low-relief areas (average relief of 3.33 m) dominated by water surfaces such as the Baltic Sea, Curonian Lagoon, major rivers (Niemen, Minija, Danė), and lakes (Figure 4). The moderate entropy index (16.14) reflects limited land cover diversity, with some localised heterogeneity tiles.

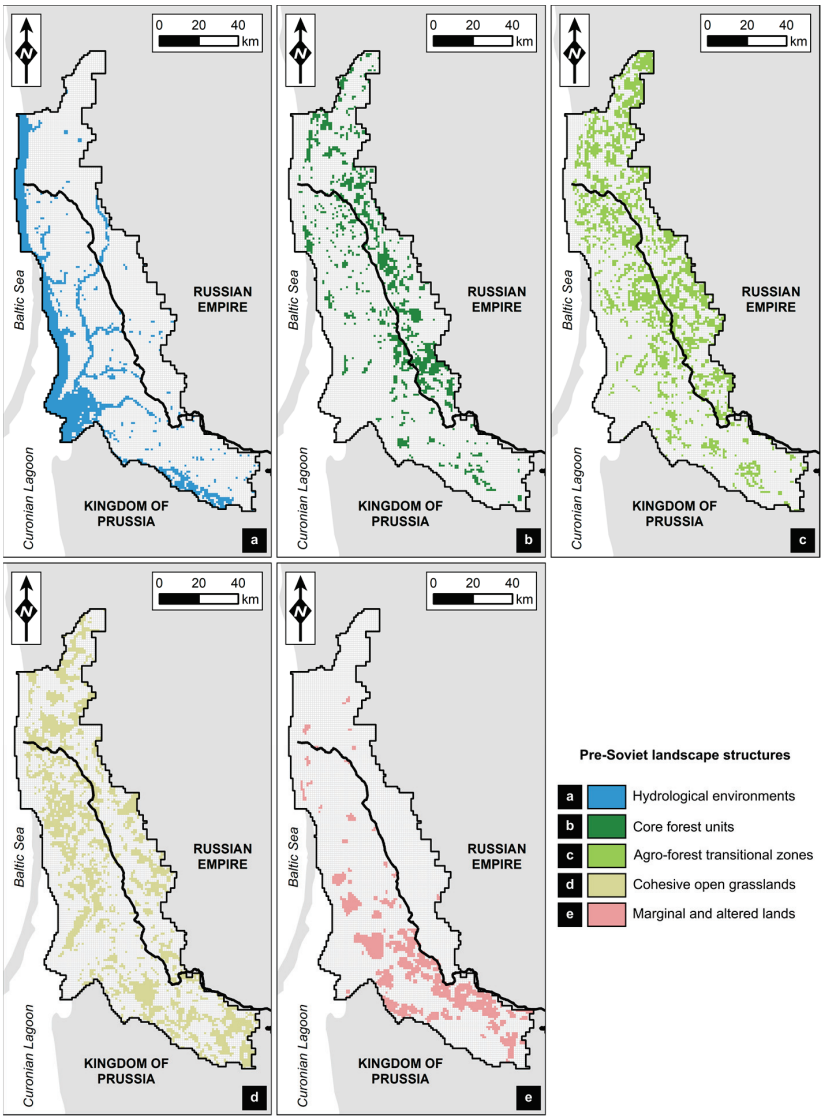


Figure 4. Spatial distribution of the pre-Soviet landscape structures with (**a**) hydrological environments, (**b**) core forest units, (**c**) agro-forest transitional zones, (**d**) cohesive open grasslands, and (**e**) marginal and altered lands.

Grasslands exhibit the highest density (47.87), a large patch size (26.90), strongest cohesion (98.87), and low fragmentation (average spatial dispersion of 2.31), making them well-structured and spatially coherent (Table 1).

Forest and wastelands are also present but appear more dispersed, with smaller patch sizes and moderate continuity.

This cluster represents the main hydrological and hydromorphic system composed of water bodies, wet meadows, and scattered shrubby or fallow lands.

Table 1. Averages of spatial metrics for land use and land cover classes in pre-Soviet "Hydrological Environments".

	Water Surfaces	Forest	Grasslands	Wastelands
Form	5.74	18.39	14.05	17.54
Cohesion	98.56	98.03	98.87	98.22
Continuity	75.85	63.9	85.66	47.70
Density	46.30	20.55	47.87	14.85
Spatial Dispersion	1.75	6.31	2.31	4.68
Size	76.86	10.68	26.90	8.85
Orientation	85.51	53.25	54.98	45.11

3.1.2. Pre-Soviet Core Forest Units

This landscape structure is primarily composed of forest areas, with low land cover diversity (entropy index of 11.53). Forests dominate, though some areas include water bodies and wastelands (Table 2).

Table 2. Averages of spatial metrics for land use and land cover classes in pre-Soviet "Core Forest Units".

	Water Surfaces	Forest	Grasslands	Wastelands
Form	19.60	18.54	0.00	15.45
Cohesion	95.64	99.03	0.00	99.18
Continuity	31.71	84.79	0.00	37.50
Density	3.85	52.44	0.00	3.60
Spatial Dispersion	4.72	2.29	0.00	7.24
Size	25.70	28.77	0.00	12.78
Orientation	66.55	54.74	0.00	16.89

These forests are mostly located in higher elevation zones (average relief of 31.76 m), especially in the large eastern part of the region, formerly under Russian control, an area showing strong territorial continuity (84.79) (Figure 4). Forest patches here are the most significant (average size of 28.77), dense (52.44), cohesive (99.03), and minimally fragmented (low dispersion of 2.29) (Table 2). While water surfaces and wastelands are marginal (low densities of 3.85 and 3.60), the water bodies tend to be circular (circularity of 19.60), indicating potential features as lakes or ponds. Coastal residual forests are also noted in the former Prussian part of the territory (Figure 4).

3.1.3. Pre-Soviet Agroforest Transitional Zones

This landscape structure represents a hybrid, transitional zone, characterised by forests and grasslands, and a higher land cover diversity (entropy index of 27.05).

Located mainly near forest cores in the eastern, formerly Russian-controlled region, it shares a similar elevation with the forest-dominated cluster (average relief of 28.59 m)

(Figure 4). Forest patches here are less dense (29.52) and smaller (17.64), but still cohesive (98.56), with slightly higher dispersion and fragmentation than the forest core cluster (Table 3).

Table 3. Averages of spatial metrics for land use and land cover classes in pre-Soviet "Agroforest Transitional Zones".

	Water Surfaces	Forest	Grasslands	Wastelands
Form	14.41	20.47	15.10	11.01
Cohesion	94.01	98.56	98.42	97.34
Continuity	40.53	76.07	78.96	37.50
Density	3.86	29.52	25.47	9.57
Spatial Dispersion	3.93	3.98	5.81	4.78
Size	26.02	17.64	14.37	4.40
Orientation	50.65	50.82	52.28	20.30

Grasslands are smaller (14.37), with moderate density (25.47), high cohesion (98.42), but lower territorial continuity (78.96) and greater local dispersion (5.81), suggesting scattered yet structurally coherent patterns (Table 3).

This structurally diverse landscape blends forest and grassland patches that, while coherent at the broader scale, are more fragmented locally, reflecting the dynamic nature of agroforestry systems. Water surfaces and wastelands are minimal (densities of 3.86 and 9.57) (Table 3).

3.1.4. Cohesive Open Grasslands

This landscape structure is defined by open lands dominated by grasslands, with low land cover diversity (entropy index of 9.40) and a moderate elevation (average relief of 20.94 m), indicating gently undulating terrain.

This is the most spatially diffuse cluster with scattered patches over almost the entire study area, with the exception of the Niemen delta and its adjacent territory to the east (Figure 4).

Grasslands here show a high patch density (36.93), moderate size (19.00), strong cohesion (98.53), and higher dispersion (4.77), suggesting scattered but territorially coherent structures (Table 4).

Table 4. Averages of spatial metrics for land use and land cover classes in pre-Soviet "Cohesive Open Grasslands".

	Water Surfaces	Forest	Grasslands	Wastelands
Form	0.34	0.00	15.12	0.00
Cohesion	90.52	0.00	98.53	0.00
Continuity	25.00	0.00	84.32	0.00
Density	1.05	0.00	36.93	0.00
Spatial Dispersion	2.38	0.00	4.77	0.00
Size	9.96	0.00	19.00	0.00
Orientation	11.59	0.00	51.17	0.00

Unlike the hydromorphic cluster, this structure consists almost exclusively of grasslands. Despite some local fragmentation, high territorial continuity (84.32) indicated a

well-connected grassland pattern across the broader landscape, typical of open, homogeneous environments.

3.1.5. Marginal and Altered Lands

This cluster is dominated by wastelands, with moderate land cover diversity (entropy index of 22.80). Grasslands and water surfaces are present but marginal.

Located mainly in the Niemen River plain and some coastal areas, it has a low elevation (average relief of 12.69 m) (Figure 4).

Wastelands show the highest density (39.80) and a significant patch size (34.92), exceeding that of forests and grasslands. Water areas are fewer in number (density of 7.43) but have the largest average patch size (40.17), influenced by the proximity of the Niemen River and deltaic aquatic formations (Table 5).

Table 5. Averages of spatial metrics for land use and land cover classes in pre-Soviet "Marginal and Altered Lands".

	Water Surfaces	Forest	Grasslands	Wastelands
Form	15.66	21.59	14.85	20.98
Cohesion	96.03	98.07	96.94	99.15
Continuity	41.71	64.51	72.68	71.24
Density	7.43	19.90	23.82	39.80
Spatial Dispersion	4.16	6.79	6.70	5.25
Size	40.17	10.71	15.42	34.92
Orientation	74.15	52.72	53.75	53.42

This cluster is marked by low territorial continuity and high spatial dispersion across all LULC types, reflecting fragmented, degraded, and structurally incoherent landscapes. Typically situated on the periphery of more structured areas, these zones represent low-dynamism, underutilised or environmentally altered lands.

3.2. Typology of Soviet Landscape (1985)

The modelling of Soviet landscape structures is based on LULC classes, some of which are identical to those of the pre-Soviet period, such as water surfaces and forests. Conversely, the large number of detailed classes related to herbaceous and wet formations (e.g., shrub, reed swamp, reed and grass, etc.) has been grouped into two main categories: grasslands and wetlands (Appendix A). The maximum average contribution of the variables to the model is comparable to that obtained for the pre-Soviet period, with a value of 0.51.

3.2.1. Soviet Hydrological Environments

Similar to the pre-Soviet model, this landscape structure is characterised by a dominance of water bodies. The low entropy index (4.39) reflects strong LULC homogeneity primarily due to the dominance of aquatic features.

While the relief is low (average of 13.85 m), it is higher than in the pre-Soviet hydrological cluster, as it includes inland water bodies like rivers, lakes, and irrigation canals, rather than being limited to the sea and lagoon (Figure 5). As a result, this cluster now spans the broader former Prussian territory, with more dispersed but still cohesive aquatic nuclei, especially in the Niemen plain.

Water surfaces here show moderate density (22.76), but are generally significant in size, spatially close (dispersion of 2.44), minimally fragmented (cohesion of 95.28), and highly

continuous (84.11), indicating a structured and connected hydrological system across sea, lagoon, and inland waterways (Table 6).

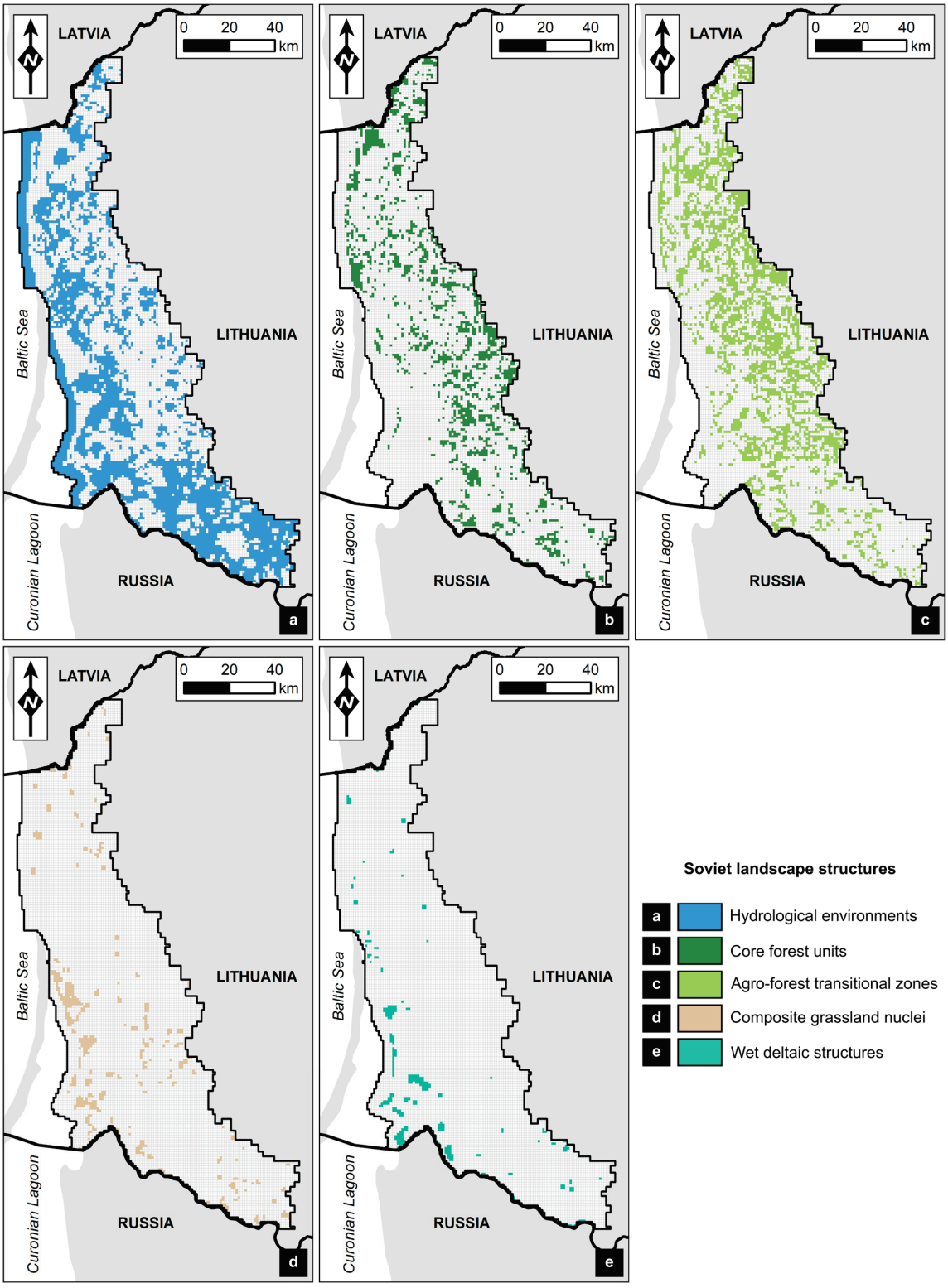


Figure 5. Spatial distribution of the Soviet landscape structures with (**a**) hydrological environments, (**b**) core forest units, (**c**) agro-forest transitional zones, (**d**) composite grassland nuclei, and (**e**) wet deltaic structures.

Table 6. Averages of spatial metrics for land use and land cover classes in Soviet "Hydrological Environments".

	Water Surfaces	Forest	Grasslands	Wetlands
Form	3.40	0.00	0.00	0.00
Cohesion	95.28	0.00	0.00	0.00
Continuity	84.11	0.00	0.00	0.00
Density	22.76	0.00	0.00	0.00
Spatial Dispersion	2.44	0.00	0.00	0.00
Size	55.74	0.00	0.00	0.00
Orientation	68.96	0.00	0.00	0.00

3.2.2. Soviet Core Forest Units

This cluster, consistent with the pre-Soviet period, is dominated by forests, with a low land cover diversity (entropy index of 12.90) and minimal presence of water surfaces (density of 0.39) (Table 7).

Table 7. Averages of spatial metrics for land use and land cover classes in Soviet "Core Forest Units".

	Water Surfaces	Forest	Grasslands	Wetlands
Form	0.84	20.33	0.00	0.00
Cohesion	88.61	98.56	0.00	0.00
Continuity	12.50	84.43	0.00	0.00
Density	0.39	45.85	0.00	0.00
Spatial Dispersion	0.00	3.72	0.00	0.00
Size	2.33	25.51	0.00	0.00
Orientation	7.15	52.45	0.00	0.00

It features the highest elevation in the region (average relief of 31.41 m), with forest areas concentrated in upland zones. Structurally, the forests remain similar to those of the earlier period: moderately sized patches (25.51), high density (45.85), strong territorial continuity (84.43), and low spatial dispersion, indicating cohesive and continuous forest cover with limited fragmentation (Figure 5).

3.2.3. Soviet Agroforest Transitional Zones

This landscape structure reflects a transitional landscape between forest and agricultural land, similar to the pre-Soviet agroforestry structure, characterised by forests and water surfaces, with relatively high land cover diversity (entropy mean of 22.36).

It spans a large portion of the study area, especially the former Russian-controlled region, excluding the Niemen plain and its western delta (Figure 5). Forest patches are less dense (31.84), smaller (18.25), and slightly more dispersed (4.00) than in core forest areas, though still highly cohesive (98.46), indicating moderate fragmentation (Table 8).

Water bodies are more residual, with low density (4.94), medium-sized patches (31.76) and reduced cohesion (93.23) and continuity (73.54) compared to the main hydrological structure (Table 8).

Unlike the pre-Soviet period, meadows are no longer prominent, making this a forest–agriculture transitional zone shaped more by woodland and water infrastructure (irrigation canals that likely serve adjacent arable lands) rather than by grasslands.

Table 8. Averages of spatial metrics for land use and land cover classes in Soviet "Agroforest Transitional Zones".

	Water Surfaces	Forest	Grasslands	Wetlands
Form	4.14	20.78	0.00	0.00
Cohesion	93.23	98.46	0.00	0.00
Continuity	73.54	76.47	0.00	0.00
Density	4.94	31.84	0.00	0.00
Spatial Dispersion	4.12	4.00	0.00	0.00
Size	31.76	18.25	0.00	0.00
Orientation	61.08	49.74	0.00	0.00

3.2.4. Composite Grassland Nuclei

This landscape structure is notably different from pre-Soviet typologies, characterised by a strong presence of grasslands, secondary forest presence, and marginal water bodies. The high entropy index (27.27) confirms this heterogeneous land cover pattern.

Grasslands show a moderate density (21.66) and patch size (24.03) but exhibit high local dispersion (8.54), with weak territorial continuity (49.88), indicating isolated and scattered clusters (Figure 5, Table 9). Despite this, their spatial cohesion remains high (98.32).

Table 9. Averages of spatial metrics for land use and land cover classes in Soviet "Composite Grassland Nuclei".

	Water Surfaces	Forest	Grasslands	Wetlands
Form	4.70	19.44	18.10	9.48
Cohesion	95.92	98.73	98.32	68.76
Continuity	77.94	81.03	49.88	0.00
Density	15.51	39.98	21.66	0.11
Spatial Dispersion	2.65	3.17	8.54	10.12
Size	57.19	25.72	24.03	0.07
Orientation	69.85	54.42	53.22	0.81

Forests have a high density (39.98) and size (25.72), with relatively low dispersion (3.17) and strong territorial continuity, resembling core forest structures in coherence but differing in context (Table 9).

Water surfaces are residual but include large patches (57.19), low dispersion (2.65), and moderate continuity (77.94), reflecting scattered but cohesive aquatic areas, especially in coastal lagoon areas (Figure 5).

This is a spatially fragmented and mixed structure, predominantly grassland-based, with significant internal variability and patchy landscape connectivity.

3.2.5. Wet Deltaic Structures

The landscape structure can be described as a deltaic wetland mosaic, characterised by the dominance of wetlands and a high diversity of LULC classes, as reflected by an elevated entropy index (average of 22.36). Located in low-lying areas (average elevation of 5.42 m), especially in the Niemen delta and along the Curonian Lagoon, this structure reflects the complexity of deltaic environments (Figure 5).

Wetland areas exhibit the highest patch density (average of 23.25), with moderate average patch sizes (28.86) and the highest levels of spatial dispersion across all LULC types (average of 9.33). These characteristics point to a highly fragmented distribution at the local scale, accompanied by limited territorial continuity (average of 47.29), indicating the presence of isolated and weakly connected wetland units (Table 10).

Table 10. Averages of spatial metrics for land use and land cover classes in Soviet "Wet Deltaic Structures".

	Water Surfaces	Forest	Grasslands	Wetlands
Form	7.07	19.17	13.71	19.30
Cohesion	95.69	98.23	98.18	98.16
Continuity	81.12	74.29	53.14	47.29
Density	18.31	26.77	21.81	23.25
Spatial Dispersion	2.65	4.51	2.70	9.33
Size	55.77	15.35	26.16	28.86
Orientation	68.13	54.37	44.97	52.37

Grasslands, though less dominant, show a similar patch size (26.16) and moderate density (21.81), marked by high local cohesion (98.18) but limited continuity across the territory (53.14) (Table 10).

Water surfaces are less frequent (density of 18.30) but from large, well-connected patches (average size of 55.77 and average continuity of 81.12), often adjacent to major aquatic systems (Table 10).

Forest, only marginally present, is defined by modest densities (26.77), small patch sizes (15.35), and moderate territorial cohesion (74.29) (Table 10).

Overall, this structure is shaped by a dispersed and heterogeneous configuration, with multiple land cover types intersecting in a fragmented yet ecologically significant, deltaic landscape. However, the spatial distribution of this landscape structure remains limited in the study area (Figure 5).

3.3. Typology of Post-Soviet Landscape (2021)

The modelling of landscape structures in the post-Soviet period is predicated on the primary LULC classes present in the designated study area, namely water surfaces, forests, meadows, and wetlands, as well as, specifically for this period, arable land. In contrast to the previous models, this model explicitly incorporates cultivated farmland. The maximum average contribution of the indexes to the modelling is 0.45, which reflects the moderate capacity of the variables selected to discriminate between landscape structures.

3.3.1. Post-Soviet Hydrological Environments

The first cluster corresponds to the coastal hydrological landscape, largely centred on the Baltic Sea, the Curonian Lagoon, and the aquatic systems of the Niemen delta,

resembling the spatial configuration observed during the pre-Soviet period (Figure 6). The structure is dominated by water surfaces, as confirmed by a very low entropy index (average of 0.47), indicating minimal land cover diversity.

The relief index (average of −0.03 m) confirms the extremely low elevation of these areas, consistent with their coastal and deltaic nature. Water patches are exceptionally large (average size of 83.34) and dense (99.62), forming a nearly continuous matrix with negligible spatial dispersion and very high levels of spatial cohesion (99.81) and territorial continuity (99.62) (Table 11).

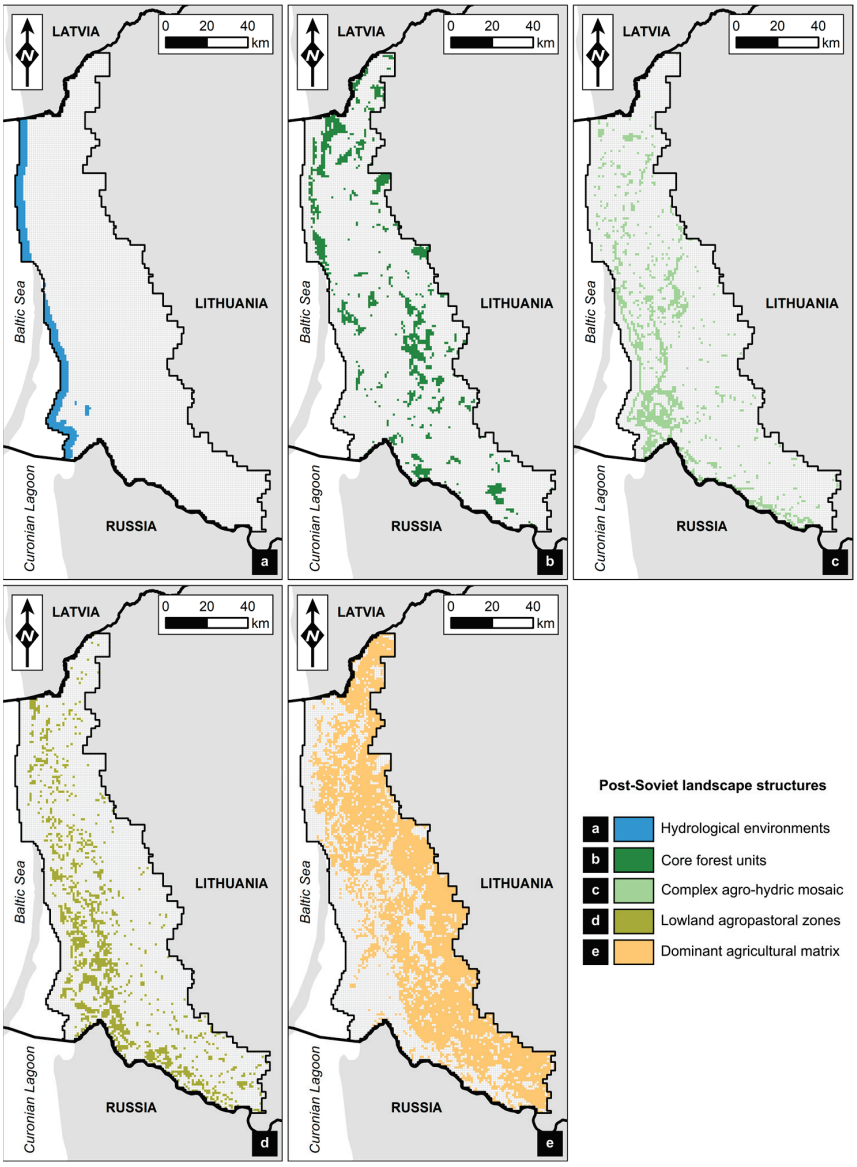


Figure 6. Spatial distribution of the post-Soviet structures with (**a**) hydrological environments, (**b**) core forest units, (**c**) complex agro-hydric mosaic, (**d**) lowland agropastoral zones, and (**e**) dominant agricultural matrix.

Other LULC classes, such as arable land (mean density of 0.02), forest (0.73), grassland (2.61), and wetland (6.92), appear only marginally, mainly along the coastal interface, highlighting the structural dominance and spatial integrity of aquatic environments.

3.3.2. Post-Soviet Core Forest Units

The second landscape structure corresponds to forest-dominated areas, as in previous periods. Forest cover is the only LULC, while the moderate entropy index (12.18) reflects limited land cover diversity.

Forest patches are large (average of 45.04) and dense (87.54), forming cohesive and compact areas. This is supported by very high spatial cohesion (98.91), strong territorial continuity (98.40), and minimal spatial dispersion (0.24) (Table 12).

Table 11. Averages of spatial metrics for land use and land cover classes in Post-Soviet "Hydrological Environments".

	Water Surfaces	Forest	Grasslands	Wetlands	Arable Land
Form	4.25	11.30	11.56	11.07	30.65
Cohesion	99.81	96.06	92.75	96.52	40.55
Continuity	99.62	47.50	45.00	57.50	25.00
Density	99.49	0.73	2.61	6.92	0.02
Spatial Dispers.	0.00	0.66	0.58	0.47	26.14
Size	83.34	38.93	5.87	26.13	0.00
Orientation	94.10	23.35	41.89	57.32	95.67

Table 12. Averages of spatial metrics for land use and land cover classes in Post-Soviet "Core Forest Units".

	Water Surfaces	Forest	Grasslands	Wetlands	Arable Land
Form	16.58	15.28	22.16	25.66	20.06
Cohesion	86.88	98.91	91.70	73.01	86.41
Continuity	51.79	98.40	93.36	34.38	59.00
Density	19.11	87.54	9.89	1.10	2.79
Spatial Dispers.	4.40	0.24	4.41	5.23	1.64
Size	29.53	45.04	2.87	0.85	5.17
Orientation	71.56	48.40	53.54	48.42	36.02

These forests are mainly located along the northern coastline, between Gargždai and Šilutė, with some occurrences on the Niemen plain and in inland northern zones (Figure 6). Their location on regional hilltops is reflected in the highest average elevation among clusters (27.41 m).

Water surfaces are also present, with notable density (19.11) and a moderate patch size (29.53), though they show higher dispersion (4.40), lower continuity (51.79), and reduced cohesion (86.88) compared to forests. These likely represent sea surfaces intersecting coastal forest tiles (Table 12).

Other LULC types remain marginal: wetlands (average density of 1.10), arable land (2.79), and grasslands (9.89).

3.3.3. Complex Ago-Hydric Mosaic

The third landscape structure corresponds to heterogeneous wet arbustive meadow patches, echoing a similar pre-Soviet configuration. It combines multiple LULC types with wetlands, water surfaces, grasslands, and forests and is marked by high entropy (47.07), reflecting strong land cover diversity.

Located primarily in the lowlands of the Nemunas Delta (average elevation of 7.47 m), this structure features small, dispersed wetland patches (density of 12.17, size of 2.08, continuity of 65.54) (Figure 6, Table 13).

Grasslands are more cohesive (density of 39.74, cohesion of 95.92, and continuity of 95.54), while forests, though less extensive (density of 23.83 and size of 7.32), are also well-structured spatially (cohesion of 94.66) (Table 13).

This cluster forms a transitional agro-wetland mosaic of diverse, small-scale patches, combining dense grasslands and forest elements with fragmented aquatic features.

Table 13. Averages of spatial metrics for land use and land cover classes in Post-Soviet "Complex Ago-Hydric Mosaic".

	Water Surfaces	Forest	Grasslands	Wetlands	Arable Land
Form	20.84	21.12	22.30	23.48	25.70
Cohesion	86.53	94.66	95.92	83.69	60.90
Continuity	54.10	86.09	95.54	65.54	85.40
Density	10.92	23.83	39.74	12.17	15.16
Spatial Dispers.	2.69	2.11	0.44	2.08	1.47
Size	12.09	7.32	7.14	3.37	3.18
Orientation	60.07	52.51	57.18	59.34	60.04

3.3.4. Lowland Agropastoral Zones

The fourth landscape structure represents an agropastoral zone dominated by wetlands, grasslands, and arable lands, with moderate diversity indicated by an entropy index of 33.26. Situated mainly in low-lying coastal zones of the southwest study area and the Niemen plain (average relief of 7.19 m), this cluster includes some residual nuclei in the northern part of the region (Figure 6).

Wetlands are relatively sparse and fragmented, with low density (7.70), small patches (2.50), higher spatial dispersion (4.21), and moderate cohesion (77.27) and continuity (57.83). Grasslands are more dominant and cohesive, exhibiting high density (50.64), larger patches (12.65), strong spatial coherence (96.46), and territorial connectivity (99.35). Arable lands show a moderate density (26.20) and patch size (5.16), with low dispersion but higher fragmentation (cohesion of 63.95) compared to other classes (Table 14).

Table 14. Averages of spatial metrics for land use and land cover classes in Post-Soviet "Lowland Agropastoral Zones".

	Water Surfaces	Forest	Grasslands	Wetlands	Arable Land
Form	10.57	22.59	21.66	25.70	25.22
Cohesion	88.35	94.32	96.46	77.27	63.95
Continuity	75.00	85.49	99.35	57.83	91.48
Density	0.23	22.05	50.64	7.70	26.20
Spatial Dispers.	0.09	3.64	0.34	4.21	0.98
Size	0.47	8.21	12.65	2.50	5.16
Orientation	12.34	51.51	58.74	61.91	58.80

This cluster typifies agropastoral areas where extensive, well-connected grasslands are interspersed with smaller arable fields and scattered wetland remnants.

3.3.5. Dominant Agricultural Matrix

The final landscape structure represents a predominantly agricultural matrix, distinguished by the dominance of arable land, accompanied by smaller proportions of grassland and marginal woodland. The entropy index (35.54) indicates moderate land cover heterogeneity despite the arable land predominance. This cluster is generally located on slightly elevated terrain (average elevation of 26.83 m), mainly along the eastern study area border, with compact nuclei in the east and more dispersed patches toward the west (Figure 6).

Arable land patches are relatively larger compared to the other clusters (average size of 10.53) and densely concentrated (density of 39.36), showing local dispersion (0.58) and strong territorial connectivity (93.31), though spatial coherence is moderate (67.12), possibly due to internal fragmentation or sub-parcelling. Grasslands are dense (35.87), with smaller, compact patches (7.34) displaying high coherence (95.38) and continuity (99.02) (Table 15). Forest remnants, though less abundant, have a moderate density (25.81) and relatively large patches (12.74), with average spatial metrics reflecting well-structured but somewhat scattered woodlands integrated into the agricultural matrix (Table 15).

Table 15. Averages of spatial metrics for land use and land cover classes in Post-Soviet "Dominant Agricultural Matrix".

	Water Surfaces	Forest	Grasslands	Wetlands	Arable Land
Form	25.44	22.16	23.18	0.00	24.02
Cohesion	77.37	95.29	95.83	0.00	67.12
Continuity	28.00	89.48	99.02	0.00	93.31
Density	1.89	25.81	35.87	0.00	39.36
Spatial Dispers.	9.88	3.06	0.55	0.00	0.58
Size	3.19	12.74	7.34	0.00	10.53
Orientation	59.03	53.96	57.44	0.00	57.90

4. Immutability and Structural Dynamics of Coastal Landscape Structures

Although the source data present incomplete and heterogeneous land use and land cover classifications, a relative stability in landscape composition can be observed over the 125-year study period (Figure 7). This stability is inferred from the presence of a consistent composition across the three periods analysed. In particular, three landscape structures appear especially persistent: (1) the hydrological network, which retains a consistent spatial framework, (2) forest cores, representing stable land cover entities over time, and (3) agricultural land use, despite the absence of explicit arable land classes in the earlier historical maps but deduced from other classes. A fourth, more localised and partially constrained structure relates to natural or semi-natural areas such as wetlands and wastelands.

While these four structures show relative stability in terms of land use and land cover composition, their internal structure evolves under the influence of political, economic, social, and cultural dynamics.

4.1. A Dual Influence of the Maritime and Lagoon Environments and the River Systems

One of the structures consistently identified across the three study periods corresponds to the hydrological network. This recurrent pattern can be attributed to the combined influence of the maritime and lagoon environments—namely, the Baltic Sea and the Curonian Lagoon—and the river systems, with the Niemen River and its delta being the most prominent components (Figure 7).

This primary hydrological structure can, however, be partially dissociated, as water surfaces are also present in other, more composite landscape structures, particularly those associated with meadows. In these cases, water surfaces, though less dominant, still contribute to a landscape characterised by a diversified and mixed spatial configuration.

The spatial extent of the main hydrological structure varied over time. During the Soviet era, the hydrological network expanded significantly beyond its primary maritime and fluvial core, covering a much larger share of the territory (Figures 5a and 7b). This expansion likely reflects the cartographic conventions of the era, which placed a greater emphasis on irrigation and drainage infrastructures implemented for agricultural modernisation. These changes can be understood as a manifestation of the broader transformation of rural landscapes initiated by collectivisation policies from the 1940s onwards.

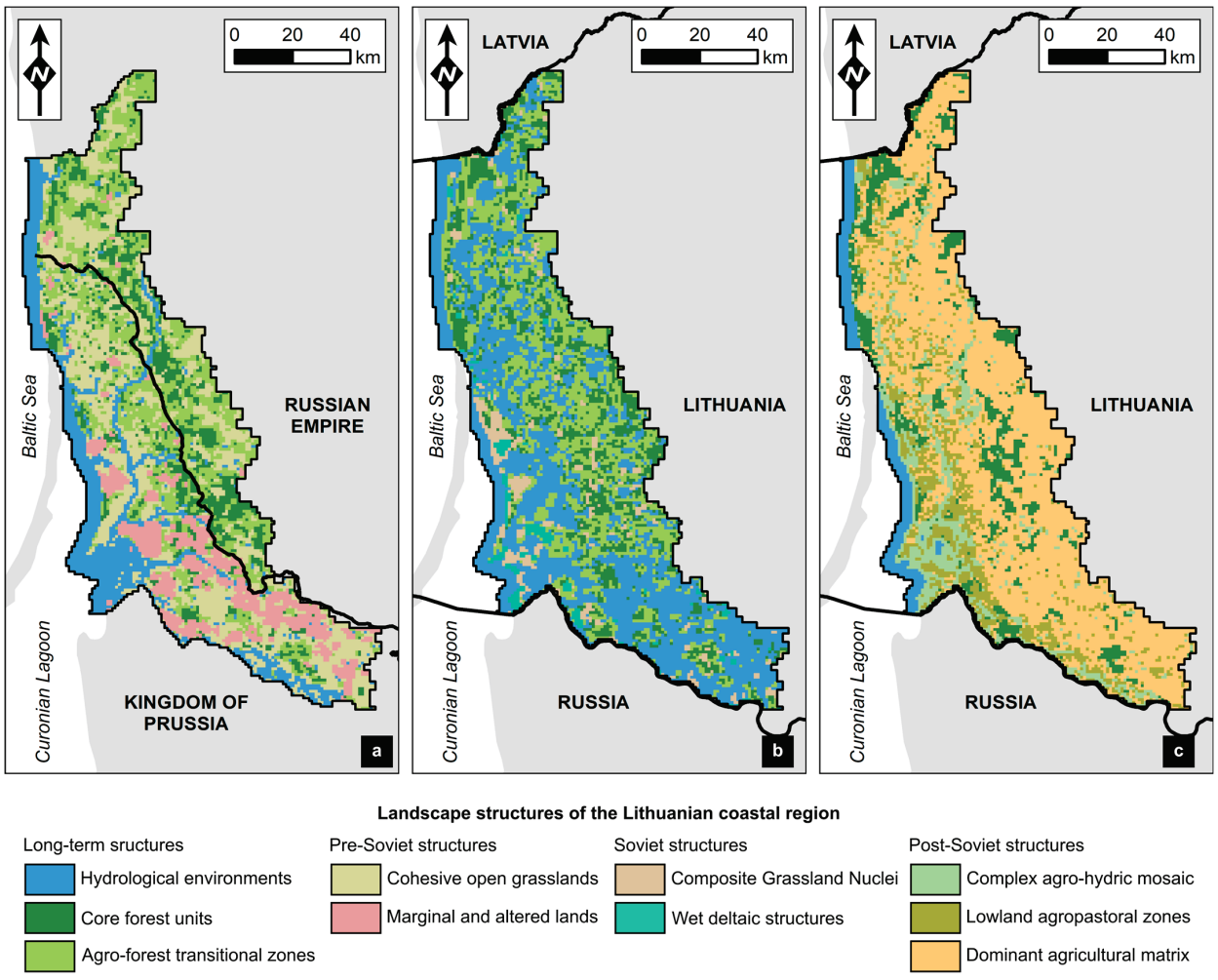


Figure 7. Spatial distribution of landscape structures for the (**a**) pre-Soviet, (**b**) Soviet, and (**c**) post-Soviet periods.

It is reasonable to assume that the number of clusters in the model would allow for a finer distinction between the maritime hydrological component and its terrestrial counterpart, thereby improving the identification of intensively irrigated agricultural zones during the Soviet period without necessarily having a class relating to arable land. Irrigation and drainage networks are responsible for a reduction in natural vegetation as well as a decrease in the diversity of land cover classes [56].

Post-Soviet modelling does not capture the full terrestrial extent of these networks due to the spatial resolution of the data, which does not allow for the detection of features smaller than 100 m^2—this being the case for most networks here. Moreover, these drainage systems have been heavily degraded with time, with some no longer functional and in need of restoration [57].

4.2. Temporal Persistence and Transformation of Forest Core Structure

The second sustainable landscape structure identified over time corresponds to forested areas, primarily located along the eastern border of the study region (Figure 7). It comprises a series of forest cores, among which the most prominent are the coastal forests (in the north of Klaipėda and near Palanga), as well as the Šilutė and Pagegiai forests on the Niemen River plain.

Beyond these stable forest areas, the location or spatial extent of forest cores varies substantially across the studied periods. These fluctuations are mainly due to differences in LULC classification across modelling iterations, where certain wooded areas may, at times, be integrated into more heterogeneous landscape structures, and at others reassigned to a dedicated forest cluster.

During the pre-Soviet period, the forest structure was characterised by geographical compactness and relative homogeneity, traits even more pronounced when transitional agroforestry zones are included. This configuration partly overlaps with the former territory of the Russian Empire (Figure 4b,c and Figure 7a), suggesting distinct cultural approaches to land use between areas under Prussian and Russian influence. The higher forest density in the Russian-administered zone may reflect a lower degree of agricultural intensification. This hypothesis is supported by historical maps that show the persistence of linear street villages typical of the medieval Teutonic period, still widespread at the beginning of the 20th century [45,58]. At that time, agrarian reforms promoting individual and family farming—already underway in much of Europe—had not yet been widely implemented in the Russian Empire, with the Stolypin reform dating only from 1906. The maps used date back to 1920 at the most. It was only after Lithuania's independence of 1918 that these changes gradually took effect for the entire study region [2].

Although the forest core structure was generally preserved during the Soviet period, it appears more diffuse and fragmented for similar morphological and configurational characteristics with the pre-Soviet period forest structure (although these results should be compared with the utmost caution given the heterogeneity of the data) (Figures 5b and 7b). As previously discussed, the land collectivisation reforms introduced in Lithuania from the 1940s led to the dismantling of numerous family farms. In certain cases, the abandonment or reallocation of agricultural land may have facilitated processes of spontaneous or state-led reforestation on unused plots [59]. Similarly, the development of irrigation and drainage canals, and ultimately the expansion of agriculture, may have contributed to fragmentation in other areas.

In the post-Soviet period, the configuration of forest cores—and more broadly, of less dense and smaller forest formations—becomes more complex to delineate (Figures 6b and 7c). These areas are frequently embedded in mixed landscape structures alongside other LULC classes, such as arable land (Table 15), complicating their clear identification. Nevertheless, a tendency toward a reduction in the number of large, discrete forest cores can be observed (Figure 6b), with the remaining ones forming more compact clusters. The post-Soviet landscape did not undergo a uniform regression, but rather a structural transformation, reflecting a coexistence of dynamics including fragmentation, spontaneous regeneration, and the reallocation of land use functions. This interpretation is

supported by the results of remote sensing analysis from the same period, which highlight an increase in forest cover in the Klaipėda district [43,60].

4.3. Temporal Variability and Ambiguity of Landscapes Shaped by Extensive and Intensive Agricultural Practices

Several identified structures are dominated by grassland, often wet or semi-wet in character. During the pre-Soviet period, these grasslands occupied a large portion of the northern half of the territory, particularly in what was formerly East Prussia (Figures 4d and 7a). Although arable land is not explicitly represented in the LULC data from this period, agricultural activities were likely well-established in this part of the territory. This assumption aligns with the agrarian reforms aimed at individualising land ownership that began in the late 19th century. Supporting this interpretation are the sociocultural characteristics of the local population, especially the "Lietuvininkai" (Prussian Lithuanians), a Protestant group that traditionally placed a strong emphasis on private land ownership, education, and agricultural productivity [61,62]. This is also reflected in the spatial structure of settlements, with dispersed, autonomous farms prevalent in this region.

In contrast, during the Soviet period, grassland-dominated structures became marginal and were mainly restricted to the southwestern end of the study area, particularly in the Niemen delta (Figures 5d and 7b). This shift can be explained by several intersecting factors. First, the collectivisation reforms initiated in the 1940s brought about profound changes in rural organisation. The subsequent intensification of agriculture likely led to the progressive conversion of grasslands into arable land [56]. This hypothesis is supported by the observation of a linear trend of grassland decline ranging from 0 to −3% between 1971 and 1990 [35].

Additionally, the Soviet maps used in this study may reflect a different approach to vegetation classification. Unlike earlier or contemporary cartographic representations, Soviet maps seldom depict grasslands as a distinct, homogeneous category. Instead, grassland-related cover types are often subdivided into more hybrid categories, such as grassland with sparse woodland, herbaceous marshland with shrubs, mixed marshland with reeds and woody elements, etc. This typological and terminological diversity reflects the practical orientation of Soviet cartography, which served military and agricultural planning purposes. As a result, grasslands—especially when fragmented or peripheral—were often subsumed under other LULC categories. This practice likely led to an underrepresentation of grasslands in Soviet datasets and complicated comparisons across periods.

Recent data reveal that arable land currently dominates much of the study zone, whether in relatively homogeneous or more diversified landscape structures (Figures 6e and 7c). This highlights the historical association of the notion of "landscape" in Lithuania with agrarian functions in rural areas [45]. However, the modelling also seems to reflect a subtler and less visible phenomenon: the gradual abandonment of agricultural land.

The decline of agricultural surfaces appears to be part of a broader structural change affecting the region's socio-economic and territorial organisation. It reflects both a declining interest in agricultural activities and the difficulties of maintaining them, particularly in the aftermath of the post-Soviet and restitution process [63]. These transformations are expressed in the emergence of more mixed LULC configurations, where arable land coexists with other classes, such as forests and grasslands. This stands in contrast to earlier periods when agricultural areas could be more easily identified due to the less diversified landscape structure, with open agricultural plains in the pre-Soviet era and clearly defined irrigated networks during the Soviet period, making interpretation more straightforward.

The increasing diversity of LULC classes within these structures may therefore both obscure and reveal the decline of agriculture in the post-Soviet period: it conceals it by

integrating it into more composite configurations but also reflects it by signalling a loss of coherence and dominance of traditional agricultural land uses.

4.4. The Niemen Delta: From Traditional Use to Protected Wetland Landscape

Several mixed structures characterise natural or semi-natural landscapes that are largely influenced by the Niemen River in a small part of the study area. These semi-natural landscapes are made up of meadows, wastelands, and wetlands, consistently identified in the three steps of modelling (Figure 7). These conditions may have led to the establishment of specific rural traditional communities, with fishermen and farmers living in the peat bogs and wet meadows, whose way of life is essentially dictated by the river and flooding cycle, preventing any intensive farming [58]. These communities were widespread during the pre-Soviet period but were largely dismantled by Soviet policies of collectivisation and village/population consolidation. As a result, these landscapes have remained under the dominant influence of natural features. Today, this region has become a Ramsar-protected wetland and is part of the Natura 2000 European network, aimed at conserving and protecting natural ecosystems. The area is now characterised by a low population density, which has helped preserve the ecological integrity of the Niemen delta. The modelling has repeatedly underscored the role of the Niemen delta in shaping the spatial configuration of certain LULC classes within broader landscape structures.

4.5. Critical Analysis of Landscape Structural Modelling

Two important aspects related to the retrospective modelling of landscape structures deserve particular attention.

The spatial ontology-based approach adopted in this study enabled the identification of structural changes by highlighting morphological and configurational variations, thereby going beyond potential differences in the interpretation of land use and land cover classes. However, it does not resolve the persistent issue of source data completeness. Nevertheless, by associating classes and inferring missing elements, certain structures could be deduced and interpreted. The clearest example concerns agricultural plots: although not explicitly represented in historical maps, they were indirectly considered in the analysis through the presence of irrigation/drainage canals and the detection of grassland areas.

The second issue relates to the robustness of explanatory variables underlying the structural model. Their average contribution proved relatively modest ($R^2 = 0.49$). This invites reflection on the choice of metrics, which were deliberately limited to avoid redundancy and balanced across functional, morphological, and configurational dimensions. However, they may have lacked the specificity or sensitivity needed to capture the full complexity of landscape structures.

The modelling algorithm may also be questioned. K-means clustering, originally sensitive to raw data variance, might have overemphasised certain variations while underestimating others. Moreover, metrics were computed separately by land use and land cover classes, potentially limiting the model's ability to identify coherent groupings, as the likelihood of divergent clustering increases with the number of metrics.

Weighting mechanisms could have enhanced the model, for instance, by considering the spatial extent of land cover classes and assigning less importance to those with limited surface area. Similarly, weighting based on the reliability of underlying datasets could reinforce the modelling process. Yet, such improvements often require auxiliary datasets to cross-validate historical information, which are not always available.

Deep learning algorithms may offer an alternative by modelling latent relationships and handling part of the inherent complexity of spatial structures.

Considering that landscapes are a component of broader spatial systems, part of the observed structures should integrate additional data, such as networks and built environments, as key structuring elements.

Finally, one hypothesis worth considering is that some of the modelling noise may stem from the absence of pre-existing structure (before the analysed period) in the model, even though it continues to influence observed spatial configurations.

These considerations open up interesting avenues for improving the reconstruction and interpretation of historical landscape structures.

5. Conclusions and Perspectives

The objective of this research is to analyse the evolution of landscape structures in the coastal region of Klaipėda, Lithuania, over 125 years. Relying on historical geospatial data from digitised maps and open-access databases, morphological and configurational metrics are applied to major land use and land cover classes. These were subsequently modelled using a multivariate machine-learning-based clustering method.

The results suggest that despite classification limitations, consistent patterns in landscape organisation can be identified through spatial reasoning, cross-class inference, and structural metrics. Five main landscape structures are identified across the pre-Soviet, Soviet, and post-Soviet periods. After a detailed examination of their spatial distribution, along with metric averages, an important aspect emerging from this research is the identification of persistent landscape structures across the pre-Soviet, Soviet, and post-Soviet periods. These enduring patterns, despite undergoing internal reconfiguration, suggest a form of evolutionary continuity that coexists with more abrupt, policy-driven transformations, or "revolutions" in land use and landscape organisation.

The identified structures were primarily shaped by the influence of hydrological systems (Baltic Sea, Curonian Lagoon, and main rivers), the extent and transitional dynamics of forest cover, the varying intensity of agricultural activity—from extensive grassland to intensive arable farming—and the persistence of natural and semi-natural environments, such as wetlands and wastelands.

Through their spatial distribution and configurational patterns, this study highlights the societal dynamics that influence their evolution, including the role of cultural factors in shaping territorial organisation. In particular, it highlights the contrast between the former Prussian territories, marked by open grasslands and pre-industrial farming practices, and the former Russian-controlled areas, where forest has remained dominant. The Niemen delta also emerged as a distinct landscape, shaped by its unique functions, spatial organisation, and environment.

A second key finding relates to the extensive transformations driven by Soviet land collectivisation policies. These are visible through the widespread irrigation networks established to modernise agriculture, the significant reduction in grasslands previously associated with extensive farming, and the fragmentation and expansion of forest cover, likely reflecting reforestation processes following land abandonment.

This study also highlighted post-Soviet transformations, particularly the abandonment of agricultural land due to declining interest in agriculture and the challenges of reappropriating land within the structural legacy of Soviet collectivisation. Compared to the more distinct agrarian landscapes of earlier periods, the post-Soviet agricultural landscape appears more fragmented and heterogeneous (mixed landscape structures).

One of the main findings of this study is that landscape transformations are predominantly structured around agricultural dynamics. The impacts of collectivisation policies, post-Soviet land restitution, and agrarian reforms promoting farm individualisation emerge

as major drivers of change. Although the analysis was limited by the incomplete availability of data for this specific land use class, the centrality of agriculture in shaping territorial organisation is evident. This observation reinforces the strong rural identity associated with the landscape [45].

It is important to mention that this study primarily focused on analysing anthropogenic dynamics, but part of the evolution of landscape structures can also be explained by natural dynamics.

The combination of morphological and configurational metrics and machine-learning-based clustering offers a significant enhancement to traditional landscape classification approaches. This method allows for a data-driven, reproducible, and quantitative characterisation of landscape structures. It captures not only land cover composition but also spatial configuration, enabling the detection of patterns that might otherwise remain hidden in aggregated or visually interpreted classifications. This approach facilitates a more granular understanding of landscape heterogeneity and evolution, supporting cross-period comparisons despite heterogeneous source data (spatial resolution, land use and land cover classifications).

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Abbreviations

The following abbreviations are used in this manuscript:

GIS	Geographic Information System
LULC	Land Use Land Cover
WSS	Within-Cluster Sum of Squares

Appendix A

Table A1. Original nomenclature and land use/land cover classes used in the modelling of pre-Soviet landscape structures.

Original Nomenclature	Modelled Land Use/Land Cover Class
Water surfaces	Water surfaces
Forests *	Forests
Meadows and bushes	Grasslands
Moors, peat, and wasteland	Wastelands
Nurseries	-
Sand and gravel	-
Willow plantations	-

* All forest types were merged into a single "forest" class.

Table A2. Original nomenclature and land use/land cover classes used in the modelling of Soviet landscape structures.

Original Nomenclature	Modelled Land Use/Land Cover Class *
Water surfaces	Water surfaces
Forests	Forests **
Herbaceous swamps	Grasslands
Open forests, forest nurseries	Forests **
Herbaceous swamps with shrubs	Grasslands -
Orchards	-
Sand	-
Meadows with shrubs	Grasslands -
Marshes with shrubs	Wetlands
Meadows	Grasslands -
Meadows with sparse forest	Grasslands -
Herbaceous swamps with open forest	Grasslands -
Shrubs	Wetlands
Reed swamps with shrubs	Wetlands
Reeds and shrubs	Wetlands
Moss swamps with sparse forest	Wetlands
Reeds, swamps with shrubs and sparse forest	Wetlands
Reeds, swamps with sparse forest	Wetlands
Reeds, swamps	Wetlands
Mixed marsh (reeds and grasses) with shrubs	Wetlands
Moss, swamps with sparse forest and shrubs	Wetlands
Herbaceous swamps with shrubs and sparse forest	Wetlands
Parks	-
Marshes with sparse forest	Wetlands
Moss, grass, swamps with shrubs and sparse forest	Wetlands
Cemetery	-
Reeds and grasses, swamps with sparse forest	Wetlands
Reeds, grasses, and shrubs	Wetlands
Peat	Wetlands

* Land cover classification was guided not only by class labels but also by the cartographic symbology and contextual indicators on historical maps. In particular, herbaceous swamp areas that were symbolically represented using grassland patterns were classified as grasslands with wet specificities. This interpretative choice reflects the dual nature of these areas, which often exhibit both herbaceous vegetation and high soil moisture, typical of seasonally wet meadows, and low-intensity wet grassland. This approach allows for a more nuanced classification when original data were ambiguous or lacked categorical precision. ** All forest types were merged into a single "forest" class.

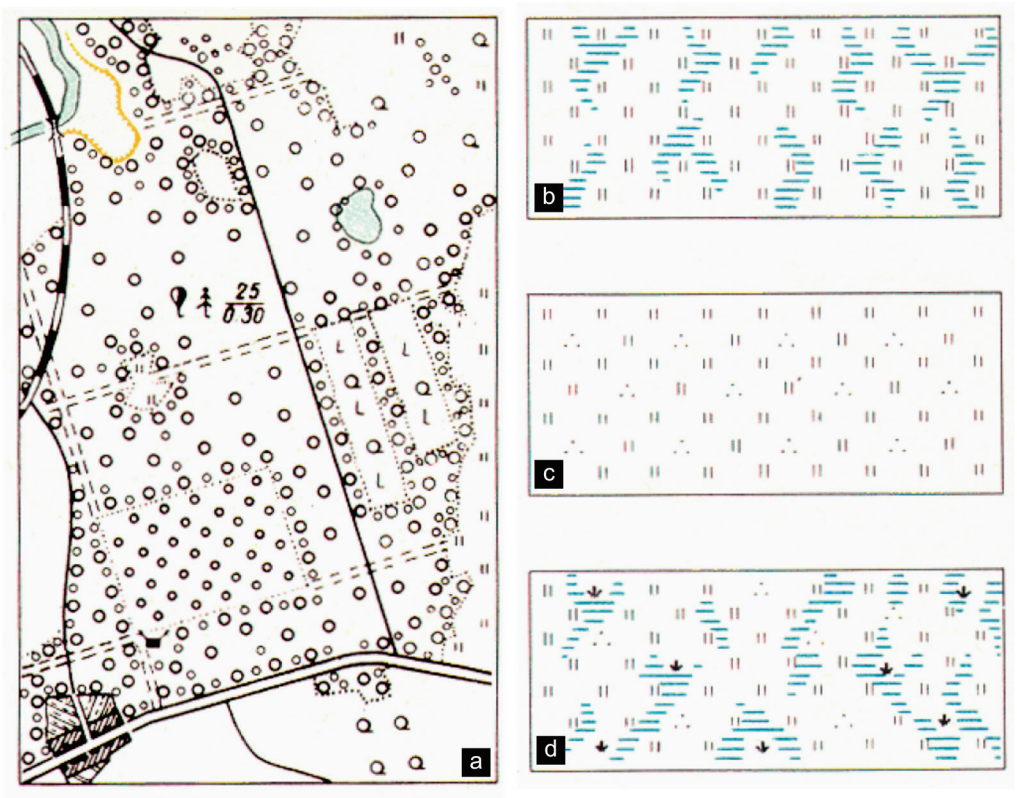


Figure A1. (**a**) "Combined symbolisation, forest with other features on the map", (**b**) "swampy meadow" (marsh land), (**c**) "hummocks in meadow", (**d**) "swampy hummocks and reeds".

Table A3. Original nomenclature and land use/land cover classes used in the modelling of post-Soviet landscape structures.

Original Nomenclature	Modelled Land Use/Land Cover Class
Tree cover	Forests
Shrubland	-
Grassland	Grasslands
Cropland	Arable lands
Built-up	-
Bare/Sparse Vegetation	-
Snow and ice	-
Permanent water bodies	Water surfaces
Herbaceous wetlands	Wetlands
Mangroves	-
Moss and lichen	-

References

1. Plakans, A. *A Concise History of the Baltic States*; Cambridge University Press: Cambridge, UK, 2011; pp. 215–448.
2. Jespen, M.R.; Kuemmerle, T.; Müller, D.; Erb, K.; Verburg, P.H.; Haberl, H.; Vesterager, J.P.; Andrič, M.; Antrop, M.; Austrheim, G.; et al. Transitions in European Land Management Regimes between 1800 and 2010. *Land Use Policy* **2015**, *49*, 53–64.
3. Ragauskaitė, A. Ethnocultural regionalisation of Lithuania or all the truth about our regions. *Acta Museol. Lith.* **2019**, *4*, 162–168.
4. Idzelis, A. Industrialisation and population change in the Baltic republics. *Lituanus* **1984**, *30*, 26–42.

5. Vaitkus, G.; Vaitkuvienė, D. Land cover changes in the Lithuanian coastal zone during 1975–2000. *Acta Zool. Litu.* **2005**, *75*, 183–187. [CrossRef]
6. Köll, A.M. Reinterpretation of economic history in the Baltic countries, 30 years after independence. *Scand. Econ. Hist. Rev.* **2024**, *73*, 93–102. [CrossRef]
7. Ubarevičienė, R.; van Ham, R. Population decline in Lithuania: Who lives in declining regions, and who leaves? *Reg. Stud. Reg. Sci.* **2017**, *4*, 57–79. [CrossRef]
8. Veteikis, D.; Šabanovas, S.; Jankauskaitė, M. Landscape structure changes on the coastal plain of Lithuania during 1998–2009. *Baltica* **2011**, *24*, 107–116.
9. Cirtautas, M. Changing periphery of the Baltic cities: Lithuanian case. *J. Archit. Urban.* **2015**, *39*, 56–69. [CrossRef]
10. Anandkumar, A.; Vijith, H.; Nagarajan, R.; Jonathan, M.P. Evaluation of Decadal Shoreline Changes in the Coastal Region of Miri, Sarawak, Malaysia. In *Coastal Management*; Academic Press: Cambridge, MA, USA; Elsevier: Amsterdam, The Netherlands, 2019; pp. 95–119.
11. Favory, F.; Van der Leeuw, S. Archaeomedes, la durabilité des systèmes spatiaux. In *Des Oppida aux Métropoles*; Economica Anthropos: Paris, France, 1998; pp. 13–44.
12. Allain, R. Formes urbaines et paysages urbains. In *Morphologie Urbaine. Géographie, Aménagement et Architecture de la Ville*; Armand Colin: Paris, France, 2004; pp. 9–24.
13. Jones, M.; Olwig, K. Thinking Landscape and Regional Belonging on the Northern Edge of Europe. In *Nordic Landscapes. Region and Belonging on the Northern Edge of Europe*; University of Minnesota Press: Minneapolis, MN, USA, 2008; pp. ix–xxix.
14. Gosme, C. Landscape. Hypergéo. 2005. Available online: https://hypergeo.eu/landscape/?lang=en (accessed on 12 May 2025).
15. García-Díez, V.; García-Llorente, M.; González, J.A. Participatory Mapping of Cultural Ecosystem Services in Madrid: Insights for Landscape Planning. *Land* **2020**, *9*, 244. [CrossRef]
16. Kivinen, S.; Vartiainen, K.; Kumpula, T. People and Post-Mining Environments: PPGIS Mapping of Landscape Values, Knowledge Needs, and Future Perspectives in Northern Finland. *Land* **2018**, *7*, 151. [CrossRef]
17. Claval, P. Géographie Culturelle, Culture des Géographes. Géoconfluences. 2003. Available online: https://geoconfluences.ens-lyon.fr/informations-scientifiques/dossiers-thematiques/remue-meninges/paul-claval (accessed on 12 May 2025).
18. Fedorov, G.M.; Mikhailov, A.S.; Kuznetsova, T. The influence of the sea on the economic development and settlement structure in the Baltic Sea Region. *Balt. Reg.* **2017**, *9*, 4–18. [CrossRef]
19. Druzhinin, A.; Gontar, N.; Mikhaylov, A. Population Dynamics in the Coastal Urban Settlements of the Baltic Sea Region. *J. Settl. Spat. Plan.* **2019**, *10*, 61–70. [CrossRef]
20. Escach, N. Réseaux de Villes et Recompositions Interterritoriales Dans L'espace Baltique. Ph.D. Thesis, École Normale Supérieure, Lyon, France, 2014.
21. Lévy, J.; Lussault, M. *Dictionnaire de la Géographie et de L'espace des Sociétés*; Belin: Paris, France, 2013; pp. 852–854.
22. Kaim, D.; Kozak, J.; Ostafin, K.; Dobosz, M.; Ostapowicz, K.; Kolecka, N.; Gimmi, U. Uncertainty in Historical Land-Use Reconstructions with Topographic Maps. *Quaest. Geogr.* **2014**, *33*, 55–63. [CrossRef]
23. Piškinaitė, E.; Veteikis, D. The results of digitising historical maps: Comparison of Lithuanian land-use structure in the 19th and 21st centuries. *Land* **2023**, *12*, 946. [CrossRef]
24. Piškinaitė, E.; Veteikis, D. Methodologies and prospects of historical land use/land cover studies in Lithuania. *Baltica* **2022**, *35*, 60–70. [CrossRef]
25. Mushtaq, F.; O'Brien, C.D.; Parslow, P.; Åhlin, M.; Di Gregorio, A.; Latham, J.S.; Henry, M. Land Cover and Land Use Ontology—Evolution of International Standards, Challenges, and Opportunities. *Land* **2024**, *13*, 1202. [CrossRef]
26. Levin, G.; Groom, G.; Svenningsen, S.R. Assessing spatially explicit long-term landscape dynamics based on automated production of land category layers from Danish late nineteenth-century topographic maps in comparison with contemporary maps. *Environ. Monit. Assess.* **2025**, *197*, 195. [CrossRef]
27. Farmer, E.; Brewer, T.R.; Sannier, C.A.D. Land cover attributed and their utility within land cover mapping: A practical example. *J. Land Use Sci.* **2010**, *7*, 35–49. [CrossRef]
28. Claramunt, C. Ontologies for geospatial information: Progress and challenges ahead. *J. Spat. Inf. Sci.* **2020**, *20*, 35–41. [CrossRef]
29. Nedd, R.; Light, K.; Owens, M.; James, N.; Johnson, E.; Anandhi, A. A Synthesis of Land Use/Land Cover Studies: Definitions, Classification Systems, Meta-Studies, Challenges and Knowledge Gaps on a Global Landscape. *Land* **2021**, *10*, 994. [CrossRef]
30. Comber, A.; Fisher, P. What is land cover? *Environ. Plan. B Plan. Des.* **2005**, *32*, 199–209. [CrossRef]
31. Kremsa, V.Š. Sustainable management of agricultural resources (agricultural crops and animals). In *Sustainable Resource Management: Modern Approaches and Contexts*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 99–145.
32. Şenol, H.İ.; Kaya, Y.; Yiğit, A.Y.; Yakar, M. Extraction and geospatial analysis of the Hersek Lagoon shoreline with Sentinel-2 satellite data. *Surv. Rev.* **2023**, *56*, 367–382. [CrossRef]

33. Gadal, S.; Gloaguen, T. Performance of Landsat 8 OLI and Sentinel 2 MSI Images Based on MNF Versus PCA Algorithms and Convolution Operators for Automatic Lithuanian Coastline Extraction. *SN Comput. Sci.* **2024**, *5*, 308. [CrossRef]
34. Bauža, D.; Baužienė, I. Evaluation of landscape changes in Lithuania in the second half of the 20th century. *Geografija* **2008**, *44*, 28–35.
35. Juknelienė, D.; Kaznavičiūtė, V.; Valčiukienė, J.; Atkocevičienė, V.; Mozgeris, G. Spatiotemporal patterns of land-use changes in Lithuania. *Land* **2021**, *10*, 619. [CrossRef]
36. Tiškutė-Memgaudienė, D. Changes of forest land cover in Lithuania during the period 1950–2017: A comparative analysis. *Res. Rural Dev.* **2021**, *36*, 274–279.
37. Ivavičiūtė, G. The change of natural landscape in Lithuania. *Res. Rural Dev.* **2020**, *35*, 213–218.
38. Feranec, J.; Soukup, T.; Taff, G.N.; Stych, P.; Bicik, I. Overview of changes in land use and land cover in Eastern Europe. In *Land-Cover and Land-Use Changes in Eastern Europe After the Collapse of the Soviet Union in 1991*; Springer: Cham, Switzerland, 2016; pp. 13–34.
39. Galinienė, J. Change in Land Use and Land Cover of Lithuanian Coastal Zone: Classification Methods Comparison and Assessment. Ph.D. Thesis, Klaipėda University, Klaipėda, Lithuania, 2020.
40. Juknelienė, D.; Narmontienė, V.; Valčiukienė, J.; Mozgeris, G. Driving Forces of Agricultural Land Abandonment: A Lithuanian Case. *Land* **2025**, *14*, 899. [CrossRef]
41. Gozdowski, D.; Žukovskis, J.; Kaziukonytė, K.; Razinkovas-Baziukas, A. Evaluation of Land Cover Changes in Southwestern Lithuania from 1984 to 2018 Using Medium Spatial Resolution Satellite Imagery. *Pol. J. Environ. Stud.* **2020**, *29*, 4041–4051. [CrossRef]
42. Sinkevičiūtė, V. Analysis of farming usage in Southern Lithuania. *Balt. Surv.* **2014**, *1*, 20–25.
43. Lekavičiūtė, J.; Gadal, S. Forest Cover Changes during 1974–2005 in the Lithuanian Coastal Region. In Proceedings of the Fourth International Scientific Conference Rural Development 2009, Kaunas, Lithuania, 15–17 October 2009; Volume 4, pp. 241–247.
44. Tercan, E.; Dereli, M.A. Development of a land suitability model for citrus cultivation using GIS and multi-criteria assessment techniques in Antalya province of Turkey. *Ecol. Indic.* **2020**, *117*, 106549. [CrossRef]
45. Bučas, J. Lietuvos kaimo kraštovaizdžio permainos ir savastis. In *Krašto Tvarkos Pagrindai*; Technologija: Kaunas, Lithuania, 2001; pp. 109–193.
46. David Rumsey Map Collection. *Königlich-Preussische Landesaufnahme oder Landvermessungsbehörden. Zeichen-Erklaerung für die Karte des Deutschen Reiches*; David Rumsey Map Collection: Stanford, CA, USA, 1887.
47. U.S. Department of the Army. *Soviet Topographic Map Symbols*; U.S. Government Printing Office: Washington, DC, USA, 1958.
48. Zanaga, D.; van de Kerchove, R.; Daems, D.; de Keersmaecker, W.; Brockmann, C.; Kirches, G.; Wevers, J.; Cartus, O.; Santoro, M.; Fritz, S.; et al. *ESA WorldCover 10 m 2021 v200*; Zenodo: Meyrin, Switzerland, 2022. [CrossRef]
49. Gibbs, J.P. A Method for Comparing the Spatial Shapes of Urban Units. In *Urban Research Methods*; D. Van Nostrand: Princeton, NJ, USA, 1961; pp. 99–106.
50. Yuill, R.S. The standard deviational ellipse, an updated tool for spatial description. *Geogr. Ann.* **1971**, *53*, 28–39. [CrossRef]
51. McGarigal, K.; Cushman, S.A.; Ene, E. FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical Maps. 2023. Available online: https://www.fragstats.org/index.php (accessed on 12 May 2025).
52. Moore, E.F. The Shortest Path through a Maze. In *Proceedings of the International Symposium on the Theory of Switching, Part II*; Harvard University Press: Cambridge, MA, USA, 1959; pp. 285–292.
53. Turner, M.G. Landscape ecology: The effect of pattern on process. *Annu. Rev. Ecol. Syst.* **1989**, *20*, 171–197. [CrossRef]
54. NASA Shuttle Radar Topography Mission (SRTM). Shuttle Radar Topography Mission (SRTM) Global. 2013. Available online: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm (accessed on 12 May 2025).
55. MacQueen, J.B. Some methods for classification and analysis of multivariate observation. In *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, Volume 1: Statistics*; University of California Press: Berkeley, CA, USA, 1967; Volume 5, pp. 281–298.
56. Povilaitis, A.; Lamsodis, R.; Bastienė, N.; Rudzianskaitė, A.; Misevičienė, S.; Miseckaitė, O.; Gužys, S.; Baigys, G.; Grybauskienė, V.; Balevičius, G. Agricultural drainage in Lithuania: Review of practices and environmental effects. *Acta Agric. Scand. Sect. B Soil Plant Sci.* **2015**, *65*, 14–29. [CrossRef]
57. Klaipėdos Rajono Savivaldybė. Potvynių Prevencijai—Investicijos į Melioracijos Sistemas. 2023. Available online: https://klaipedos-r.lt/potvyniu-prevencijai-investicijos-i-melioracijos-sistemas/ (accessed on 20 June 2025).
58. Atkocevičienė, V.; Valčiukienė, J.; Juknelienė, D.; Agintaitė-Kirstukienė, K. Analysis of the 20th century villages in Nemunas Delta Regional Park. *Balt. Surv. Int. Sci. J.* **2016**, *2*, 15–22.
59. Zundė, P. The collectivisation of Lithuanian agriculture (1940–1952). *Lituanus* **1963**, *9*, 82–88.

60. Ivavičiūtė, G. The changes of forest area in Klaipėda county during the period between 2005–2019. *J. Balt. Surv.* **2020**, *12*, 8–13. [CrossRef]
61. Vareikis, V. Memellander/Klaipėdiškiai Identity and German-Lithuanian Relations in Lithuania Minor in the Nineteenth and Twentieth centuries. *Sociol. Mintisi Ir Veiksmas* **2001**, *6*, 54–65. [CrossRef]
62. Levchenkov, A.V.; Gumenyuk, I.S. The spatial development of the rural settlement of East Prussia: Kaliningrad region. *Int. J. Econ. Financ. Issues* **2015**, *5*, 30–36.
63. Sujetovienė, G.; Dabašinskas, G. Ecosystem Service Value Changes in Response to Land Use Dynamics in Lithuania. *Land* **2023**, *12*, 2151. [CrossRef]

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Residential Location Preferences in a Post-Conflict Context: An Agent-Based Modeling Approach to Assess High-Demand Areas in Kabul New City, Afghanistan

Vineet Chaturvedi and Walter Timo de Vries *

Chair of Land Management, Centre of Land, Water and Environmental Risk Management-Department Aerospace and Geodesy, School of Engineering and Design, Technical University of Munich, Arcisstraße 21, 80333 München, Germany; vineet.chaturvedi@tum.de
* Correspondence: wt.de-vries@tum.de

Abstract: As part of the post-conflict reconstruction and recovery, the development of Kabul New City aims to bring relief to the existing capital city, Kabul, which has experienced exponential population growth, putting heavy pressure on its existing resources. Kabul New City is divided into four subsectors, and each of them is being developed and is expected to reach a target population by 2025, as defined by the master plan. The study's objective is to determine which of the four zones are in demand and need to be prioritized for development, as per the model results. The data collection involves an online questionnaire, and the responses are collected from residents of Kabul and Herat. Agent-based modeling (ABM) is an emerging method of simulating urban dynamics. Cities are evolving continuously and are forming unique spatial patterns that result from the movement of residents in search of new locations that accommodate their needs and preferences. An agent-based model is developed using the weighted random selection process based on household size and income levels. The agents are the residents of Kabul and Herat, and the environment is the land use classification image using the Sentinel 2 image of Kabul New City. The barren class is treated as the developable area and is divided into four sub-sectors. The model simulates three alternative growth rate scenarios, i.e., ambitious, moderate, and steady. The results of the simulation reveal that the sub-sector Dehsabz South, being closer to Kabul city, is in higher demand. Barikab is another sub-sector high in demand, which has connectivity through the highway and is an upcoming industrial hub.

Keywords: population growth; cumulative probability; weighted demand

1. Introduction

Managing urbanization in a sustainable manner is a challenge for developing countries and, more so, for the countries in conflict. Especially for the latter category, the resources and capacities to make strategic decisions are not available, and the spatial developments are seemingly random and discretionary. A specific case concerns Afghanistan. Afghan cities experienced a rapid increase in their population after the fall of the Taliban in 2001. Kabul, the capital, faced the maximum brunt of this increase in the population. During the US-led NATO operation, Kabul witnessed a large-scale migration of refugees and the internally displaced rural population to Kabul, and the recent deportation of Afghan refugees from Pakistan has resulted in overcrowding in Kabul and the need for creating sustainable housing to ease this pressure. Most of the refugees are looking for suitable

housing facilities at various economic strata to settle themselves afresh, as they have been uprooted. The rapid growth in population has brought new urban challenges, including an increase in housing demand, leading to the mushrooming of informal settlements, shortage of drinking water, inadequate infrastructure facilities, unemployment, traffic congestion, lack of green spaces, recreation facilities, waste management, water, air, and noise pollution. To offset these challenges, the expansion of the city of Kabul is proposed, creating an area referred to as the Kabul New City. Although there exists a master plan developed by the Japanese Development Cooperation Agency (JICA) [1], several factors may influence how and where this area will grow and what sort of land will be used for this. Mirwais [2] analyzed the spatial structure of Kabul New City in comparison with major Japanese cities, and highlighted key spatial mismatches that may affect implementation. This suggests that, despite strong planning intentions, contextual adaptation remains a critical challenge in Kabul's urban development.

Compared to other post-conflict cities such as Mosul in Iraq, Aleppo in Syria, or Tripoli in Libya, Kabul presents a distinct urban trajectory. At the time of the NATO-led operation starting in 2001, its population was 1 million, and as of 2023, it is now a thriving city of 5 million. Mosul was under ISIS from 2014 to 2017, during which time it suffered massive destruction [3], while in the case of Kabul, under NATO presence, Operation Enduring Freedom brought stability and security to the city. This relative security made Kabul a more attractive destination for rural migrants seeking safety and opportunities, contributing to rapid urbanization. However, this population surge has placed enormous pressure on the city's infrastructure and housing systems. Unlike cities such as Mosul, which suffered extensive damage, Kabul's challenge has been managing unplanned growth, rather than the post-war reconstruction of physical assets.

Given this unknown, and considering the limited availability of data on people's preferences and behavior in Kabul, the objective of this paper is to develop a land use model to model and predict the relationship between household size and income levels with the preferred region for relocation. With the growth of the population, various land use types compete to meet the needs of the growing population. The model relies on the various factors that people consider when choosing a place to live, especially when moving to a newly developed city. The decisions that households make are largely dependent on their existing location, the size of the household, and income levels. Some of the factors that influence households to relocate are employment opportunities, transportation, weather, healthcare, basic amenities, cost of living, safety, affordable housing, etc. Other than economic and physical factors, social and cultural factors play an important role while choosing a residential location, and, more importantly, religious factors [4]. Ref. [5] carried out a study on the residential preferences on the basis of socio-demographic groups and the neighborhood. The spatial distribution of residential preferences of different age groups of individuals suggests that the younger people prefer to live closer to their place of work, the middle-aged group prefer to be closer to family and friends and within a clean environment, and, as for the older-aged group, it is proximity to family and a clean and quiet environment that matters. With respect to sociodemographic determinants of residential preferences, there is a strong relationship between preferences and the existing neighborhood environment [6]. Cities that are academic centers with a large student population have preferences for residential location that are more in harmony with the commute and the access to transportation [7]. Residential preferences of the elderly largely depend on their education level, health status, and income level [8].

To accommodate for the various factors influencing the choices of people and thus determining urban growth, agent-based modeling (ABM) is a useful tool. ABM has been utilized in

a variety of application domains, including modeling complex situations such as emergency evacuation, spread of epidemics, urban dynamics, growth patterns, land use change, and several others, to find solutions to practical problems. ABM allows us to model human behavior and their interaction with one another and with their environment. ABM has been extensively used to simulate urban dynamics. For example, Crooks et al. [9] used an ABM to simulate the spread of informal settlements in Addis Ababa, showing how household decisions respond to institutional and spatial constraints. Benenson [10] used ABM for modeling residential mobility. In land use change simulation, one of the primary strengths of ABM is the ability to simulate human decision-making processes using human behavior, environment, and a set of policies or rules [11]. Ali Termos et al. [12] developed an agent-based model of West Asian urban dynamics, explicitly designed to capture refugee and migrant flows and their effects on urban housing markets and segregation in the Middle Eastern capital of Beirut.

Although the Kabul New City master plan defines broad land use categories, it does not specify how different household groups—particularly low-income, displaced, or returnee populations—will interact with these spaces over time. Given Afghanistan's dynamic and uncertain post-conflict context, the ABM developed in this study provides a means of identifying likely settlement hotspots within the planned zones and informs how service rollout and infrastructure investment can be prioritized in a phased and demand–responsive manner. The model does not seek to alter designated land uses, but to enhance implementation planning through behavioral insights.

The study seeks to answer the following research questions: (1) How do household-level characteristics, specifically household size and income levels, shape residential preferences within the planned zones of Kabul New City? (2) To what extent can ABM be used to simulate bottom-up housing demand in a post-conflict urban context marred by displacement, informal settlements, and institutional uncertainty? And (3) Which sub-areas in Kabul New City are likely to experience early concentrations of demand under different population growth scenarios, and how can this help planners, decision makers, and investors to decide which areas to prioritize for development?

This paper first introduces the main tenets of ABM, followed by a description of the study area, the methodology of data collection, data analysis, discussion, and conclusion.

2. Theory

ABM follows the bottom-up approach for simulating a system [13]. ABM learning-embedded models have been used for simulating land growth by learning from the past growth patterns to aid in decision-making [14]. A shift in residential preference is studied with respect to the imposed restrictions and perceived accessibility to facilities, mobility by car and public transport amongst sociodemographic groups during the COVID-19 pandemic [15]. The results of the study reveal a preference for a compact urban location, despite the restrictions imposed.

Several agent-based models have been designed to model the location preferences of households, but very few are based on studies conducted on cities under post-war reconstruction and recovery. ABM models have been applied to study the effect of housing policies on housing choices [16]. Several methods of modeling involve the coupling of ABM with other methods for analyzing the complex urban dynamics. Jing Wu et al. [17], in their study, used cellular automata and ABM to emulate the spatial evolution of the population and the driving forces behind changes in the spatial pattern. In another study, Shirzadi Babakan and Alimohammadi [18] used ABM and the NSGA-II algorithm to simulate residents' choice of location according to their preferences and characteristics, which include housing rent, accessibility to facilities, environmental pollution, and distance from workplace and previous residence, wherein the

agents compete with each other for their desired alternative location. In a stylized ABM model, the relationship between urban sprawl and income segregation was studied, based on the Alonso bid rent theory, resulting in the emergence of urban patterns [19].

While ABM provides a valuable tool for simulating residential decision-making, it is essential to examine these preferences in a post-conflict context through a broader theoretical foundation, one that incorporates socio-cultural, institutional, and spatial dynamics. Studies on post-conflict displacement reveal that housing decisions extend beyond economic factors. Fagen [20] highlights that returnees often avoid returning due to insecurity, lack of services, and inadequate housing in areas of origin. Designers of post-conflict housing schemes for IDPs emphasize socio-cultural congruence, participation, and flexibility in site and design choices [21]. UN-Habitat and UN-HCR frameworks further affirm that secure land tenure and the restoration of housing, land, and property rights are critical for stable resettlement [22]. Hébert et al. [23] developed an ABM to simulate how forced migrants make relocation decisions based on safety, social networks, and infrastructure. Barbé [24] estimates that over 70% of Kabul's population resides in informal settlements, which lack basic urban services and tenure security. The master plan proposes relocating these communities to the newly planned city in Deh-Sabz, aiming to curb unplanned sprawl in central Kabul and provide a higher standard of infrastructure and living conditions in a formally recognized urban environment. This introduces an institutional aspect to residential preferences, where decisions are shaped not only by residential choice, but also by the possibility of tenure security, trust in the governance, and access to basic amenities.

3. Materials and Methods

3.1. Study Area

The study area is the Kabul New City, which is part of the Kabul Metropolitan area and is located at 69°36′18″ longitude, 34°20′42″ latitude, at an elevation of 1847 m, approximately 10 km northeast of Kabul (Figure 1). Kabul New City is situated in the Dehsabz and Barikab districts and other areas lying between Kabul's International Airport and Bagram Airbase. The new city is divided into four sub-areas: Barikab in the north, Dehsabz North in the east, Paymonar in the west, and Dehsabz South in the south. It is an Urban Development mega-project started by the Afghan government in 2006, covering an area of 744 km^2. The city's master plan was developed with the support of the Japanese International Cooperation Agency [1]. The project aims to tackle the challenges faced by the capital city, Kabul. Some of the challenges include the growth in the population exceeding the sustainable limit and the pressure on the available water resources.

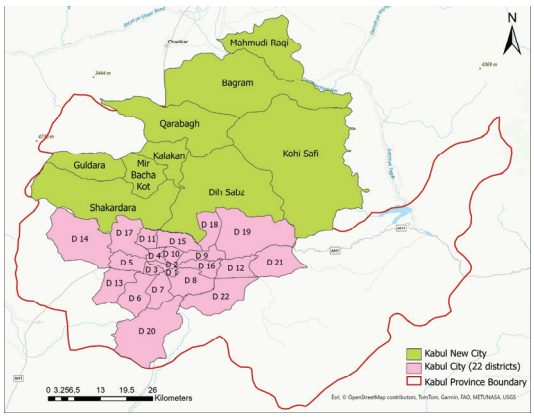


Figure 1. Map showing the location of Kabul New City, along with Kabul City and Kabul Province boundary.

Kabul New City is divided into four sub-centers. All four zones have been allocated development projects, including the Industrial, Commercial District, Agriculture, and Residential zones. The ABM model maps the residential preferences of people, based on their household size and income levels.

3.2. Data Source

The research utilizes Sentinel 2 harmonized images for classification using the cloud computing platform Google Earth Engine. The image is from 2024 for the months between March and June. A Random Forest classifier is adopted for the classification of the image. The image is classified into five classes: Built, Fields, Water, Hills, and Barren. Training and testing samples are collected for each of the classes by visual interpretation and Google Earth, in combination with Google Maps satellite view. The overall classification accuracy achieved is 77%, with a Kappa of 0.72. The following indices (Table 1) are employed to obtain the best results.

Table 1. Indices used for classification.

Image Feature	Formula	References
Normalized Differential Vegetation Index (NDVI)	$B8 - B4/B8 + B4$	[25]
Normalized Differential Building Index (NDBI)	$B11 - B8/B11 + B8$	[26]
Bare Soil Index (BSI)	$(B11 + B4) - (B8 + B2)/(B11 + B4) + (B8 + B2)$	[27]
Built-Up Index (BUI)	NDBI-NDVI	[28]
Soil-Adjusted Vegetation Index (SAVI)	$((B8 - B4) \times (1 + 0.5))/(B8 + B4 + 0.5)$	[29]
Clay Mineral Ratio (CMR)	B11/B12	[30]
Iron Oxide index (IOI)	B4/B2	[31]
Normalized Differential Water Index (NDWI)	$(B3 - B8)/(B3 + B8)$	[32]
Modified Normalized Difference Water Index (MNDWI)	$(B3 - B11)/(B3 + B11)$	[28]

Apart from the indices mentioned in the Table, the Grey Level Cooccurrence Matrix (GLCM), Digital Elevation Model (DEM), and the bands 'B2', 'B3', 'B4', 'B8', 'B11', 'B12' are used. The classified image is then prepared for use in the agent-based model for modeling the city's growth, to reach a target population for 2025, as mentioned in the JICA report on the basis of the location preference-based survey. The barren class is divided into four sub-sectors: Barikab, Dehsabz South, Paymonar, and Dehsabz North, as shown in Figure 2. The total area under the barren land is 733 km^2, and the area under the barren class for each of the sub-sectors is given in Table 2.

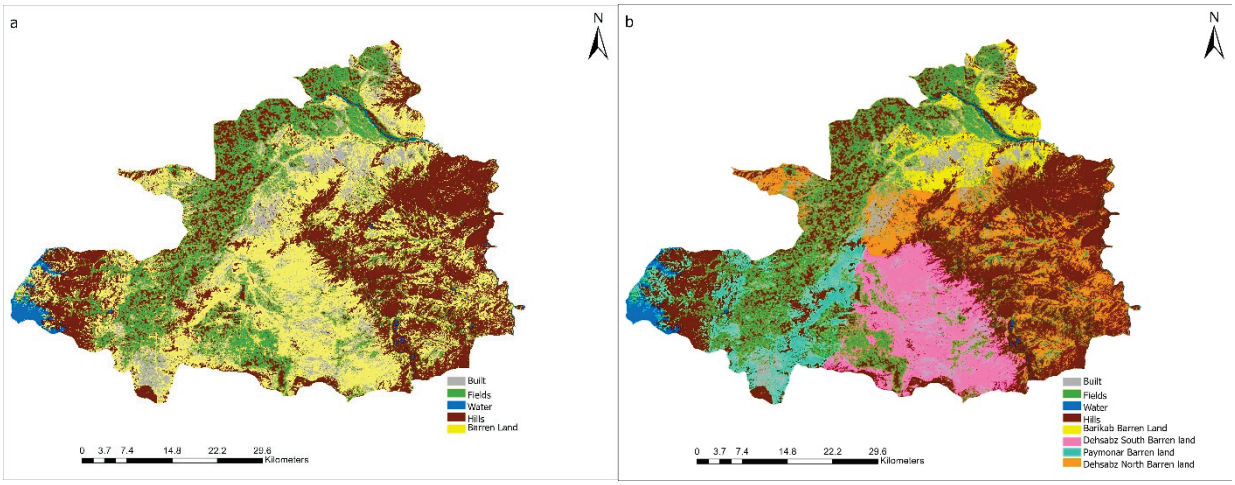


Figure 2. (**a**) Classified image with 5 classes. (**b**) Barren class subdivided into the four sub-areas.

Table 2. Total areas covered by each class.

Class	Area in km^2
Built	268.96
Fields	438.67
Water	36.49
Hills	803.87
Barikab_Barren	121.86
Dehsabz South_Barren	241.78
Paymonar_Barren	151.51
Dehsabz North_Barren	218.20

The model is simulated using the NetLogo 6.3.0 software, which is a platform for developing ABM. To bring the classified image to NetLogo, the image is down-sampled using 4 × 4 mode aggregation, reducing the original grid size from 398 × 562 to 99 × 140. The initial population of the Kabul New City is 140,000 [33]. The initial population for each sub-sector is assigned to the classes as given in the Table 3, and the targets to be achieved are provided in Table 4.

Table 3. Initial population.

Sub-Sectors	Initial Population
Barikab	9841
Dehsabz South	27,112
Paymonar	71,671
Dehsabz North	31,376

Source: [33].

Table 4. Target population.

Sub-Sectors	Target Population
Barikab	194,841
Dehsabz South	460,833
Paymonar	342,671
Dehsabz North	501,376

Source: [1].

3.3. Questionnaire-Based Survey for Location-Based Preference

An online questionnaire (Supplementary Materials) was prepared in the native language, Dari, and English, and the responses were collected from residents of Kabul and Herat. The questions ranged from their willingness to move to a new location and their reasons for location choice, to their household size and income levels. The questionnaire was shared through an online form, and the respondents were randomly selected on an informal basis. A total of 100 online surveys were distributed to residents of Kabul and Herat. Due to the ongoing political instability and security concerns, only 51 valid responses were received. Many internally displaced persons (IDPs) and refugees lacked access to email or internet-enabled devices, which limited their participation. To address this, assistance was sought from former colleagues and local contacts to help facilitate data collection through informal networks. Carrying out a survey in a post-conflict situation comes with its own challenges. Flexibility in methodology is required in conflict and post-conflict zones [34]. A mixed research methodology was adopted, which includes in-depth interviews with households of varying sizes, with a focus on refugees and internally displaced persons (IDPs), to record conflict-related migration motivation. A few respondents were unwilling

to share personal information, but were willing to participate in the survey, which did not require disclosing information related to them, but opinions on the preferences for relocating to the KNC. The study ensured gender inclusion and respondents from diverse professional backgrounds, i.e., farmers, engineers, shop owners, community leaders, and homemakers. The ethics of informed consent were implemented before sharing the survey form with respondents [35]. The respondents were made aware of the purpose of the research, its potential benefits, and the final outcome.

3.3.1. Agent-Based Model

ABM simulation outputs were based on three population growth-rate scenarios, which JICA describe in their Final Report for the Kabul New City: ambitious growth rate at 19%, moderate growth rate at 14.5%, and steady growth rate at 9.9%. The weights assigned to household size and income levels are shown in Table 5. The model calculates the weighted demand and the number of years to reach the target population for 2025. The weighted demand tracks the number of people who preferred each class based on the combination of household size and income levels, and the weights from the weighted preference table. A weighted preference table is calculated from the responses received from the survey. The weight represents the proportion of time each region was selected for a given household size and income level. The results obtained from running the ABM model were based on the three growth scenarios.

Table 5. Example of Weighted Preference Table Used in the Model.

Income Range	Household Size	Preferred Region (Class)	Weight
19,700–78,100	6	10	0.25
19,700–78,100	6	11	0.75
78,100–348,000	7	11	1.00
Above 348,000	3	10	0.50

The agent-based model simulates urban population growth and spatial distribution across four sub-areas of the Kabul New City, i.e., Barikab (class 10), Dehsabz South (class 11), Paymonar (class 12), and Dehsabz North (class 13). The aim is to analyze how household attributes, specifically income and household size, influence locational preference, population growth patterns, and the time required for each region to reach a specified target population. The study used the Netlogo software for the ABM, which comes with a number of choices and selections to make the model run. These include defining the agents, spatial environment, spatial scale, temporal scale, initialization, preference assignment, probabilistic region allocation, growth dynamics, stopping condition, output, and visualization. The process workflow is described in the flowchart in Figure 3.

3.3.2. Agent (Households)

Agents in this model represent individual households, a unit of analysis for residential location preference models. Each household is described by three attributes.

- R_i: Region class: Refers to the specific planning sub-region within Kabul New City (e.g., Barikab, Dehsabz South).
- I_i: Income category.
- H_i: Household size (e.g., 7, 13, 33).

The attributes selected directly govern the reproduction probability and spatial preferences, which are the key factors of urban growth.

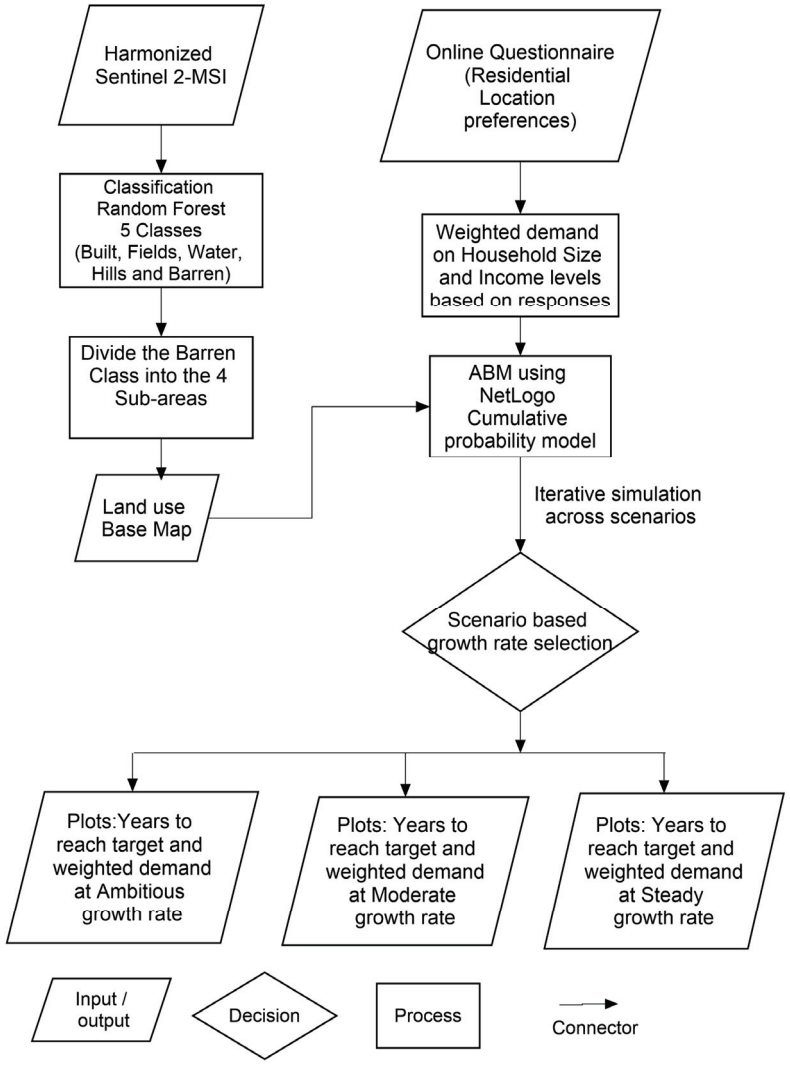


Figure 3. Process flow for scenario-based modeling of relocation preferences in Kabul New City using ABM.

3.3.3. Spatial Environment

The environment is composed of discrete grid cells ("patches") within the NetLogo platform, each assigned a class label representing one of the four sub-regions derived from the classification of the Sentinel 2 satellite image. The environment allows the model to assign the agents to the preferred discrete cells. Patches labeled as one of the four planning classes (10 = Barikab, 11 = Dehsabz South, 12 = Paymonar, 13 = Dehsabz North) are active for settlement. These regions were chosen because they represent the developable land identified in the master plan of Kabul New City, ensuring planning relevance.

3.3.4. Temporal Scale

The model runs in discrete steps, with each tick representing one calendar year. This time resolution balances computational efficiency with urban planning timelines, where population and infrastructure changes typically occur annually.

Initialization

- Region Mapping: a spatial input file parsed through a load-image-only procedure initializes patch class labels, converting raster imagery into a structured simulation space.

- Population Seeding: the create-region-population procedure seeds each region with an initial population, ensuring that each sub-region starts with a baseline number of households.

3.3.5. Preference Assignment, Probabilistic Region Allocation, and Stopping Condition

Households make locational choices based on a weighted preference, as shown in Table 5, which maps combinations of income levels and household sizes to preferred regions. This table determines the probabilistic assignment of preferred regions for new households, based on income and household size. These weights are derived from survey data and introduce heterogeneity and stochasticity into agent behavior. A weighted random selection algorithm assigns new households to regions, based on normalized weights. This reflects context-driven preferences, acknowledging that households may not always choose the optimal location, but tend to prefer certain regions more strongly.

At each tick, households reproduce with the probability determined by the model's growth rate parameter (e.g., in the case of an ambitious growth rate of 19.3%). Offspring households inherit parental attributes and are assigned a preferred region. They are only placed in regions that have not yet met their target population. This ensures that growth is demand-driven. The simulation terminates once all four regional populations meet their predefined targets, aligning with the planning objective of controlled urban expansion. The formulas explaining the process are described in Table 6.

Table 6. Key model formulas.

Formula	Description
$P(R_j \mid I_i, H_i) = w_{ij} / \Sigma_{k=1}{}^{n} w_{ik}$	Probability that a household with income level I_i and household size H_i prefers region R_j, based on normalized weights w_{ij} from the preference table.
$\Delta P_j = P_j(\text{target}) - P_j(t)$	Remaining population capacity in region R_j at time step t.
$D_j(t) = \Sigma_{i=1}{}^{N} H_i \times 1(\text{preferred}(a_i) = R_j)$	Cumulative demand in region R_j, where the indicator function equals 1 if agent a_i prefers region R_j.
$p(\text{growth}) = 0.099$	Annual probability of reproduction for each household.
Stopping Criterion: $P_{10}(t) \geq P_{10}(\text{target}) \wedge P_{11}(t) \geq P_{11}(\text{target}) \wedge P_{12}(t) \geq P_{12}(\text{target}) \wedge P_{13}(t) \geq P_{13}(\text{target})$	The model halts once all regional population targets have been achieved or exceeded.

3.3.6. Output and Visualization

The model generates two plots: "Years to Reach Target" and "Weighted Demand", which track temporal changes in population accumulation and regional settlement preferences. These plots allow for the monitoring of both the pace and spatial concentration of urban growth, offering planners insights into when and where population thresholds are reached or exceeded. By visualizing demand pressure on each sub-region, the outputs facilitate prioritization of infrastructure investments, assessment of planning interventions, and evaluation of alternative development scenarios. In this way, the model serves not only as a predictive tool, but also as a decision-support system for urban policy formulation under conditions of uncertainty and demographic changes.

4. Results

The basis of the research is the responses received from an online survey, which was conducted with residents from Kabul and Herat, the two key cities experiencing population growth and pressures of migration. A total of 51 respondents participated in the survey, and their responses are utilized for calculating the weights to assess the demand for the four sub-sectors.

Drawing on the choices in the ABC model, the NetLogo software first populated the patches with the initial population, resulting in Figure 4a. It then ran the model for each year, and populated each class/region with the turtles on the basis of the weights assigned to the preferred location. The model was simulated for the three alternative growth rate scenarios as projected by JICA in their master plan report, using the predicted population growth rate in the period 2008–2025 (ambitious growth rate of 19%, moderate growth rate of 14.5%, and steady growth rate of 9.9%). The simulation ran till the target population for each of these scenarios was reached. Figure 4b portrays the results for the ambitious growth rate scenario.

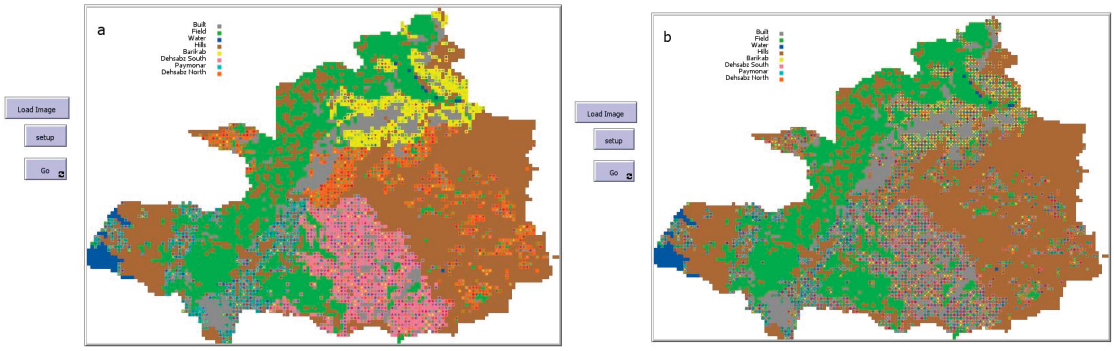


Figure 4. (**a**) Populate patches with the initial population. (**b**) Reaching the target population for all four regions in the case of an ambitious growth rate of 19.3%.

The model simulates the number of years to reach the target and the weighted demand for the regions at thresholds of 100,000 and 300,000. As can be seen from the plots in Figure 5, under the ambitious growth rate, it will take 17 years to reach the target, 22 years under the moderate growth rate scenarios, and 34 years under the steady growth rate scenario.

Weighted demand thresholds are determined by assigning weights given to the preferred class based on the household size and income levels, based on a weighted random selection. As can be seen from Figure 6, for the ambitious growth rate, Dehsabz South is the first to reach the 100,000 threshold in 7 years and will take 12 years to reach the 300,000 threshold. The second region to reach the 100,000 threshold is Barikab, in 8 years. Paymonar reaches the 300,000 threshold in 13 years. Dehsabz North takes 9 years to reach the 100,000 threshold, and 15 years to reach the 300,000 threshold. In the case of the moderate growth rate, Barikab and Dehsabz South are the first to reach the 100,000 threshold, in 10 years, followed by Paymonar in 11 years and Dehsabz North in 12 years. Dehsabz South is the first to reach the 300,000 threshold, in 16 years, followed by Paymonar in 17 years and Dehsabz North in 19 years. The results of the simulation under the steady growth rate reveal Barikab and Dehsabz South reaching the 100,000 threshold in 14 years, followed by Paymonar in 15 years and Dehsabz North in 17 years. Dehsabz South reaches the 300,000 threshold in 23 years, followed by Paymoar in 24 years and Dehsabz North in 27 years.

The results of the simulation for the three alternative growth rates demonstrate that Dehsabz South is the first to reach the threshold in all three scenarios, due to its moderate size and proximity to Kabul. Barikab quickly reaches the weighted demand thresholds of 100,000 and stops growing further, as the target population for Barikab is 194,841. One of the reasons Barikab meets the target early is because of the default household size of 33. Paymonar builds demand over time, due to wider preferences and decent land availability. Dehsabz North is the last to reach the weighted demand thresholds, due to poor terrain and the low weights in the preference table.

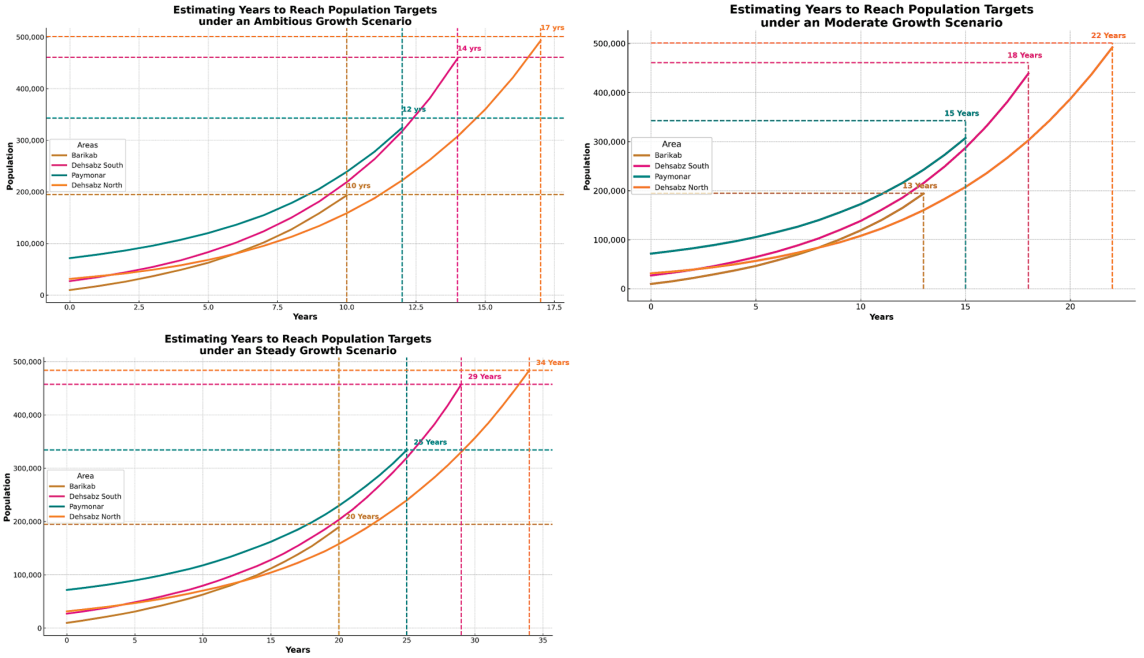


Figure 5. Number of years to reach the target.

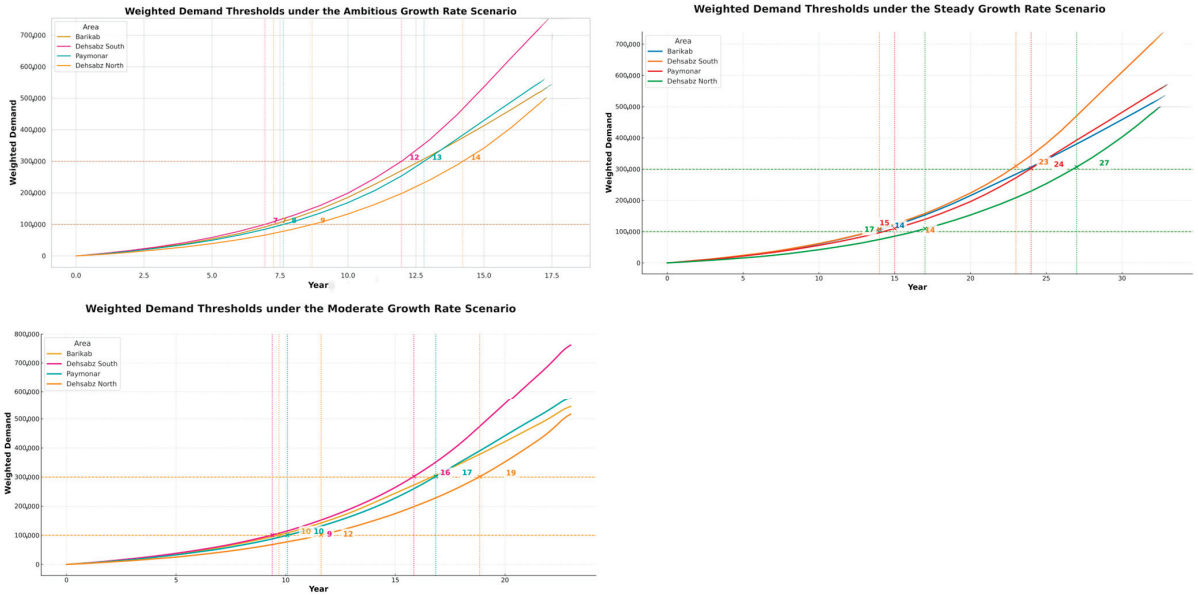


Figure 6. Weighted demand at 100,000 and 300,000 thresholds.

5. Discussion

Whilst the ABM using the Netlogo software helps to create predictions of urban growth, which could help with preparatory, mitigation, or regulatory actions, the results also need to be critically evaluated. There are four issues that require further investigation: the weighting of influencing factors, the choice of scenarios, the role of the probability functions in the individual choices and aggregation of individual choices, and finally, the choice of the Netlogo software for the ABM.

First, the weighting of factors may be contested. The model simulates how and where households decide to rank and choose locations for their residence, assuming that household size and income levels are the most probable factors influencing this choice.

The aggregate of individual choices of the households results in the emergent behavior at the system level. It incorporates a growth mechanism via a probabilistic reproduction rate, which is defined by the three alternative growth rates. However, this model has some drawbacks. All the preferred weights are fixed. They do not evolve or change according to regional conditions, which may vary, such as available space, quality of life, etc. The model does not enforce land use limits, and the population can grow, irrespective of the space constraint.

Secondly, the simulation results across the three growth scenarios, i.e., ambitious, moderate, and steady, consistently show that Dehsabz South and Barikab are the first regions to meet the weighted demand threshold (100,000 and 300,000, respectively). This makes the two regions attractive for relocation when weighted against household size and income levels. Barikab is being developed as an agricultural economic zone and is located between Parwan and Kabul, next to the highway and close to Bagram airbase, giving the strategic advantage for the new settlers for employment opportunities in the upcoming industrial park and the agro-processing sector. It also has a relatively flat land area, making it attractive for residential development. The industrial park will be developed, and industrial subsidies will be granted to open businesses, making Barikab a preferred location. Proximity to Kabul and the recent development of highway and road connectivity from Tarakhel to Dehsabz make Dehsabz South attractive for relocation. Dehsabz South also has the largest area under barren land, approximately 241 km^2, for development. A large portion of the Dehsabz South land consists of brick kilns, which were originally located in the Kabul district [31]. The area, which was subject to land grabbing by warlords, was considered unsafe; however, with the arrest of the warlords, the security situation has improved [36]. Although Paymonar consists of the largest flat land, it has poor accessibility to the existing Kabul city, which could be the reason why it ranks lower in the preferred sectors for relocation. Most of the area of Dehsabz North is in the hilly tract, with a steeper slope, leaving a very small area under flat land, making it the least favorable for relocation. These findings suggest that geographical features, accessibility to Kabul city, and economic development plans are the key drivers of relocation dynamics in the location preference model.

A third remark concerns the use of probability functions on the basis of which the ABM runs. The advantage of the turtle model is that it can simulate uncertain and emergent behavior in the social system of residential house seekers. Not every house seeker uses the same factors and makes the same choices, and thus, the probability functions help to map randomness in this behavior. By varying probability, one can even create different scenarios to test sensitivity and critical tipping points. As such, the model proves to be helpful in predicting and mitigating certain actions. On the other hand, the probabilistic outcomes may not seem realistic, and may hide or fail to reveal unexpected behavior. In the choices for residential areas, there may be much more isomorphic mimicry than one would normally expect; i.e., people may choose not based on their individual rationality, but rather mimicking what other people have done. This may propel certain attractions to certain areas, which the model itself may not have foreseen. Tuning the 'right' probability may thus be more complex than initially modelled by the software.

A fourth critical issue is the choice of the Netlogo software in making the predictions. Even though Netlogo is a popular and frequently used software for researchers in the geospatial domain, running the software when the number of agents and interactions increases and aiming to obtain visual outputs may take a long time. For in-depth spatial analyses, one still needs to rely on additional GIS software (any GIS software, version 3.5) and/or programming languages. In our case, we could have opted for alternative software

packages with more GIS integration capabilities (such as MASON or GAMA), but as the main emphasis of this study was to obtain initial predictions of urban growth in a context where limited data are available or accessible, we opted to rely on the more mainstream software. What we did obtain was at least a number of first spatio-temporal scenarios, which can be used as the basis for further longitudinal studies on this specific case.

The simulation results obtained from the ABM model not only provide a theoretical insight, but are also relevant for urban policy formulation for Kabul New City. Kabul New City is a multi-stakeholder project. According to the land use plan drafted in the master plan report (JICA), all four sub-areas cater for residential housing projects, and the private sector will play a major part in the development. The private developers are obliged to allocate affordable housing under government policy, and this should be implemented in all four sub-areas. The demand for relocation to Dehsabz South is higher than that of other sub-areas. Dehsabz South is the first to cross the weighted demand threshold of 300,000 households, according to all three growth rate scenarios, and as such, the current allocation of 1500 ha is projected to fall short under the standard density assumption. It will cross the 300,000 threshold in 12 years under the ambitious growth rate, which is approximately short of 643 ha. This would require an expansion of residential land or densification through vertical housing and compact development with sustainable infrastructure, and should be accompanied by a mass transit system. In light of the results derived, ABM provides a valuable framework for testing policy alternatives like the regularization of informal settlements, relocation compensation, or land redistribution in a post-conflict context in Afghanistan, where insecure land rights, absence of formal land tenure, and limited institutional trust influence urban development.

While the current ABM incorporates household size and income as the primary determinants of relocation, it is important to recognize that, in a post-conflict context such as Kabul, agent behavior is also significantly influenced by cultural and socio-political legacies. Kabul is a city characterized by ethnically diverse settlements. Ethnically-based clustering in Kabul has deepened over time, mostly due to insecurity, lack of formal land access, and lack of inclusive planning. The new master plan drafted by JICA seeks to address the issue of ethnic segregation by connecting the proposed Kabul New City with the existing urban fabric through integrated transport networks, inclusive zoning policies, and the equitable distribution of public services, challenges that were not adequately addressed in previous master plans [37]. Insights from in-depth interviews revealed that many respondents lost government employment following the regime change and were subsequently forced into the informal economy, taking up work as street vendors and day laborers. Due to limited financial capacity, these individuals are often unable to afford formal rental housing, and are pushed into informal settlements. Interviewees also highlighted a growing concern around water scarcity in Kabul. According to the Kabul Urban Design Framework, the municipality is now permitting the construction of high-rise buildings in areas previously designated for low-rise structures. This has encouraged speculative investment in real estate, particularly by wealthier individuals seeking to capitalize on housing demand. However, these developments largely depend on groundwater extraction, and, in several districts, groundwater levels have reportedly declined by 50 to 60 m. This trend, if unchecked, could exacerbate Kabul's looming water crisis and disproportionately impact low-income and displaced populations who lack access to resilient infrastructure.

6. Conclusions

In the context of uncertain urban growth in a country with limited data, the objective of this study was to generate a land use model that could predict the behavior of house-seeking citizens in choosing their preferred residential location, based on their household

size and income levels. We argue that ABM models are best suited to simulate people's behavior in making relocation choices, as they are ideal for studying urban growth and demand for residential land, as in the case of Kabul New City. The model we created relied on using the Netlogo software, and was based on the online survey and the responses received from the residents of Kabul and Herat. In parallel interviews with the CRIDA staff, refugees and IDPs' insight was provided into the status of development of the Kabul New City Development and the challenges faced by them to attract investments, feasibility, and constraints in the housing provision and service delivery.

While the model is grounded in household size and income, and quantifiable and observable traits, its usefulness in a post-conflict setting lies in identifying how displaced and economically vulnerable populations interact with formal spatial plans. The findings, though derived from a modest dataset, reflect how socio-economic stressors (e.g., job loss, relocation after deportation, housing affordability) influence residential demand in new developments. Thus, the ABM becomes a proxy for understanding broader post-conflict urban behaviors in the absence of reliable institutional data.

Although the results indicate most likely scenarios of urban land demand, there are some limitations: (1) they require micro-level data to calibrate behavior, (2) there is high computation cost in the case of large-scale models, (3) there is oversimplification of behavioral assumptions, and (4) validation and verification require comparison with observed data, which is often lacking.

Since the results of the sample are too small and are not representative of the population, the model may have a bias, due to insufficient sample size. However, a trend can be established from the results of the model. Dehsabz South is the most preferred region for relocation, which matches the satellite growth scenario due to its proximity to the capital, Kabul. In the case of Barikab, it quickly reaches the weighted demand threshold due to the survey data, where, a large household-size preferred location being Barikab, it absorbs the demand fast. The household size preferring Paymonar is moderate-to-low, and therefore, it falls third in the preferred region for relocation. Dehsabz North is the least preferred, and forms a deferred growth pattern. Dehsabz North is a predominantly hilly region with elevation gradually increasing towards the north, which makes it less attractive for relocation. However, other than being the least preferred location in the model, the household size has impacted the result, with the smaller household size preferring Dehsabz North for relocation, making it the slowest in the absorption of the new turtles. Finally, to make the model realistic and futuristic, integrating factors like accessibility and GDP will influence the choice of relocation. This will bring a shift in the model from a static preference simulator to a spatial-economic behavior model, making it more realistic and policy-oriented.

In a context where land use has already been predesignated through a master plan, the added value of this agent-based model lies in its ability to identify areas of high residential preference, particularly among displaced and low-income households. Given that Kabul New City is a multi-stakeholder initiative involving government planners, international donors, and private investors, the model supports more targeted development and investment planning. By highlighting zones with higher anticipated demand under different growth scenarios, it enables stakeholders to prioritize infrastructure rollout, minimize investment risk, and optimize returns, ensuring that the implementation of the urban plan is responsive to actual behavioral patterns and not just top-down zoning.

To make the model more realistic, and also useful for other cases with similar characteristics, further research would be necessary. Introducing land price and zoning rules will make the model more realistic. Adding different types of agents, like developers, policy

makers, planners, and government agencies, will influence the growth pattern. Future studies should consider connectivity and economic opportunities, as these factors have a direct influence on household decision-making in an agent-based framework.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14071502/s1, online questionnaire.

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References

1. Japan International Cooperation Agency (JICA); Dehsabz City Development Authority (DCDA); Ministry of Urban Development (MoUD). JICA Report. Japan International Cooperation Agency (JICA): Tokyo, Japan, 2009.
2. Jamali, M. An Analysis of Spatial Structure of Kabul New City: A Comparison with Infrastructure Framework and Land Use of Japanese Major Cities. 2021, pp. 1101–1114. Available online: https://www.academia.edu/download/76057104/IRJET_V8I11176.pdf (accessed on 2 July 2025).
3. Saeed, Z.O.; Almukhtar, A.; Abanda, H.; Tah, J. Mosul City: Housing Reconstruction after the ISIS War. *Cities* **2022**, *120*, 103460. [CrossRef]
4. Sinniah, G.K.; Shah, M.Z.; Vigar, G.; Aditjandra, P.T. Residential Location Preferences: New Perspective. *Transp. Res. Procedia* **2016**, *17*, 369–383. [CrossRef]
5. Dökmeci, V.; Berköz, L. Residential-location preferences according to demographic characteristics in Istanbul. *Landsc. Urban Plan.* **2000**, *48*, 45–55. [CrossRef]
6. Li, J.; Auchincloss, A.H.; Rodriguez, D.A.; Moore, K.A.; Diez Roux, A.V.; Sánchez, B.N. Determinants of Residential Preferences Related to Built and Social. Environments and Concordance between Neighborhood Characteristics and Preferences. *J. Urban Health* **2020**, *97*, 62–77. [CrossRef] [PubMed]
7. Jaroszewicz, J.; Majewska, A. Group spatial preferences of residential locations—Simplified method based on crowdsourced spatial data and mcda. *Sustainability* **2021**, *13*, 4690. [CrossRef]
8. Li, H.; Duan, C.; Chunyu, M.D. A study of the factors influencing the residential preferences of the elderly in China. *Sustainability* **2021**, *13*, 5488. [CrossRef]
9. Patel, A.; Crooks, A.; Koizumi, N. Slumulation: An agent-based modeling approach to slum formations. *J. Artif. Soc. Social. Simul.* **2012**, *15*, 2. [CrossRef]
10. Benenson, I. Multi-agent simulations of residential dynamics in the city. *Comput. Environ. Urban Syst.* **1998**, *22*, 25–42. [CrossRef]
11. Ralha, C.G.; Abreu, C.G.; Coelho, C.G.C.; Zaghetto, A.; Macchiavello, B.; Machado, R.B. Environmental Modelling & Software: A multi-agent model system for land-use change simulation. *Environ. Model. Softw.* **2013**, *42*, 30–46. [CrossRef]
12. Termos, A.; Picascia, S.; Yorke-Smith, N. Agent-based simulation of west Asian urban dynamics: Impact of refugees. *Jasss* **2021**, *24*, 2. [CrossRef]
13. Macal, C.M.; North, M.J. Agent-based modeling and simulation: ABMS examples. In Proceedings of the Winter Simulation Conference, Miami, FL, USA, 7–8 December 2008; pp. 101–112. [CrossRef]
14. Li, F.; Li, Z.; Chen, H.; Chen, Z.; Li, M. An agent-based learning-embedded model (ABM-learning) for urban land use planning: A case study of residential land growth simulation in Shenzhen, China. *Land Use Policy* **2020**, *95*, 104620. [CrossRef]
15. Wolday, F.; Böcker, L. Exploring changes in residential preference during COVID-19: Implications to contemporary urban planning. *Environ. Plan. B Urban. Anal. City Sci.* **2023**, *50*, 1280–1297. [CrossRef] [PubMed]

16. Jordan, R.; Birkin, M.; Evans, A. An agent-based model of residential mobility: Assessing the impacts of urban regeneration policy in the EASEL district. *Comput. Environ. Urban Syst.* **2014**, *48*, 49–63. [CrossRef]
17. Wu, J.; Mohamed, R.; Wang, Z. Agent-based simulation of the spatial evolution of the historical population in China. *J. Hist. Geogr.* **2011**, *37*, 12–21. [CrossRef]
18. Babakan, S.; Alimohammadi, A. An Agent-Based Simulation of Residential Location Choice of Tenants in Tehran, Iran. *Trans. GIS* **2016**, *20*, 101–125. [CrossRef]
19. Guo, C.; Buchmann, C.M.; Schwarz, N. Linking urban sprawl and income segregation—Findings from a stylized agent-based model. *Environ. Plan. B Urban Anal. City Sci.* **2019**, *46*, 469–489. [CrossRef]
20. Fagen, P.W. *Refugees and IDPs After Conflict: Why They Do Not Go Home (Special Report No. 268)*; United States Institute of Peace: Washington, DC, USA, 2011. Available online: https://www.usip.org/publications/2011/04/refugees-and-idps-after-conflict (accessed on 7 April 2025).
21. Afolabi, A.O.; Oluwatayo, A.; Oyeyipo, O. Assessment of designers' perception of post-conflict housing reconstruction. *Constr. Econ. Build.* **2018**, *18*, 27–47. [CrossRef]
22. Roy, A. Urban informality: Toward an epistemology of planning. *J. Am. Plan. Assoc.* **2005**, *71*, 147–158. [CrossRef]
23. Hébert, G.A.; Perez, L.; Harati, S. *An Agent-Based Model to Identify Migration Pathways of Refugees: The Case of Syria*; Advances in Geographic Information Science; Springer International Publishing: Cham, Germany, 2018; pp. 45–58. [CrossRef]
24. Barbé, D. Population Displacement and Urban Transition in Kabul City: Current Spatial Structure, Social Issues and Recommendations for a New Development Plan. *Sci. Po-Fall* 2013. Available online: https://www.researchgate.net/publication/260796612_Population_Displacement_and_Urban_Transition_in_Kabul_City_Current_Spatial_Structure_Social_Issues_and_Recommendations_for_a_New_Development_Plan (accessed on 2 July 2025).
25. Huang, C.; Zhang, C. Characterizing urban growth in Vientiane from 2000 to 2019 using time-series optical and SAR-based estimates of urban land. *Int. J. Appl. Earth Obs. Geoinf.* **2022**, *109*, 102798. [CrossRef]
26. Abdi, A.M. Land cover and land use classification performance of machine learning algorithms in a boreal landscape using Sentinel-2 data. *GIScience Remote Sens.* **2020**, *57*, 1–20. [CrossRef]
27. Mzid, N.; Pignatti, S.; Huang, W.; Casa, R. An analysis of bare soil occurrence in arable croplands for remote sensing topsoil applications. *Remote Sens.* **2021**, *13*, 474. [CrossRef]
28. Osgouei, P.E.; Kaya, S.; Sertel, E.; Alganci, U. Separating built-up areas from bare land in Mediterranean cities using Sentinel-2A imagery. *Remote Sens.* **2019**, *11*, 345. [CrossRef]
29. Gitelson, A.A.; Kaufman, Y.J.; Stark, R.; Rundquist, D. Novel algorithms for remote estimation of vegetation fraction. *Remote Sens. Environ.* **2002**, *80*, 76–87. [CrossRef]
30. Tran, D.X.; Dominati, E.; Lowry, J.; Mackay, A.; Vibart, R.; Pearson, D.; Devantier, B.; Noakes, E. Effects of spatial data resolution on the modelling and mapping of soil organic carbon content in hill country grassland landscapes. *Soil Use Manag.* **2024**, *40*, e12966. [CrossRef]
31. Dewitt, J.D.; Chirico, P.G.; Alessi, M.A.; Boston, K.M. Remote sensing inventory and geospatial analysis of brick kilns and clay quarrying in Kabul, Afghanistan. *Minerals* **2021**, *11*, 296. [CrossRef]
32. Talukdar, S.; Singha, P.; Mahato, S.; Pal, S. Land-Use Land-Cover Classification by Machine Learning Classifiers for Satellite Observations—A Review. *Remote Sens.* **2020**, *12*, 1135. [CrossRef]
33. Habibi, S.M.; Ono, H.; Shukla, A. Geographical Information System (GIS) Based Multi-Criteria Decision Analysis for Categorization of the Villages: In the Case of Kabul New City Villages. *Urban Sci.* **2021**, *5*, 65. [CrossRef]
34. Rafiqul Islam, M. Field research in the conflict zone: An empirical study of the Chittagong Hill Tracts in Bangladesh. In *Field Guide for Research in Community Settings (December)*; Edward Elgar Publishing: Gloucestershire, UK, 2021; pp. 154–166. [CrossRef]
35. Moss, S.M.; Uluğ, Ö.M.; Acar, Y.G. Doing research in conflict contexts: Practical and ethical challenges for researchers when conducting fieldwork. *Peace Confl.* **2019**, *25*, 86–99. [CrossRef]
36. Foschini, F. Land Grabs (2): Deh Sabz, the New and the Old. 2013. Available online: https://www.afghanistan-analysts.org/en/reports/rights-freedom/land-grabs-2-deh-sabz-the-new-and-the-old/ (accessed on 2 July 2025).
37. Sarwari, F.; Ono, H. An Analysis of Urban Ethnic Inclusion of Master Plans—In the Case of Kabul City, Afghanistan. *Urban Sci.* **2023**, *7*, 3. [CrossRef]

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Influence Mechanism, Simulation, and Prediction of Urban Expansion in Shaanxi Province, China

Chenxi Li [1,2], Huimin Chen [1] and Yingying Fang [1,*]

[1] School of Public Administration, Xi'an University of Architecture and Technology, Xi'an 710055, China; lichenxi@xauat.edu.cn (C.L.)
[2] Technology Innovation Center for Land Engineering and Human Settlements, Shaanxi Land Engineering Construction Group Co., Ltd., Xi'an Jiaotong University, Xi'an 712000, China
* Correspondence: fangyingying@xauat.edu.cn

Abstract: The purpose of this study is to analyze the temporal and spatial characteristics of urban expansion and its influencing factors in Shaanxi Province, China, as well as simulate future land use and predict the situation and development stage of urban expansion. An understanding of these factors is conducive to the coordinated development of the population, resources, and the economy; the optimization of the urban spatial layout; and the high-quality development of Shaanxi Province. Research methods: With IDRISI Selva17 and the expansion intensity index, the CA–Markov model was adopted to simulate and predict the land use type based on the land use data of Shaanxi Province from 2000 to 2020. The urban built-up areas in Shaanxi Province have been continuously expanding in the past 30 years, especially since 2010, when expansion slightly accelerated, and the expansion intensity changed, first rising and then falling. The Kappa index is as high as 0.70, which further confirms the accuracy of the land use spatial evolution prediction by the CA–Markov model. By combining the urban expansion index with the simulation model, this paper provides an in-depth analysis of the internal relationship between the historical evolution of and future trends in construction land expansion because of the high-quality coordinated development of Shaanxi Province and extends the research perspective with creative ideas.

Keywords: Shaanxi province; urban sprawl; expansion intensity index; expansion rate index; CA–Markov model

1. Introduction

The accelerating pace of urbanization remains a critical global research priority. According to the World Cities Report 2022 by UN-Habitat, 56% of the global population resided in urban areas in 2021, with projections indicating that this proportion will rise to 68% by 2050 [1]. Concurrently, the OECD's report "Rethinking Urban Sprawl: Moving Towards Sustainable Cities" estimates that 70% of the global population (86% in OECD nations) will inhabit urban areas by mid-century, underscoring cities' escalating socioeconomic significance [2]. However, urban expansion frequently exacerbates spatial inequalities through mismatched population migration and residential development. In Lagos, Africa's largest metropolis, 60% of residents occupy informal settlements where infrastructure coverage falls below 20%, epitomizing a dual-city dichotomy between formal and informal urban systems [3]. Mumbai's Dharavi slum exemplifies extreme density–pressure

mismatches, accommodating over 1 million inhabitants within 3 km^2—a population density of 334,000 persons/km^2—far exceeding municipal service capacities [4].

Driven by the wave of urbanization, China's urbanization level has significantly increased from 36.22% in 2000 to 66.16% in 2023. This growth trend indicates that China's urban development is moving at a rapid pace, and the ongoing expansion of urban land space has become a fundamental aspect of urban development. Sustainable urban development is the main concern in urban expansion in China, which is currently undergoing a significant transition from quantitative to qualitative urbanization. Understanding the spatial and temporal evolution characteristics of built-up urban areas, simulating the state of urban growth, and forecasting future development trends are therefore crucial for urban development.

Scholars worldwide have adopted multifaceted approaches to investigate urban expansion, exploring its scale, rate, and impacts on land use transitions from diverse perspectives. Current research on urban land expansion primarily focuses on three domains: (1) the spatiotemporal characteristics and evolutionary patterns of urban expansion [5]; (2) the driving mechanisms behind urban expansion [6]; (3) the socioeconomic, climatic, and eco-environmental impacts of urban spatial growth. These studies address core issues of urbanization through interdisciplinary lenses. For instance, Ouyang et al. (2020) analyzed the spatiotemporal evolution of urban land expansion in specific urban agglomerations from 1990 to 2015, revealing its effects on landscape ecology and providing critical insights into human–nature interactions [7]. They further developed a comprehensive indicator system integrating population, economy, and land use coordination to assess the "human–land relationship" during urban expansion, highlighting the synergistic roles of natural, economic, and demographic drivers. Yu et al. (2017) systematically investigated urban expansion in Wuhan from 1995 to 2015 using GIS Model Builder and the common edge measurement method, elucidating the dynamic processes and spatial characteristics of urban sprawl [8]. Recent studies have advanced urban expansion simulation through integrated models, such as the PLUS model for scenario-based projections [9,10] and the FLUS model combining the In-VEST model [11]. While the CA–Markov model is widely applied for its efficiency in spatial dynamics [12,13], its reliance on historical transition probabilities may overlook spatial constraints. Urban expansion monitoring has emerged as a research hotspot [14–16], with multidimensional quantitative methods—tailored to regional specificities and data availability—widely applied to evaluate expansion patterns [17]. While simulation models demonstrate efficacy in projecting urban spatial changes under resource constraints, their oversimplified assumptions often fail to capture the intrinsic mechanisms of spatial evolution [18,19]. To address these limitations, this study proposes an integrated monitoring model combining urban expansion indices and simulation modeling. This framework not only optimizes historical expansion data but also simulates urban spatial dynamics in multiple scenarios, enabling the systematic analysis of causal factors. Furthermore, it supports spatial optimization for evidence-based urban planning and policy formulation [20,21]. Meanwhile, this study proposes a dual-model framework comparing the CA–Markov and PLUS models, rigorously validating their accuracy in predicting land use transitions. Collectively, the existing research provides a robust theoretical foundation for analyzing spatiotemporal features, predictive modeling, and optimization strategies in urban expansion.

Based on the urban expansion history of Shaanxi Province over the past two decades, this paper conducts an in-depth investigation into its spatiotemporal characteristics, identifies the influencing factors driving its development, and simulates land use projections for Shaanxi Province in 2030. This research holds significant academic and practical value for

optimizing urban spatial layouts, adapting to and guiding rational land use change trends, and effectively curbing disorganized expansion in super-large cities.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

Shaanxi Province, located in central China along the middle reaches of the Yellow River, occupies a strategically significant position in the inland northwest region. It is bordered by Shanxi to the east, Inner Mongolia to the north, Ningxia and Gansu to the west, Sichuan and Chongqing to the south, and Hubei and Henan to the southeast. Covering an area of 205,600 km^2, the province is administratively divided into 11 prefecture-level cities—Xi'an, Tongchuan, Baoji, Xianyang, Weinan, Yan'an, Hanzhong, Yulin, Ankang, Shangluo, and the Yangling Demonstration Zone, along with 76 counties and cities. Shaanxi Province's unique geographical structure has a profound influence on its urban layout and development mode. Shaanxi Province is located in central China, winding along the middle reaches of the Yellow River. It has a complex and diverse terrain that is higher in the north and west and gradually decreases in the middle and east. In terms of geographical distribution, the Qinba Mountains in the south of Shaanxi Province occupy about 36% of the province's area; the north of Shaanxi Province is a vast plateau area, accounting for about 45%; and the central Guanzhong Plain, although only about 19%, is the core area of the province. The Guanzhong region, with its flat and open terrain serving as a geographical advantage, has a relatively dense urban distribution and a large scale, forming a number of economically active and culturally prosperous urban clusters. In contrast, due to the rugged terrain and inconvenient transportation, the urban layout of northern and southern Shaanxi Province is more dispersed, and each seeks a development path in a specific natural environment. In the process of urbanization, the phenomenon of urban expansion in Shaanxi Province also presents distinct regional characteristics. The Guanzhong area continues to give full play to its geographical advantages, and the urban area continues to expand outward, which promotes the rapid development of the economy and society. On the other hand, in northern and southern Shaanxi Province, under the premise of maintaining the balance of the ecological environment, the urbanization process is prudently promoted, with the aim of achieving sustainable development. This regional difference in urban expansion reflects not only the diversity of the geographical environment in Shaanxi Province but also the different choices and strategies of different regions on the road to urbanization. Taking the provincial capital Xi'an as an example, the land use in its central urban area is characterized by high intensification and efficient use, and its expansion mode is more characterized by filling, so the expansion rate is relatively gentle [22]. In contrast, the urban fringe has more abundant land resources and better expansion conditions, and its expansion speed is much faster than that of the central area, showing a more significant extensional development trend. In terms of spatial layout, construction land has gradually expanded in the southeast direction, while it has rapidly developed by leaps and bounds in the northwest direction [23]. However, these expansion trends are accompanied by a series of complex land use challenges and urgent issues. As a model of the western region taking the lead in entering the ranks of urban society, Shaanxi Province, with its unique charm and development potential, has attracted substantial population migration in the province and even the whole northwest region and promoted the continuous and steady growth of the provincial population. Urban planning that does not match development leads to inefficient land use, insufficient urban space, and increasingly serious urban problems such as traffic congestion and environmental pollution [24–26].

Based on significant differences in its natural geography, Shaanxi Province is divided into three major regions: Guanzhong, northern Shaanxi Province, and southern Shaanxi Province. As an ancient transportation hub connecting eastern and western China, the Guanzhong Plain has historically witnessed the prosperity of important trade routes such as the Qinchi Road and the Silk Road. Today, with the opening of the Longhai–Lanxin Railway, the Guanzhong region continues to play a key role in facilitating the flow of goods, technological exchanges, and cultural integration between the eastern and western regions. Northern Shaanxi Province, located north of the Beishan Mountain Range, with the vast Loess Plateau in the south and the Mao Wusu Sandy Land in the north, is not only a sacred place in China's modern revolutionary history but also carries a deep cultural heritage and natural features. Southern Shaanxi Province encompasses the Han River basin—a major tributary of the Yangtze River—and the Qinba Mountain area, located upstream of the Jialing River, and is endowed with abundant natural resources and a unique ecological environment, making it a "green pearl" of the province (see Figure 1).

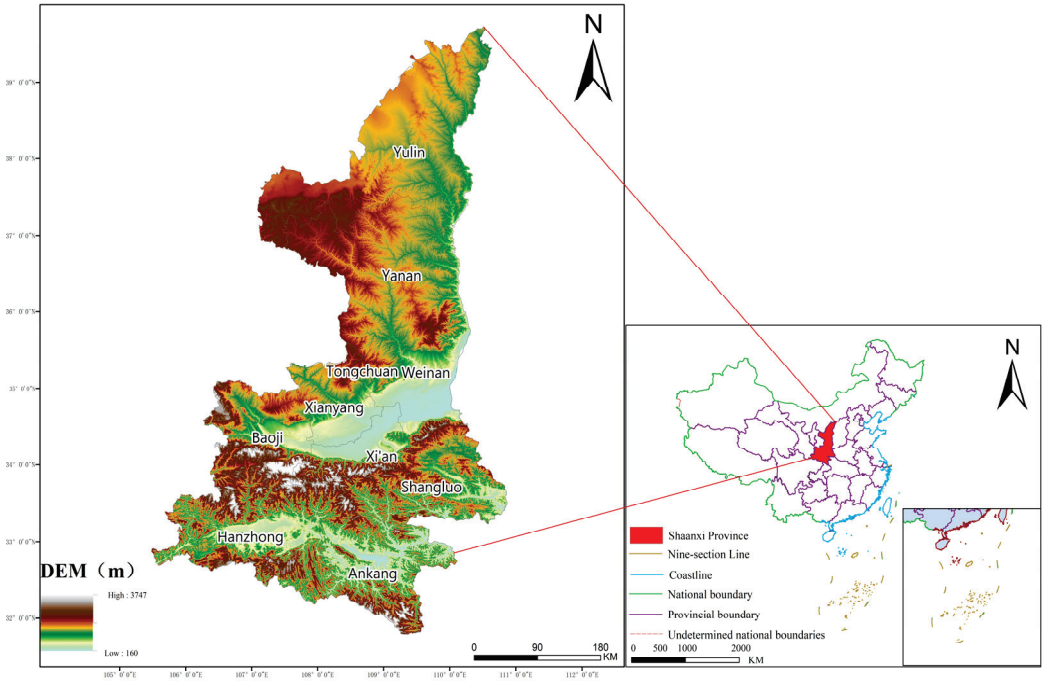


Figure 1. An overview map of the study area. The map was produced based on the standard map with review number GS(2023)2767, downloaded from the standard map service website of the State Administration of Surveying, Mapping and Geoinformation (SAGGI). The boundaries of the base map have not been modified. The same applies below.

In 2022, Shaanxi Province's Gross Regional Product (GRP) exceeded USD 327 million, and its Gross Per Capita Product exceeded CNY 82,000. By the end of 2022, the size of the resident population had reached 39.56 million, of which the proportion of the urban population was 64.02%. With the booming economy and growing population, the imbalance between the supply and demand of land is becoming increasingly prominent, which, in turn, is driving the continuous expansion of cities.

2.2. Data Sources

Landsat ETM/OLI8 image data with a 30 m × 30 m resolution were obtained for the years 2000, 2010, and 2020 from the National Geographic Data Cloud website. The images

were captured between June and September in each respective year. The detailed data types and sources are shown in Table 1.

Table 1. Data sources.

Data Type	Data Name	Resolution	Data sources
Land Use Data	Land use data in 2000, 2010, and 2020.	1 km	Resources and Environmental Science and Data Center, Chinese Academy of Sciences (https://www.resdc.cn, accessed on 1 July 2024)
Natural Environment Data	Elevation	1 km	Geospatial Data Cloud (https://www.gscloud.cn/, accessed on 19 July 2025)
	Slope	1 km	
Socioeconomic Data	Population Density	1 km	Global Change Research Data Publishing & Repository (http://www.geodoi.ac.cn/, accessed on 18 July 2025)
	GDP	1 km	
	Proximity to Highway	1 km	OpenStreetMap (https://www.openstreetmap.org/, accessed on 20 May 2025)
	Proximity to Primary Road	1 km	
	Proximity to Secondary Road	1 km	
	Proximity to Tertiary Road	1 km	

2.3. Data Processing

In the data processing of this study, remote sensing and geographic information software ArcGIS v10.8.2 were used, and the triangular grid method was used for accurate geometric correction. In order to accurately delineate the boundary of the central city, the spatial analysis module is used to process the classified images, and the grid images of three selected time points are generated. These raster images are combined with the administrative regions and land use data of the same period, and then vectorized to make a detailed map of the distribution of construction land in Shaanxi Province in the third phase. All raster data are clipped using the Chinese standard map boundary, and the unified resolution is 1 km. The coordinate system is re-projected as WGS_1984_UTM_Zone_49N.

The preprocessed land use maps of 2000 and 2010 underwent identical processing procedures and served as unified input data for both the CA–Markov and PLUS models, thereby eliminating interference from data discrepancies on subsequent accuracy comparisons.

3. Research Methodology

3.1. Expansion Intensity Index and Expansion Rate Index

In studies on the dynamic characteristics of urban land expansion, two key indicators are commonly employed: the Urban Expansion Intensity Index (UEII) and the Urban Expansion Rate Index (UERI). The UEII is primarily used to quantify the extent of built-up urban area expansion over a specified time period, while the UERI focuses on measuring the speed of this process. The formulas for these two indices are presented below:

$$\mathrm{UEII} = \frac{(U_b - U_a)}{U_a} \times 100\% \quad (1)$$

$$\mathrm{UERI} = \frac{(U_c - U_d)}{(T_c - T_d)} \times 100\% \quad (2)$$

In these formulas, U_a and U_b in (1) and U_c and U_d in (2) are defined as the urban built-up area at two different time nodes to distinguish the scale of urban development at

different stages; T_c and T_d are introduced as two specific research time sequence identifiers, corresponding to different time nodes, to analyze the changes in the built-up urban area during these time sequences, where T_c and T_d denote start and end years.

3.2. CA–Markov Model

Markov modeling, a method based on Markov chain process theory, is widely used in the prediction of event probabilities. The core assumption of this approach is the memoryless nature of event evolution, meaning that the probability distribution of future states depends solely on the current state, rather than on previous states [27]. Therefore, in dynamic land use simulations, a land use transition can be treated as a stochastic process that adheres to the Markov property. In this context, different land use types are represented as potential states, and the transitions between these types reflect the probabilities of state changes (Table 2). Based on this framework, the Markov model is capable of effectively capturing the probability of transitions between land use types and generating reliable predictions. The mathematical formulation is presented below:

$$S_{t+1} = P_{ij} \times S_t \tag{3}$$

In the above expression, S_t and S_{t+1} represent the system at moments t and $t + 1$, while P_{ij} is used to describe the transfer probability of transitioning from state i to state j.

Table 2. 2000–2010 land transfer matrix.

	2010							
2000	**Cultivated Land**	**Forest Land**	**Grass Land**	**Water Body**	**Urban and Rural, Industrial and Mining, Residential Land**	**Unused Land**	**Grand Total**	**Transfer-out Amount**
Cultivated land	69,873	766	744	132	348	4	71,867	1994
Forest land	12	46,431	47	5	24	10	46,529	98
Grass land	121	579	76,756	24	34	40	77,554	798
Water body	98	7	13	1742	5	2	1867	125
Urban and rural, industrial and mining, residential land	1	0	3	0	3059	0	3063	4
Unused land	31	8	131	4	6	4666	4846	180
Grand total	70,136	47,791	77,694	1907	3476	4722	205,726	3199
Transfer volume	263	1360	938	165	417	56	3199	

A Cellular Automaton (CA) is a discretized dynamical simulation tool that integrates the concepts of time, space, and state to model the spatial dynamics of complex systems over time [28]. Its mathematical model can be represented as follows:

$$S_{t+1} = f(S_t, N) \tag{4}$$

In the constructed model, the finite discrete state of the cell is represented by S, t and t + 1 represent different time nodes, N refers to the adjacent region of the cell, and f is the regular function of the local transformation. Together, these key elements guide the dynamic evolution within complex systems.

3.3. PLUS Model

The PLUS model is a method to simulate land use change on the plot scale. The model integrates multi-dimensional driving factors such as social economy, environment, and policy, and couples spatial constraints and geographical conditions to realize the prediction of land use dynamic change. Its significant advantages are reflected in the ability to describe the details of land use conversion on a high-resolution spatial scale, and to

quantitatively evaluate the effects of different policies and development plans through scenario analysis, providing high-precision scientific basis for urban planning and land management decisions [29].

In the PLUS model, the neighborhood influence factor is one of the core mechanisms that drive the cellular automata to run. This factor quantifies the degree to which a specific land use type in the simulation unit is affected by the land use of the adjacent area (whether the same or different), and its value is expressed as an influence coefficient within the range of [0, 1]. The coefficient value approaching 1 indicates that the land use type has a strong tendency of spatial expansion and agglomeration. On the contrary, the coefficient value approaching 0 reflects that its spatial distribution is less affected by the adjacent area (Table 3).

Table 3. Domain weight setting in 2020.

Type	Cultivated Land	Forest Land	Grass Land	Water Body	Urban and Rural, Industrial and Mining, Residential Land	Unused Land
Domain weight	1	0.746	0.085	0.023	0.243	0.07

The specific calculation formula for the neighborhood weights is as follows:

$$X^* = \frac{X - X_{min}}{X - X_{min}} \quad (5)$$

X* denotes the min-max normalized value; X represents the change area of each land use type between the two-period land use data; X_{max} is the maximum change area among all land use types; and X_{min} is the minimum change area among all land use types.

The cost conversion matrix represents the conversion rules between land use types and clearly stipulates whether mutual conversion is allowed between categories. The matrix is characterized by Boolean logic value: if a land use type can be converted to another type, the corresponding matrix element is assigned to 1; conversely, if the conversion is prohibited, the assignment is 0 [30] (Table 4).

Table 4. Land conversion cost matrix setting.

Type	Cultivated Land	Forest Land	Grass Land	Water Body	Urban and Rural, Industrial and Mining, Residential Land	Unused Land
Cultivated land	1	1	1	1	1	1
Forest land	1	1	1	0	1	1
Grass land	1	1	1	1	1	1
Water body	1	0	1	1	0	1
Urban and rural, industrial and mining, residential land	1	1	1	0	1	1
Unused land	1	1	1	1	1	1

3.4. Precision Testing

The Kappa coefficient is widely regarded as an effective measure for assessing the accuracy of remote sensing interpretations and the degree of similarity between two images. In this study, the Kappa coefficient is used as an evaluation metric to verify the accuracy of the CA–Markov model in simulating land use changes in Shaanxi Province [31]. The calculation method for the Kappa coefficient is outlined as follows:

$$\text{Kappa} = \frac{P_o - P_c}{P_p - P_c} \quad (6)$$

$$P_o = \frac{n_1}{n}, P_c = \frac{1}{N} \quad (7)$$

In the formula, P_o represents the proportion of grids correctly simulated, P_c is the expected proportion of grids correctly simulated, P_p is the proportion of grids correctly simulated assuming an ideal classification, n is the total number of grids, n_1 is the number of grids correctly simulated, and N is the number of land use types.

A Kappa coefficient below 0 indicates poor agreement between the simulation and actual data. A value between 0 and 0.2 suggests weak consistency, while a value ranging from 0.2 to 0.4 reflects low consistency. Values between 0.4 and 0.6 represent moderate consistency, and a Kappa coefficient between 0.6 and 0.8 indicates significant agreement. Finally, a value between 0.8 and 1 signifies an optimal agreement between the simulation and the actual data [32].

4. Findings

4.1. Spatial and Temporal Characteristics of Urban Land Expansion in Shaanxi Province

Table 5 shows the built-up urban area of Shaanxi Province in 1990, 2000, 2010, and 2020. Overall, the built-up urban area of Shaanxi Province has been expanding over the past 30 years, especially since 2010, when expansion slightly accelerated. The intensity of expansion changed over time: between 1990 and 2000, the intensity of expansion was negative, after which it rose and then fell. Due to the small size of the urban built-up area in the previous period, the rate of expansion gradually accelerated after 2000, and the intensity of expansion began to decrease between 2010 and 2020 (Figure 2).

Table 5. Area expansion of Shaanxi Province Center from 2000 to 2020.

Parameters	1990	2000	2010	2020
Urban area (km^2)	413	381	719	1243
Expansion area (km^2)	/	−32	338	524
Expansion intensity (%)	/	−7.75%	88.71%	72.88%
Rate of expansion (km^2/a)	/	−3.2	33.8	52.4

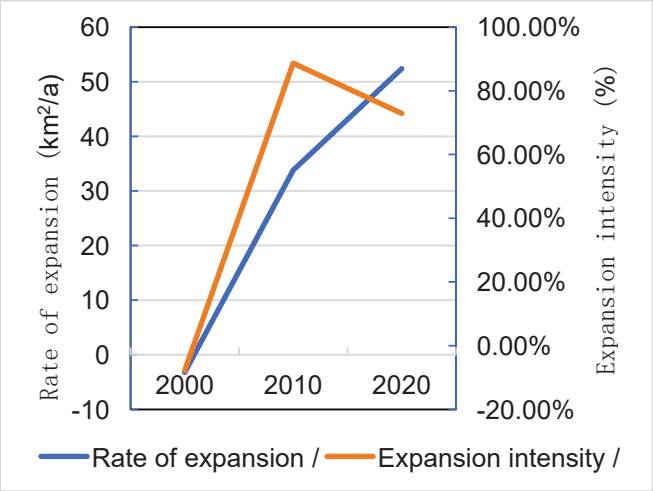


Figure 2. Expansion curve of Shaanxi Central City.

The trajectory of urban development is characterized by the expansion of the central urban area and its gradual integration with the surrounding regions, ultimately achieving the strategic goal of regional integration [33]. In Xi'an, prior to the formation of the

metropolitan area, the core urban area was mainly limited to six urban areas centered on the Bell Tower. In the 1985 urban layout, the radius of Xi'an's main urban area was about 5 km, while the distance to Xianyang City was around 15 km. In recent years, the urban spatial layout of Xi'an has significantly changed. The western boundary has seamlessly merged with the main city of Xianyang, creating a vast radius of 30 km, which marks a significant shift in the city's center of gravity to the west. This process not only reflects the close ties between the two cities but also marks significant progress in the regional integration strategy, which is important for promoting regional economic development and urbanization.

4.2. Factors Influencing Urban Land Expansion in Shaanxi Province

The evolution of the urban spatial structure is the result of the interweaving of multiple factors, covering human activities, the geographical environment, and other dimensions. Urban expansion is guided and regulated by urban development planning policies, while economic and population growth are the core forces driving its development. Specifically, population growth triggers a surge in demand for land for functions such as residential, educational, employment, and recreational activities, while booming economic development promotes land expansion for factory construction and commercial land [12]. The government's macro policies have had a profound impact on the allocation of land resources and the direction of expansion, while the ecological basis of urban expansion has been constrained by natural conditions such as road transportation networks and water system layouts. Based on an in-depth analysis of the development history of central urban areas in Shaanxi Province over the past two decades, these influencing factors are grouped into five core dimensions: natural geographic conditions, transportation network construction, economic development dynamics, policy-oriented effects, and historical and cultural background (see Figure 3).

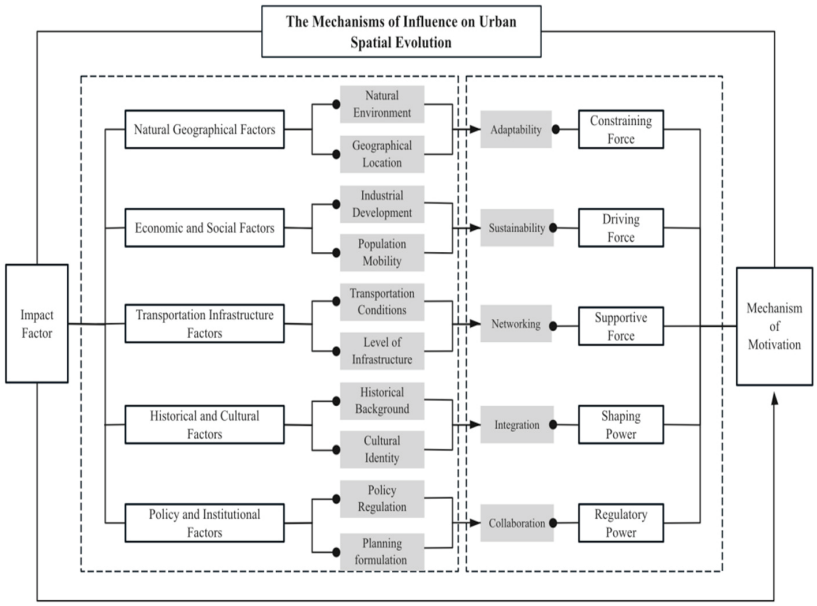


Figure 3. Mechanisms influencing urban spatial evolution.

4.2.1. The Binding Force of Natural Geography

The pronounced topographic diversity across Shaanxi Province exerts a fundamental constraint on urban expansion patterns. The flat terrain of the Guanzhong Plain facilitates efficient infrastructure development and connectivity, enabling contiguous, low-cost

outward expansion and fostering the formation of dense, large-scale urban clusters. Conversely, the rugged topography of the Loess Plateau in the north and the Qinba Mountains in the south acts as a significant physical barrier. Expansion is largely confined to narrow valleys and river corridors where developable land is scarce and fragmented. This severely limits the potential scale and contiguity of urban development, forces dispersed settlement patterns and increases the costs and complexities of infrastructure provision. Consequently, the rate and spatial configuration of urban expansion are directly dictated by the binding force of the underlying natural geography.

4.2.2. The Supporting Force of the Transportation Network

The continued optimization and expansion of transportation networks, especially the construction of modern transportation infrastructure such as highways and high-speed railroads, have significantly enhanced regional connectivity and accessibility. This improvement not only makes remote areas easily accessible but also leverages their potential to attract investment, increase population flow, and foster industrial concentration, which in turn promotes the orderly expansion of urban land. The layout of the transportation network is equally important to the shaping of the urban spatial structure. For example, the introduction of urban rail transit often leads to the formation of a checkerboard spatial layout that combines ring and radial patterns, which not only optimizes the internal transportation routes of the city but also promotes the efficient allocation of urban land. A well-planned transportation network can effectively guide the development of urban land toward intensification and high efficiency. The establishment of additional traffic arteries in the peripheral or suburban areas of the city can guide enterprises and residents to migrate to these areas, thus dispersing the population and industrial pressure in the core area of the city and achieving the intensive use and optimal allocation of land resources. In addition, the improvement of the transportation network also promotes close inter-regional ties and cooperation, accelerates the flow and sharing of resources between cities in the region, and lays a solid foundation for the coordinated development of the regional economy.

4.2.3. The Driving Force of Economic Development

With the sustained and rapid economic growth in Shaanxi Province, there has been an increasing demand for land resources for all types of economic activities, covering a wide range of dimensions, including commercial, industrial, residential, and public facilities. In order to meet these diverse demands, the scale of urban land use has had to correspondingly expand. Economic development has been accompanied by a profound restructuring of the industrial structure, with Shaanxi Province undergoing a transition from a secondary- to a tertiary-led industry. This shift has led to a decrease in the demand for traditional industrial land and a significant increase in the demand for land in new fields such as commerce and services, which in turn has driven the optimization and expansion of the urban land structure. The attraction of economic prosperity is reflected not only in the convergence of capital but also in its ability to introduce advanced technology, management concepts, and development models, injecting new vitality into local industries and pushing the economy to a higher level. The implementation of these investment projects often requires supporting land resources, further accelerating the pace of urban land expansion. For example, as the capital city of Shaanxi Province, Xi'an's rapid economic development and accelerated urbanization are directly reflected in the significant increase in the pace of urban land expansion, which has become a microcosm of regional economic development [34]. According to the Xi'an 2024 State-owned Construction Land Supply Plan announced by the Xi'an Municipal Bureau of Natural Resources and Planning, Xi'an plans to supply over

50,000 mu (approximately 35 km^2) of construction land. This plan reflects not only Xi'an's confidence and determination in economic development but also the actual demand for urban land expansion. Xi'an also promotes the efficient use of urban land and coordinated development by optimizing the spatial layout of the city and strengthening the construction of transportation networks. For example, in the Xi'an Land Space Ecological Restoration Plan, the term "Central City Ecological Infrastructure Enhancement Zone" is explicitly mentioned, and the scope and functional positioning of the central city is clearly defined. These measures help to achieve a virtuous cycle of economic development, ecological environmental protection, and the sustainable use of urban land.

4.2.4. Regulatory Power of Policy Guidance

Government policies and development plans have a significant impact on the direction and pace of urban land expansion. For example, in order to promote the development of a certain area, the government may invest more resources, including land resources, thus promoting the expansion of urban land in that area [35]. The policy orientation guides the layout of urban land by formulating urban development plans and land use plans, which specify the direction and key areas of urban development. For example, in the Xi'an City Land Space Ecological Restoration Plan, the concept of the "Central City Ecological Infrastructure Enhancement Zone" is put forward and clearly outlines the scope and functional focus of the central city. This policy orientation has directly influenced the direction and layout of urban land expansion in Xi'an, making urban land use more rational and efficient.

4.2.5. Integration of History and Culture

Shaanxi Province's profound historical and cultural heritage significantly integrates with, and thereby shapes, urban expansion dynamics, primarily through preservation constraints and tourism-driven development. The concentration of major heritage sites within or near existing urban cores imposes stringent regulatory limitations on surrounding development. Urban planning designates protected zones with strict controls on building height, density, and land use type to safeguard heritage integrity. This actively directs expansion away from these core heritage vicinities, altering its spatial trajectory and often slowing the pace in historically sensitive corridors. On the other hand, this cultural integration also fuels expansion in other directions. Heritage sites act as powerful tourist magnets and cultural anchors, stimulating demand for supporting infrastructure, cultural, and commercial districts nearby, albeit outside the strict protection zones. This tourism-oriented development becomes a distinct driver of land conversion in designated areas, demonstrating how the integration of historical–cultural assets not only constrains expansion in one context but actively channels and stimulates it in others, creating unique spatial patterns around cultural landmarks.

4.3. Simulation and Prediction of Urban Land Expansion in Shaanxi Province

This study employed land use data from 2000 and 2010 to predict the 2020 spatial land use pattern through both CA–Markov and PLUS models. The CA–Markov model integrated transition matrices and suitability atlases as simulation rules. The predictive results were rigorously validated against actual 2020 land use data using GIS-based spatial overlay subtraction [36], while the PLUS model utilized a patch-generating land use simulation strategy. Validation against actual 2020 data revealed that the CA–Markov model achieved an overall accuracy of 83.48% and a Kappa coefficient of 70%, indicating high reliability (Figure 4). In contrast, the PLUS model yielded a Kappa coefficient of

38%, reflecting moderate consistency. The superior performance of the CA–Markov model underscores its efficacy in capturing contiguous urban expansion patterns in Shaanxi Province (Figure 5).

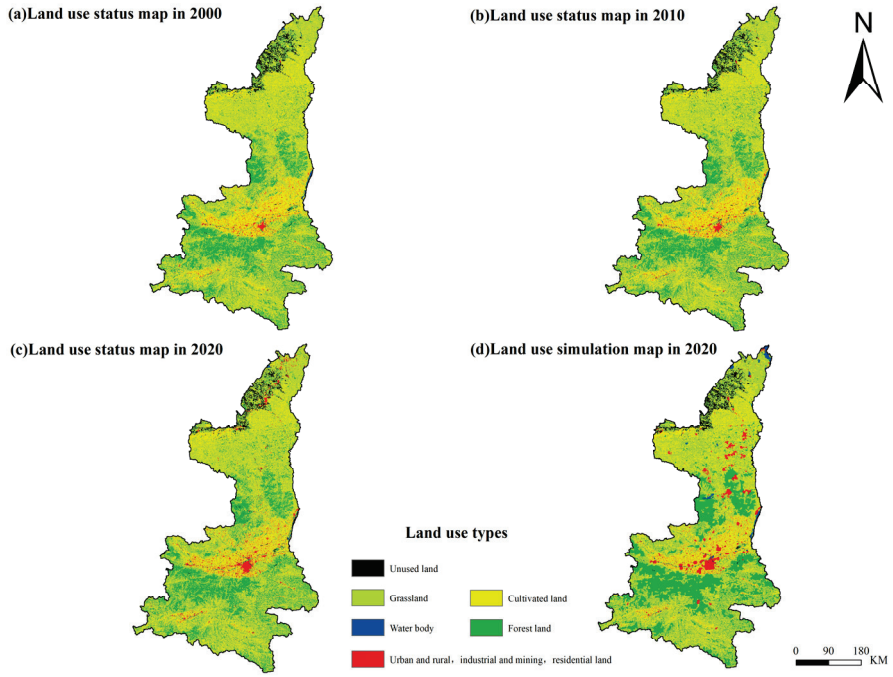


Figure 4. Map of current land use in 2000, 2010, and 2020 and land use simulation for 2020.

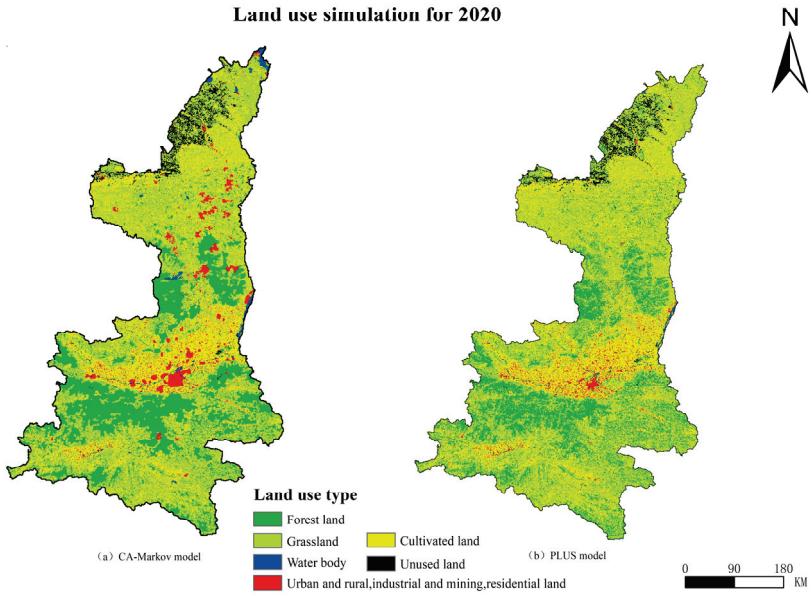


Figure 5. Land use simulation maps of the CA–Markov model and PLUS model in 2020.

In addition, Figure 4 shows that the construction land in northern Shaanxi Province is significantly reduced compared with 2020, and there may be two reasons. First, the Grain for Green Project will convert some suitable urban land into forest land; second, due to the decline of mining industry, some resource-exhausted cities have implemented contractionary planning to reduce the demand for industrial land. Some industrial and mining land has been converted into other types of land, and the outflow of population has led to the merger and revocation of residential areas.

A systematic analysis of the spatial simulation efficacy revealed exceptional consistency between modeled and observed land use dynamics, thereby verifying the methodological rigor and implementation validity. To enhance predictive precision, we recalibrated the suitability atlases using 2010 as the updated baseline. Leveraging the 2010–2020 land transition matrix and refined suitability parameters as guiding principles, the CA–Markov model successfully projected the 2030 land use distribution (Figure 6), providing critical insights for territorial spatial planning.

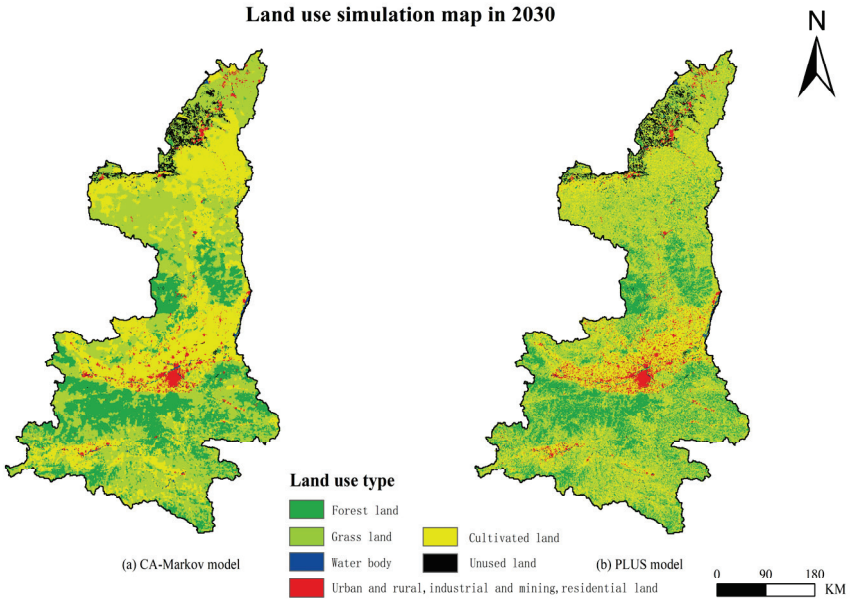


Figure 6. Land use simulation maps of the CA–Markov model and PLUS model in 2030.

Furthermore, the PLUS model integrates land expansion analysis strategies and multi-class random patch seeding mechanisms. By incorporating driving factors such as socioeconomic conditions and the natural environment, it successfully predicts the land use distribution for 2030 (Figure 6).

The CA–Markov model significantly overestimates urban land and underestimates cultivated land in the 2020 simulation. The PLUS model urban land is low, but the error is small and closer to the actual value. The 2030 CA–Markov model predicts that land use in 2030 will rebound, and urban land will shrink, while the PLUS model predicts that cultivated land will continue to decrease and urban expansion, which may be related to the sensitivity of the PLUS model to human driving forces (Table 6).

Table 6. Two-model simulation of land area comparison.

	Year	Cultivated Land	Forest Land	Grass Land	Water Body	Urban and Rural, Industrial and Mining, Residential Land	Unused Land
Actual land area(km^2)	2000	71,863	46,596	77,593	1871	3072	4817
	2010	70,147	47,847	77,736	1909	3480	4693
	2020	67,015	48,031	79,071	1724	5586	4388
The CA–Markov model simulates the area of land type (km^2)	2020	61,318	54,221	74,434	3077	7426	5252
The PLUS model simulates the area of land type (km^2)	2020	68,480	49,078	77,858	1909	3839	4648
The CA–Markov model simulates the area of land type.(km^2)	2030	70,375	46,690	78,063	1666	4575	4408
The PLUS model simulates the area of land type.(km^2)	2030	65,092	49,169	79,062	1689	6558	4182

5. Discussion

An in-depth analysis of the spatial and temporal evolution of urban land expansion and its driving forces is essential for understanding the regional urbanization process, revealing the spatial pattern of land use, and guiding transportation, demographic, and economic planning in the region. Given the accelerated urbanization process and inappropriate use of land resources, urban ecosystems and residents' quality of life are facing increasing challenges [37]. Therefore, predicting future urban expansion trends is vital for the rational allocation of land resources and sustainable urban development.

5.1. Comparison with Existing Research

The existing research mostly separates the expansion index and the simulation model. This paper combines the expansion intensity index with the CA–Markov model. This framework not only optimizes the historical expansion data but also simulates the urban spatial dynamics under multiple scenarios, supports systematic causal analysis, and provides spatial optimization support for evidence-based urban planning and policy formulation.

5.2. Research Limitations

Combining the urban expansion index and the simulation model, we not only comprehensively analyzed the spatial and temporal characteristics of construction land expansion in Shaanxi Province between 2000 and 2020 but also explored the driving mechanisms behind it. Based on these analyses, we simulated the land use distribution pattern of Shaanxi Province in 2030. Combining the urban expansion index with the simulation model, we comprehensively analyzed the intrinsic connection between the historical evolution of construction land expansion and future trends in the high-quality coordinated development of Shaanxi Province, thus achieving an innovative expansion of research perspectives. However, due to limited data acquisition channels and the lack of long-term images, this study failed to compare multiple cities, and it is difficult to fully explore the influencing factors of urban expansion in Shaanxi Province. Further research is needed on the mechanisms of urban expansion.

5.3. Future Research Prospects

Looking ahead, the proportion of construction land in Shaanxi Province is expected to continue to climb, and the mode of urban expansion will be dominated by external expansion, further promoting the expansion of the city's scale and improvements in its functions. In order to balance urban development and the construction of ecological civilization, Shaanxi Province should optimize the efficiency of land use and take effective measures, such as construction land consolidation and arable land reclamation [38]. At the same time, the scientificity and rationality of urban planning should be enhanced, and the pattern of urban land use should be actively regulated to avoid over-expansion and achieve the rational allocation and sustainable development of land resources, thus promoting the high-quality upgrading of the urbanization process in Shaanxi Province.

6. Conclusions

From the in-depth analysis of the results of the prediction of various types of land use in Shaanxi Province, combined with the regional slope, rivers, and other natural elements, the following conclusions are drawn:

(1) There are significant trends in land use. In the time span from 2000 to 2030, the growth trend of construction land was substantial, while the area of arable land showed a significant shrinking trend, with the main direction of transformation being toward construction land and unutilized land, demonstrating an obvious dynamic change trend.

(2) On the basis of an in-depth analysis of the development history of central urban areas in Shaanxi Province over the past two decades, the influencing factors of urban land expansion in Shaanxi Province are categorized into five core dimensions: natural geographic conditions, the construction of transportation networks, the trend in economic development, the role of policy orientation, and historical and cultural background.
(3) Multiple suitability factors, such as topography and road network density, were introduced to evaluate the suitability of land transfer. The results show that the multi-criteria evaluation method possesses a high degree of rationality and accuracy and is an effective tool for formulating the rules of land use transformation. Its Kappa index is as high as 0.70, which further confirms the accuracy of the method. Meanwhile, it also provides strong support for the applicability of the CA–Markov model in the simulation and prediction of the spatial evolution of urban land use.

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References

1. United Nations Human Settlements Programme. *World Cities Report 2022: Envisaging the Future of Cities*; United Nations Research Institute for Social Development: Geneva, Switzerland, 2022.
2. OECD. *Rethinking Urban Sprawl: Moving Towards Sustainable Cities*; OECD Publishing: Paris, France, 2018.
3. UN-Habitat. *Global Urban Indicators Database: Lagos Metropolitan Analysis*; United Nations Human Settlements Programme: Nairobi, Kenya, 2022.
4. World Bank. *Slum Upgrading in Mumbai: Spatial Equity and Service Delivery*; World Bank Urban Development Series: Tokyo, Japan, 2021.
5. Chen, L.; Gong, C.; Guo, Y.; Guo, Y.; Su, J.; Xu, X.; Xu, G. Integrating macro-micro perspectives to measure urban land expansion in Minsk, Belarus. *J. Urban Manag.* 2025; *in press*. [CrossRef]
6. Mansour, S.; Alotaibi, O.; Alnasrallah, M. Geospatial modelling of urban expansion effects on the land ecosystems in Kuwait using random forest and cellular automata. *J. Urban Manag.* 2025; *in press*. [CrossRef]
7. Ouyang, X.; Zhu, X. Spatio-temporal characteristics of urban land expansion in Chinese urban agglomerations. *Acta Geogr. Sin.* **2020**, *75*, 571–588.
8. Yu, Y.; Hu, S.; Tong, Y. Research on modeling for urban expansion pattern recognition based on shared boundary analysis. *Geogr. Geo-Inf. Sci.* **2017**, *33*, 78–81.
9. Zhang, X.; Liu, Y.; Wang, W. Simulation of multi-scenario land use change and its impact on ecosystem services in China based on PLUS-InVEST model. *Acta Ecol. Sin.* **2025**, *19*, 1–17.
10. Huang, L.; Cheng, A.; Liu, X. Simulation and prediction of land use change and carbon storage spatiotemporal evolution in Yulin city based on the PLUS-InVEST model. *Environ. Sci.* **2025**, 1–15.
11. Reng, Y.; Liu, X.; Xu, X. Multi-scenario simulation of land use change and its impact on ecosystem services in Beijing-Tianjin-Hebei region based on the PLUS-InVEST model. *Acta Geogr. Sin.* **2023**, *43*, 4473–4487.

12. Wang, K.; Qin, J.; Ma, H. Spatial-temporal evolution simulation and ecological response of urban expansion in western new city of Chongqing based on CA-Markov model. *J. Univ. Chin. Acad. Sci.* **2023**, *40*, 496–505.
13. Cheng, C.; Hu, Y.; Feng, Y. Construction of urban ecological zones based on CA-Markov model: A case study of the main urban area of Jinzhong. *Acta Ecol. Sin.* **2020**, *40*, 1455–1462. [CrossRef]
14. Bagheri, B.; Tousi, S.N. An explanation of urban sprawl phenomenon in Shiraz Metropolitan Area (SMA). *Cities* **2017**, *73*, 71–90. [CrossRef]
15. Li, Y.; Meng, D.; Ye, H.P. Spatiotemporal pattern and driving forces of typical Russian cities: Based on remote sensing decision fusion and multiple discrete regression model. *Geogr. Res.* **2021**, *40*, 2967–2985.
16. Li, G.D. Spatio-temporal change of global land cover and China's contribution. *Acta Geogr. Sin.* **2022**, *77*, 353–368.
17. Guan, D.; He, X.; He, C. Does the urban sprawl matter in Yangtze River Economic Belt, China? An integrated analysis with urban sprawl index and one scenario analysis model. *Cities* **2020**, *99*, 102611. [CrossRef]
18. Chen, Y.; Xue, Y.; Hu, Y. How multiple factors control evapotranspiration in North America evergreen needleleaf forests. *Sci. Total Environ.* **2018**, *622*, 1217–1224. [CrossRef]
19. Liao, J.; Shao, G.; Wang, C. Urban sprawl scenario simulations based on cellular automata and ordered weighted averaging ecological constraints. *Ecol. Indic.* **2019**, *107*, 105572. [CrossRef]
20. Yuan, M.Y.; Li, J.X.; Zeng, L. Spatial-temporal Change and Driving Forces Analysis of Land-use in Xi'an City. *Sci. Technol. Eng.* **2022**, *22*, 13846–13855.
21. Fan, X.; Qie, H. Analysis on the Characteristics of the Tempo-spatial Evolution of Xi'an Metropolitan Area. *Urban Dev. Stud.* **2021**, *28*, 34–39.
22. Ge, Y.; Han, L.; Zhao, Y. Spatio-temporal analysis of urban expansion in Xi'an from 1984 to 2016. *Shengtaixue Zazhi* **2019**, *38*, 1491–1499.
23. Xu, P.; Du, P. Remote Sensing Monitoring Analysis of City Expansion and Land Use Change in Xi'an. *J. Beijing Union Univ.* **2018**, *32*, 42–51.
24. Xiao, H.; Xue, F.; Yang, Y. Relationships between construction land expansion and habitat quality change and coupling coordination in Xi'an. *J. Arid Land Resour. Environ.* **2023**, *37*, 56–64.
25. Li, C.; Lou, N.; Yang, Y. Study on the relationship between spatio-temporal evolution of road network and urban spatial change in Xi'an. *Sci. Surv. Mapp.* **2021**, *46*, 173–180+200.
26. Li, J.; Sun, S.; Zhao, D. Evaluation of spatial distribution of urban functions based on road network density—Taking Xi'an as an example. *Res. Dev.* **2023**, *6*, 97–105.
27. Li, Y.; Chang, J.; Wang, Y. Land use simulation and prediction in the Yellow River Basin based on CA-Markov model. *J. Northwest Agric. For. Univ.* **2020**, *48*, 107–116.
28. Gan, X.; Chen, J. Application of cellular automata model in urban expansion of Chengdu city. *Remote Sens. Inf.* **2022**, *37*, 116–122.
29. Wang, B.; Liao, J.; Zhu, W. The weight of neighborhood setting of the PLUS model based on a historical scenario: A case study of land use simulation of urban agglomeration of the Golden Triangle of Southern Fujian in 2030. *Acta Geogr. Sin.* **2019**, *39*, 4284–4298.
30. Ouyang, X.; He, Q.; Zhu, X. Simulation of impacts urban agglomeration land use change on ecosystem services value under multi-scenarios:Case study in Changesha-Zhuzhou-Xiangtan urban agglomeration. *Econ. Geogr.* **2020**, *40*, 93–102.
31. Li, Y.; Lin, A.; Wu, H. Refined simulation of urban land use change with emphasis on spatial scale effect. *Acta Geogr. Sin.* **2022**, *77*, 2738–2756.
32. Liu, X.; Li, X.; Wei, X. Study on Fusion Demarcation of Urban Development Boundary Based on MCR and CA Model: A Case Study of Xuzhou City. *China Land Sci.* **2020**, *34*, 8–17.
33. Gao, X.; Song, Z.; Li, C. Landscape Pattern Optimization in Baiyangdian Basin Based on Landscape Ecological Risk Assessment. *Shengtai Yu Nongcun Huanjing Xuebao* **2023**, *39*, 174–183.
34. Zhu, L.; Zhao, M.; Li, Y. The Space-time relationship between ecosystem service value and human activity intensity in Xi'an metropolitan area. *Hengtai Yu Nongcun Huanjing Xuebao* **2024**, *40*, 325–334.
35. Li, T. Research on the Spatial Development of the New Zone Located in the Edge of Xi'an City Since the 1990s—Xi'an Economic-Technological Development Area. Master's Thesis, Xi'an University of Architecture and Technology, Xi'an, China, 2015.
36. Gao, X.; Yang, L.; Wanqing, L. Land use change and ecosystem service value measurement in Baiyangdian Basin under simulated multiple scenarios. *Shengtai Xuebao* **2021**, *41*, 7974–7988.
37. Song, B.; Zhou, Z. Influence of road network on landscape pattern in Xi'an metropolitan zone. *Jilin Daxue Xuebao, Diqiu Kexueban* **2017**, *47*, 1521–1532.
38. Li, C.; Wu, K.; Gao, X. Manufacturing industry agglomeration and spatial clustering: Evidence from Hebei Province, China. *Environ. Dev. Sustain.* **2020**, *22*, 2941–2965. [CrossRef]

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Spatiotemporal Evolution and the Impact of Changing Political–Economic Systems on Tourism Spatial Planning and Land Use: The Case of Kupari, Dubrovnik, Croatia

Sanja Hajdinjak [1], Jasenka Kranjčević [2,*] and Božo Benić [3]

[1] Temedica, Bayerstraße 69, 80335 Munich, Germany; sanja.hajdinjak@temedica.com
[2] Institute for Tourism, Vrhovec 5, 10000 Zagreb, Croatia
[3] Department for Urbanism, Spatial Planning and Environmental Protection in Dubrovnik, Pred Dvorom 1, 20000 Dubrovnik, Croatia; bbenic@dubrovnik.hr
* Correspondence: jasenka.kranjcevic@iztzg.hr; Tel.: +385-98-808-061

Abstract

Existing research on tourism spatial planning primarily focuses on different political and economic systems (PESs)—but most often within capitalist democracies. However, there is a lack of research examining how frequent changes in PESs (capitalism, socialism and recapitalism) act as critical points, as they affect tourism spatial planning legislation, land use and spatial management. By analysing the spatiotemporal evolution of the Kupari tourist zone in Croatia (1880–2024), we investigate how PES changes act as critical turning points that shape tourism spatial planning and administrative practices. Key results reveal that tourism recovery and resilience are closely linked to the stability of PESs. Frequent PES changes (1) reduce the overall resilience of tourism and its institutions, (2) lead to recurring changes in tourism spatial planning legislation (e.g., ownership and land use) and (3) disrupt the positive correlation between space and tourism development. Frequent changes in PESs are reflected in legislation, as well as in challenges of compromise for issues closely related to tourism and spatial management. Only a stable PES can enable continuous monitoring of legislation and its spatial consequences in real time. An integrated methodology for monitoring legislation, together with a framework for spatial management, offers practical solutions for the sustainable management of tourist areas. These findings provide both scientific evidence and practical strategies for better harmonization of legislation with the resilience of tourism spatial planning on the eastern coast of the Adriatic Sea.

Keywords: spatiotemporal evolution; political and economic system (PES); tourism spatial planning; Kupari; Croatia

1. Introduction

The relationship between spatial planning and tourism in capitalist democracies has been widely researched, with increasing emphasis on achieving spatial resilience through optimal use of land (as a limited resource) while simultaneously ensuring economic growth and job creation through the tourism industry [1,2]. However, much less research has been done on how this relationship looks in other types of political and economic systems (PESs), such as socialist one-party or monarchical autocracies. As a result, there is limited research that tracks changes in PESs—in terms of transitions from one economic, political and social system to another and how these affect spatial planning and land use in relation

to tourism [3–5]. Existing research has, so far, failed to provide a coherent theoretical framework for studying changes in PESs.

Our analysis has far-reaching implications because it aims to show how changes in a PES represent structural breaks in the framework of spatial planning and land use that divert the development of economic sectors such as tourism from the path set in the past. While this opens opportunities for policy makers, investors and local communities to effect change, we also show that any transition presents significant challenges for key actors involved in implementation. Changes in a PES disrupt existing balances—political systems, territorial–administrative organization and laws change, which is a problem for public administration, investors and policy makers, as they must implement projects following the new rules of the game [6,7]. The closer the relationship between the new PES and political, economic and organizational institutions, the larger and more comprehensive the interruptions in the spatial planning system and the more they affect overall development.

For empirical data on the effects changes in a PES on spatial planning, we turn to contemporary Croatia—specifically, the Kupari tourist resort in the Dubrovnik region, located in Central and Southeastern Europe. The Kupari resort was conceived in the 1880s and, therefore, has a history spanning more than a century. During the 20th century, Central and Southeastern Europe witnessed several changes in the PES—the collapse of multinational empires; the formation of new monarchies and nation states; the rise of Nazism and socialism; and, finally, the introduction of capitalist democracies. These changes in the PES led to the transformation of socioeconomic and political paradigms, opening new paths of development and enacting new laws. Moreover, tourism had already become an important branch of the economy in modern Croatia during the period of Yugoslav socialism, and its importance increased further after Croatia became an independent democracy. The Dubrovnik area is world-famous for its UNESCO-protected medieval walls, and tourists from all over the world flock to visit it, ensuring that tourism receives priority treatment from politicians but also putting pressure on spatial planning and land use. Therefore, the case study of the Kupari resort in Southeastern Europe offers a suitable case to test how and why spatial planning in the tourism sector adapts to changes in the PES.

The aim of this paper is to investigate whether frequent changes in the PES affect the recovery and resilience of spatial planning for tourism and its institutions, as well as legislation, and whether such changes can disrupt the quality of the relationship between space and tourism.

Therefore, the article is structured as follows. Section 1 presents an introduction to the research. Section 2 refers to the theoretical framework and relevant literature. Section 3 refers to the methodology and data. Section 4 refers to the impact of the PES on the development of the tourist resort of Kupari divided according to socioeconomic systems. Section 5 presents a discussion, and Section 6 draws conclusions and outlines directions for future research.

2. Theoretical Framework and Literature Review

In academic literature, spatial planning and land use are most often considered through their applications in practice [8]. Certain researchers consider land use planning and land use from the economic perspective, i.e., through a transaction-cost theory [9]. Given that land is a limited resource, the system of land use (policy, planning and use), in addition to being related to the economy and society (social justice, public goods and interest, personal integrity, etc.), is also related to environmental sustainability.

Although the comparison of spatial planning and land use concepts and systems of different countries is possible using planning decisions (planning concept, evaluation of the implementation, evaluation of the administration, etc.), it is not an easy process

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due to differences in historical, political, social and economic circumstances and a lack of multi-layered criteria for evaluation of land use implementation [10]. Even when a political system changes (but the economic system is kept—for example, capitalism), land use evaluation comparison is difficult because of a lack of multi-layered criteria [11]. This indicates that a rational yet flexible and fair implementation of spatial and land use planning requires, in practice, an understanding of the essence and purpose of the two [12].

Against this background, we research how spatial planning legislation and implementation change through time within the same geographical space. In doing so, we analyse legislation and its implementation. We rely on the theoretical framework of historical institutionalism, which suggests that, once established, institutional patterns tend to persist [13–15]. Once the PES changes, institutions tend to reproduce themselves, even when the intention of policy makers is to change them. Abrupt reforms occur as a result of so-called critical moments or shocks that destabilize the existing equilibrium. Reforms that occur between periods of critical moments can be characterized as gradual and incremental changes. According to historical institutionalism, reforms of spatial planning and land use policies depend on the historical path that led to the current state.

This approach has already been employed to study the intersection of politics, economy, spatial planning and land use policy across longer periods of time in various contexts. Petursson and Vedeld [16] showed that protected-area regimes represent the most enduring, path-dependent institutions, exemplifying continuity throughout major societal transformations while being conducive to the interest of political elites. Also focusing on nature conservation, Yakusheva [17] showed it was the legacy of pre-socialism, strengthened during the socialist period, that affected the management capacities of national parks in Poland and Slovakia. Land reforms and management approaches have been also found to be strongly embedded in structural conditions and global processes, driven by technological and economic drivers [10,18].

Building on this literature, we argue that PES changes represent important critical junctures, punctuating the establishing equilibria [14]. In the aftermath of a critical juncture, a PES is built on existing formal and informal institutions as institutional patterns continue their reproduction. We expect that spatial planning, land use and tourism institutions, once established, will exhibit a tendency to reproduce themselves. Our theoretical contribution focuses on the measurement of the effects of PES change. We hypothesize that PES changes result in opportunities for dramatic changes—the more drastic a PES change, the larger the changes in the systems of spatial planning and land use. However, despite even the most drastic PES changes, certain ideas and structures from earlier PESs will tend to reproduce, albeit adapted to the new conditions.

3. Methodology and Data

There is no research on the evolution of the Kupari resort across spatiotemporal evolution. To understand how PES changes affect this specific resort case, we collected data through archival research and the sources made available online by the Croatian Government on Kupari-related decisions and processes (Figures 1 and 2).

We fill this gap by researching how spatial planning and land use frameworks change across different PES types while focusing on the tourism sector. More specifically, we examine three different PES types—capitalist monarchical and socialist one-party autocracies and capitalist democracies. We do this to analyse spatial planning and changes in its implementation under a transition to a new political, social and economic system. In doing so, we rely on historical institutionalism as a theoretical framework, which allows us to analyse not just how spatial planning and land use were developed and implemented across different PESs but also how changes were implemented. We demonstrate that, as

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pathbreaking as they are, new institutions are never adopted in a vacuum—existing laws prevail until new laws can be made. New laws inevitably build on the existing laws and structural conditions (such as the level of economic development or education), which tend to persist through PES changes.

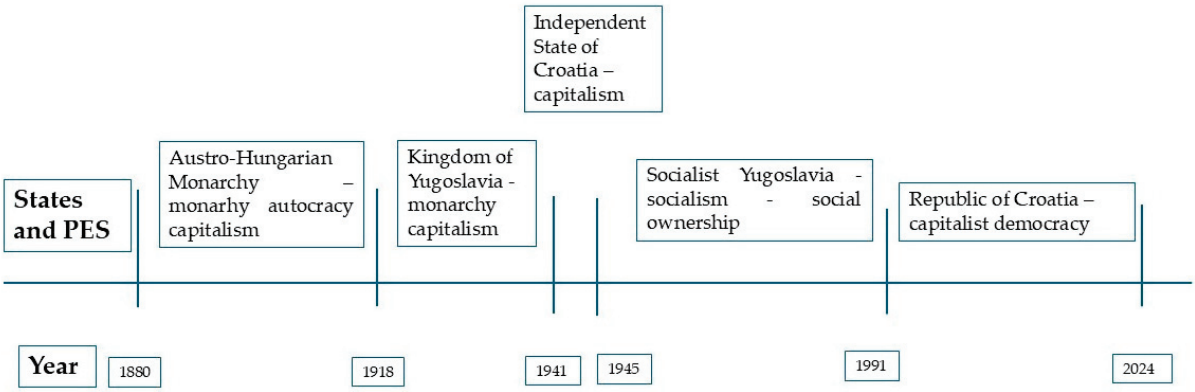


Figure 1. Spatiotemporal evolution and changes in political–economic systems that influenced the Kupari tourist resort.



Figure 2. Position of the Kupari tourist zone in Croatia near Dubrovnik and the eastern coast of the Adriatic Sea.

This article analyses three PES changes that occurred in the territory of modern-day Croatia—(1) the transition from the Austro-Hungarian Monarchy (capitalist monarchical autocracy) to the Kingdom of Yugoslavia (capitalist monarchical autocracy), (2) then to Yugoslavia (socialist one-party autocracy) and, finally, (3) to an independent Croatia (capitalist democracy). Our analysis covers the period between the end of the 19th century and the beginning of the 21st century—more specifically, 1880–2020. We track spatial planning and land use legislation in each of these four PESs and observe its implementation through a tourism prism across the three PES changes. We focus on the case study of Kupari, a tourism resort located in the southernmost part of modern-day Croatia. The Kupari

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resort is selected due to its long history, which allows us to trace how legislation and its implementation looked in practice across three PES changes.

For the earliest analysed PES (between the end of the 19th century and the end of the Second World War), to the best of our best knowledge, there are no existing studies on spatial planning and land use focusing on the territory of the Dubrovnik region or even modern-day Croatia. Therefore, our efforts to understand spatial planning and land use in that period represent pioneering efforts and are based on the analysis of the relevant laws and their implementation, as chronicled in the few existing publications depicting the era. For data, we relied mostly on archival materials—more specifically, on laws, different types of plans, blueprints and local newspapers.

In comparison, spatial planning in the tourism sector during the second PES change that we looked into, i.e., the transition to Yugoslav socialism, has received more academic attention [19,20]. There is scholarly agreement that Yugoslav planning efforts resulted in rather sustainable socialist tourism [21]. Socialist planning and tourism [22,23], as well as the transition from state socialism to capitalism [3,24–26], have also been increasingly studied. We rely on the extant secondary literature, as well as on legislation, to understand how the framework changed and was implemented.

The disintegration of Yugoslavia in 1991 marked the third PES change that we studied. In this era, a capitalist economic system and democracy as a political regime were established. The literature on spatial planning and tourism in Croatia largely focuses on efforts to ensure sustainable, long-term development, along with local community engagement, as contrasted by pressures for evermore tourism growth and profit [27,28]

However, very few papers have analysed how PES changes affect spatial planning in the tourism sector [3]. An exception is the literature on the transition from socialist one-party autocracies to capitalist democracies. This literature suggests a lack of clear rules of the game for private-sector initiatives in the tourism industry resulted in a rather chaotic so-called "wild" tourism, as evident in all formerly socialist European countries [4,5,29]. In addition, for earlier periods, sources are scarcer, making it harder to glean the effects of PES changes. Archaic language used in the earlier periods represents another distinct obstacle in assessing the effects of PES changes on spatial planning in tourism.

Our analytical approach is described as follows. For each of the three above-outlined PES changes, we investigate political, economic and territorial–administrative aspects. We then study what kind of legislative solutions marked each PES and investigate their implementation. To understand path dependency, we pay attention to issues inherited from the previous PESs that continued to permeate spatial planning, land use and tourism development after the change took place. Finally, we investigate how Kupari resort, specifically, was affected throughout these four PESs.

4. The Impact of PESs on the Development of the Tourist Resort of Kupari

4.1. Croatia in the Austro-Hungarian Monarchy

In the second half of the 19th century, modern-day Croatia was a part of the Austro-Hungarian Monarchy. More specifically, the Dubrovnik area, where Kupari is located, was then a part of the Kingdom of Dalmatia, the southernmost crownland of the Monarchy. Being on the border with the Ottoman Empire, Dalmatia was administratively mishandled and economically underdeveloped.[1] Towards the end of the 19th century, the Dalmatian economy suffered blows in two important sectors: winemaking and shipbuilding. Unemployment and emigration to overseas countries were high, and land prices were low—suitable conditions for speculation, investment and construction [31].

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It was also a period in which important structural and organizational changes took place in the entire Monarchy. Serfdom was abolished in 1848, and administrative preconditions for the functioning of a capitalist economy were put in place. By the end of the 19th century, the land register and cadastre were modernized (1881 for the area of modern-day Croatia); the civil engineering administration was reorganized; and new regulations with respect to land use, civil engineering titles, jurisdiction over the organization of new construction areas and the construction of public and private buildings were introduced [32]. Despite modernization, already in this period, there was a mismatch between the cadastre and land registries, as some land plots were not entered in the land registries. However, as few land transactions took place, the administration was sufficiently equipped to handle transactions within legally defined deadlines [33].

By the second half of the 19th century, tourism had already been well developed in the broader region of Central Europe. However, in the kingdom of Dalmatia, tourism was still in its infancy, and hotels existed only in the larger towns of Zadar, Split and Dubrovnik. It was at the end of the 19th century that interest in economic development of the southern Adriatic increased. Beyond existing and established destinations, investors looked for new, attractive and cheap locations [34,35].

These efforts were hindered by local governments; they were unprepared for investments and could not provide all the necessary technical infrastructure (water supply, drainage, electricity supply, etc.), and investors complained about difficulties accompanying their investments. There were not enough skilled construction or tourism workers in the area[2], and equipment had to be imported from more developed parts of the Monarchy [37].

Land use and construction in the Kingdom of Dalmatia were regulated through the Construction Act Construction Act 1886 [38]. The Act recognized residential, commercial (tourism would fall in this category) and public land use (roads, squares, parks, etc.). Sectoral plans for railways and roads were already being made, but regional spatial plans (with multisectoral planning in mind) did not exist yet. Land- and district-level political authorities oversaw the formation of new bathing sites in the maritime domain and the approval of new construction areas based on site plans that could be described as precursors of spatial plans.

Concentrated (vs. dispersed) construction represented a legal requirement with the purpose of saving land as a valuable resource. Each building plot needed access to a public road, rainwater drainage and water supply. Park and green areas were proscribed both on building plots and in public areas. If a larger cluster of new buildings was planned, a blueprint would have to accompany the project outline. The importance of public health was already recognized—exhaust gases and smoke could not be emitted directly towards an adjacent building.

Zooming in on Kupari, at the end of the 19th century, the area was an industrial site—more specifically, one of the largest brick factories in Dalmatia. However, in 1912, as the factory faced financial difficulties, Count Bernhard Caboga-Cerva, the factory owner, joined forces with Czech investors Jaroslav Fencl and Jan Máša, who bought neighbouring plots in Srebreno Bay and devised a new spa project [34,39]. In 1912, they founded the Dubrovnik Bathing and Hotels Company [40] and started preparing the necessary documentation for the development of a tourism resort in Kupari [39].

Following Article 15 of the Construction Act [38] and the site plans (which included a sketch of the geographical position of the area, as well as all land parcels and buildings and borders between parcels), the investors obtained approval from the district-level authorities for the development of a new tourist resort at the location of the existing brick exploitation field and a construction permit from the civil engineering administration, as well as a

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permit for the development of a bathing site from land-level authorities. However, WW I started, and investments in Kupari had to be postponed.

4.2. Between the World Wars

After the end of WW I, the Austro-Hungarian Monarchy disintegrated, and most of modern-day Croatia, including large parts of Dalmatia, became part of a newly formed Kingdom of Serbs, Croats and Slovenes soon renamed the Kingdom of Yugoslavia.[3] The new state encompassed areas that were previously parts of two empires (the Austro-Hungarian Monarchy and the Ottoman Empire), while the centre of power switched from Vienna to Belgrade. Three rounds of administrative reorganization took place in the following three decades,[4] affecting policy-making and implementation capacities [41]. These reorganizations affected spatial planning legislation and its implementation.

More precisely, it took 13 years for a new Construction Act [42] to come into force. Compared to legislation of the Austro-Hungarian era, which was specifically designed with Dalmatia in mind, this Act represented the norm for the entire territory of the Kingdom of Yugoslavia. It was more detailed and recognized more land use purposes, including streets, roads, squares, gardens, parks, playgrounds, cemeteries, fairs, infrastructure and airports.

However, the implications of this law for the case of Kupari could not be observed, as the construction of the resort preceded legislative efforts of the new PES. The plan to convert the factory into a tourist resort could not wait for the establishment of a new state apparatus and the adoption of new legislation. The investors pressured the local-level political authorities to allow them to continue developing the project based on the pre-WW I permits, so construction activities began immediately after the war ended, using the Austro-Hungarian legal framework from 1886 [39].

The former brick factory in Kupari immediately saw radical change in land use. In a short period of time, the space was transformed from a factory to an exclusive tourism resort. Specifically, main construction works included the demolition of some of the factory buildings and of a chimney, which were unsuitable for tourism purposes. The building once used for the baking of Mediterranean tiles was preserved as the core of the hotel complex and converted into the Grand Hotel (Figure 3). In 1921, a bathing cabin was built in the adjacent Srebreno Bay. Following the 1886 legislation, landscaping of green/park areas, as well as the construction of roads, a power plant, water supply, sewerage network and sports grounds, also took place. The resort was luxuriously equipped, and an air route for seaplanes from Prague to Dubrovnik via Zagreb was introduced in 1935/1936 to ameliorate the long journey of Czech tourists from Central Europe [43].



Figure 3. Kupari tourist resort through spatiotemporal evolution and the impact of PES changes on tourist spatial development (1880–2024).

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WW II interrupted the continuity of interwar tourism development in the whole territory of modern-day Croatia, deteriorating nearly all technical conditions and destroying the overall network of tourism organizations and institutions [44]. During the war years, most hotels were either closed or used for non-assigned purposes, due to which they were in a neglected, damaged and destroyed state at the end of the war [45]. Tourism activities at Kupari were also halted, while tourism contacts with foreign countries were severed.

4.3. From a Capitalist Monarchical Autocracy to a Socialist One-Party Autocracy

In this section, we analyse how the transition from a capitalist monarchical to a socialist one-party autocracy affected spatial planning, focusing particularly on tourism and the case study of Kupari. We divide this period into three sub-periods: first, the period in the immediate aftermath of WW II, where war damage and a lack of socialist legislation led to the hasty reconstruction of existing tourism capacities and the development of new ones to satisfy the vacationing needs of the working class; second, the period between the 1960s and 1970s, where continuously growing tourism demand resulted in increasingly more sophisticated spatial planning (data-driven and taking a broader, regional perspective into account) but also beset by the need to build ever more accommodation units; and, third, the decade of 1980s, where planning already considered health, the environment and public participation while the expansionist plans of the earlier periods started to be re-evaluated.

4.3.1. Early Post-War Period

The aftermath of WW II saw a drastic PES change—the monarchical regime was replaced by a single-party regime, private ownership was replaced by social ownership and central planning replaced a market-driven economy. Territorially, Yugoslavia was divided into six republics and two autonomous regions. As this organization significantly differed from the pre-WW II organization, the policymaking and implementation capacities were initially insufficient [46].

Numerical cadastral measurements were completed for larger towns, but land registries did not follow suit, which increased the mismatch between the cadastre and land registries [33]. In addition, updating of the land registries for the purpose of registering private property was neglected, as social ownership largely replaced private ownership [47].

Following the ideology of state socialism, newly founded hospitality companies were owned by the state, which ensured a steady flow of funds [48]. In these first post-war years, the tourism industry was established on ideological foundations based on the vacationing needs of the Yugoslav working class and guests from the so-called Eastern Bloc countries. To provide means of vacationing for the working class, the post-war construction restoration of the tourist industry in the territory of Croatia was carried out incompletely and unsystematically, and only the most necessary construction repairs were performed as part of the renovation itself. Construction renovation of hospitality facilities was mostly limited to hotels, boarding houses, holiday homes and resorts. The main goal was to set up as many accommodation units as possible—as soon as possible and with as few resources as possible—to meet the requirements of rapidly growing domestic tourism [44].

In the early post-WW II period, formal legislation adapted to the socialist principles of preparation and arrangement of construction land still did not exist, while the remediation of consequences of the ravages of war, as well as rapid modernization, led to intense and often uncoordinated construction throughout the country. Therefore, in 1947, the Institute of Urban Planning (IUP) of the Social Republic of Croatia was founded with the task of continuously studying and resolving the urban-planning issues of towns and settlements. The Institute would become an important and invaluable source of expertise, imbuing Yugoslav legislation with sophisticated spatial planning procedures [49].

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For the Kupari case, it was the Czech owners who renovated their hotels. In 1947, the first post-war tourists arrived in Kupari. However, following the Yugoslav break with the Soviet Union, political relations between Yugoslavia and other socialist countries were severed. As a result, Czechs withdrew from Kupari in 1948 [45]. In the same year, the Law on the Nationalization of Rental Buildings and Construction Land 1958 [50] was passed, which resulted in the liquidation of the private sector throughout the country, including the hospitality industry of the Dubrovnik Riviera. As a result, Kupari was declared a company of general national importance and fell under the administrative operational management of the Yugoslav People's Army (JNA) [48].

The Yugoslav break with the Soviet Union led to a period of transition to a new economic system of so-called socialist self-management. The main goal was to move the management of companies into the hands of workers and to separate management from the state. In the first half of 1950, the hospitality sector started maintaining itself by independently supplying necessary products through the free market [48].

At the same time, the country was swept by rapid processes of urbanisation, while tourism took on unexpected proportions, as manifested in a spontaneous albeit sharp surge in the number of tourist accommodation units, strong increases in domestic and foreign tourism trade and the growth of investment operations in tourism. It proved necessary to coordinate and plan the development of tourism and to develop plans that would consider the projection of long-term tourism development onto space [44]. However, spatial planning, as a discipline, had still not been systematized professionally or legally. The continuous efforts of urban planners to draft spatial plans and consider more professional and complex spatial-planning problematics, as well as considering specific questions from wider socio-political, economical, technical and design perspectives, prompted the IUP, in 1954–1956, to develop the Methodology of Regional Spatial Planning, a multi-disciplinary approach to drafting spatial plans [51].

However, the drafting of spatial plans and tourism development plans required the collection of data on the existing state of the coast from different perspectives. Therefore, in 1959, the development of the Methodology and Directions for Drafting a Long-Term Tourism Development Program 1959 [52] was initiated. This methodology provided an analysis of the existing spatial and technical tourism conditions and was supposed to "recognize" tourist areas to define the type and character of tourism, as well as the necessary tourism construction with the application of a spatial criterium. For the first time, the spatial-receptive conditions of tourism supply were analysed to determine the prospective potentials of tourism demand [21].

In the meantime, global tourism trends were rapidly changing. The abrupt development of the automotive industry and the construction of campsites influenced tourist mobility and spatial planning (indirectly). The guest structure was also changing; tourists were no longer only members of the working class, who were now joined by other domestic and foreign guests, who chose locations with more comfortable accommodation that offered contemporary content.

Since the accommodation units at Kupari no longer met such tourist needs and demands, the military management recognized the need not only for thorough reconstruction of existing hotels but also for overall spatial reconstruction of the tourist complex, with the aim of achieving better categorization, expanding the tourism offer and increasing in the number of arrivals.

Already in 1948, the first post-war urban-planning design was produced for Kupari, which planned thorough renovation and comprehensive spatial reconstruction of the existing tourist complex. However, this design never saw implementation. In 1958, a first large-scale post-WW II modernization program for Kupari was drafted, including accom-

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panying urban-planning and architectural designs for as many as seven new edifices [53]. These would then be implemented in the following period.

4.3.2. Spatial Planning and Tourism Boom in the 1960s and 1970s

The year 1961 was crucial for the drafting of municipal spatial plans aimed at enabling the connection of spatial and socio-economic plans at the level of local communities. The Urban Planning and Regional Spatial Planning Act [54] prescribed that towns, settlements, special-purpose areas and wider areas be built and arranged in accordance with the guidelines of regional and urban-planning spatial plans. The plans were supposed to be drafted in relation to the projected development of regions and settlements for an extended period of time (for a period of at least twenty years) based on the analysis of the current state and the possibilities of development of a settlement and its gravitational area and in accordance with the regional spatial plan and the principles of social and other plans influencing the spatial development of a particular settlement.[5]

The passing of the Act in question occurred when construction was already underway at Kupari. Several edifices were demolished; most remaining buildings were renovated, and new accommodation units were also built—Gorica Hotel (Goričina I), with a café and lounge bar, in 1962 and Pelegrin Hotel in 1963 (Figure 3). In 1964, directly alongside the entrance to the military resort, the construction of a third hotel began; however, construction was halted soon after the foundation had been laid and was never resumed [53]. Along with the struggle for better hotel categorization came the struggle to operate longer and to host guests year-round; in terms of the length of occupancy of the accommodation units, record holders were higher-category hotels, whose clientele were more serious and affluent [48].

On a small cape northwest of Kupari Valley, in the second half of the 1960s, a separate residential zone was formed for high-ranking government and military officials. Here, in 1966, the most luxurious hotel at Kupari was built—Galeb Hotel—near which two more meticulously planned residential villas of the highest category were built in 1988. Documentation of the hotel and the villas has been lost, and it remains unknown whether the construction of the zone was preceded by the drafting of an urban-planning design [53].

In the 1960s, a spatial database was gradually created, covering the area of the Croatian Adriatic. Tourism became a strategic development goal (on republic and federal levels) and began to be viewed as part of overall development at the local, regional, republic and federal levels [44]. Initiatives for the regulation of construction on the coast and coastal islands, prompted by the intense building of hotels and secondary accommodation facilities, the non-planned expansion of urban settlements, etc., enabled the drafting of a series of important studies and spatial plans. Head of production of all plans was the previously mentioned IUP. The key projects that were created in this period were part of a joint development programme of the United Nations and the Socialist Federal Republic of Yugoslavia (SFRJ) Government—the South Adriatic Regional Plan (1969) [55], the Upper Adriatic Regional Plan [56][6] and the Project of Protection of Human Environment of Yugoslavia's Adriatic Region [57]. The main guiding principle of these activities, alongside economic effects, was a desire to find a way to permanently preserve the values and attractions on which the tourism offer was based. Therefore, wherever space allowed, tourist accommodation capacities were planned and, in some places, implemented based on the principle of acceptable spatially decentralized concentrations alongside maximum preservation of the coastline [58].

Despite significant positive results achieved by the first spatial plans, the analysis of spatial and urban development from 1971 and beyond showed that the mastery over processes was falling significantly behind the country's socio-economic development, espe-

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cially regarding the concentration and distribution of the population and the workforce [49]. In 1973, the new Physical Planning and Land Use Act was passed [59]. In accordance with its provisions, spatial plans had to be based on the starting principles of social and economic development and on the data and analyses of the natural, historic, demographic, social, economic and technical components of space. The planning and arrangement of space was defined as a continuous activity and obligation of socio-political communities, which were obliged to monitor the process of urbanization and implementation of spatial arrangement plans and to conform them with the achieved degree and projected development dynamics, as well as newly emerging needs, possibilities and technical accomplishments.

A distinctive feature of the 1973 Act [59] was the introduction of the new term "spatial developmental plans". Specifically, while the implementation plans specified urbanist–technical and other prerequisites for the development, construction, reconstruction and recovery of areas encompassed by the urban plan, the developmental plans encompassed spatial plans of socio-political communities (municipalities, municipalities and republics). These plans had long-term directions and were drafted based on developmental assessment over the next 20 to 30 years. The Act also put emphasis on the drafting of a detailed plan for the use and purpose of the area and introduced an obligation to develop guidelines of protection and enhancement of the human environment, as well as public consultation and public discussion [49].

After the new constitutions of the SFRJ and Socialist Republic of Croatia had been passed in 1974, self-governing interest communities were established as new forms of social organization and planning.[7] This was a period of expansion, the growth of towns and grand ambitions. The plans were drafted multi-disciplinarily, while sectoral collaborations and projections, analyticity and the application of standards and models were intensified [45,53].

It is exactly these newly emerged circumstances that set up the framework of the second large-scale modernization of the military resort at Kupari.[8] Global tourism trends changed yet again, and the structure of accommodation capacities became unfavourable once more. Since the demand grew continuously, already in 1972, a decision was made on new construction, i.e., the enhancement of accommodation capacities and modernization [53]. What followed was a series of spatial-planning endeavours that were supposed to define an overall arrangement of the resort; however, it was not until the Implementation Urban Plan of the Sports, Recreation and Tourism Zone of Župa Dubrovačka—Kupari from 1976 [60] that clear urban-planning criteria and detailed guidelines of land arrangement and use were established.[9] The construction works—which also included the enhancement of the resort's technical equipment, as well as the arrangement of the beach, sports and recreational areas, children's playgrounds, parks and other horticultural areas—began in 1975[10] and proceeded in several stages until 1980 [62] (Arsenić 1989). The organization of the space of the Kupari Valley was conducted so that the construction of larger edifices was inhibited in intensely green areas, i.e., only the interpolation of smaller volumes for hospitality and entertainment purposes was permitted. The limitations on new construction especially referred to the areas of Goričina Hill in the northeast and Pelegrin Hill in the southwest, and the urban-planning concept positioned the new volumes peripherally in relation to the valley so that they followed the terrain's gradient, with account was taken of orientation, panoramas and traffic [62]. Only Kupari Hotel, constructed in 1975, deviated from this concept [53].

In the period of the second large-scale modernization, the previous manner of service provision at the resort also changed. Štrand Hotel, Grand's dependence and Villa Kisela were demolished, while Pelegrin Hotel was renovated and connected to the newly built Kupari Hotel with a connecting tract. The renovation of Grand Hotel was completed in

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1979, and the reconstruction of Gorica (Goričina I) began immediately after, as well as the construction of the new Goričina II Hotel in place of a demolished café and lounge bar.

4.3.3. Protection of Nature and Deflation of Expansionist Tourism Plans

The 1980s saw the reconsideration of earlier (more ambitious) planning concepts, the harmonizing of interests and the resolution of conflicts with progress towards the rational and real. After the passing of the Associated Labour Act 1976 [63], the Social Planning Act 1978 [64] and the Spatial Planning and Physical Planning Act (1980, 1986) [65], spatial planning became a constituent part of a unified system of social planning, i.e., a continuous activity that was based—at least in theory—on the results of scientific research and the monitoring of the state of development in space [53]. The spatial plans that were made based on the provisions of the 1980 Act—which was subsequently supplemented with the Regulation on the Content and Manner of Drafting Spatial Plans from 1985 and 1987—were made on the basis of topographic–cadastral backgrounds in two phases—as a basic concept and as a planned proposal. Both phases were subject to public consultation and discussion; prior to the municipal assembly, the implementation of the urban plan was also passed by the local community to which the plan refers. At the same time, tourism began to be increasingly associated with human well-being, as well as with care for the environment. In 1980, the Construction Land Act was passed [66], and the following year saw the passage of the new Law on Construction of Buildings [67].

However, neither of these acts reflected the system of arrangement and use of land at Kupari, where nothing had been constructed for a full decade at that point, save for the maintenance of the existing state. This leads us to the next phase of our analysis—the introduction of democracy and capitalism as Croatia proclaimed its independence from Yugoslavia.

4.4. From Socialism to Democracy and Capitalism

The Croatian war for independence began in March 1991. As armed conflicts started, the Croatian Parliament proclaimed the independence of Croatia from Yugoslavia in July 1991. In parallel with war events, a PES change—from a one-party autocracy to democracy and from socialism to capitalism—took place. War plunged a hole in tourism sector, but the PES change had more far-reaching consequences on political and economic structures and on spatial planning.

The transition from socialism, a system in which the means of production are owned by either the state or workers' associations, to a market economy meant that market logic would replace socially oriented planning efforts and that socially owned and managed tourism companies would largely have to be privatized. In fact, some of the hotel companies were privatized early on [68,69], but a significant portion, including former military bases and lavish tourism resorts, were left to decay and never put back to tourism use [30].

The success and the timing of tourism privatization can be explained by the damage tourism infrastructure suffered as a result of armed conflicts. In the conflict areas, some hotels were shelled. Elsewhere, resorts were used as temporary residences for refugees fleeing areas of intense conflict and, as a result, slowly decayed over the years [70]. Kupari belongs to the first group of tourism properties damaged during the war. Immediately after the Republic of Croatia proclaimed independence in 1991, the naval forces of the Yugoslav People's Army (JNA) began looting the Kupari property. This was the start of the destruction of the military resort, which continued in late 1991 and early 1992, when the resort was severely damaged by direct shelling.

In some cases, the putting of tourism infrastructure back to use was further complicated by transfers of control from the Yugoslav military to the civil state administration.

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Kupari resort, under the control of JNA during the period of socialism, illustrates this well—the resort was officially ceded to the Croatian state only in 2001 following the signing of the Yugoslav Agreement of Succession Issues. This meant that the changes to the PES delayed the development of the tourism sector as legal successors needed to be identified.

The functioning of the administrative apparatus changed as well. Primarily for political and ideological reasons, a new system of territorial organization was put in place. Tiny newly introduced municipalities became the lowest organizational units. Due to this organizational fragmentation, municipalities often lacked administrative capacities for self-management, making policy implementation difficult. The existing spatial planning system was merely transplanted to the new territorial and administrative organization, making it compulsory for each of the small municipalities to develop spatial plans. Individual tourism projects often required interventions in both county- and municipal-level plans, and detailed, project-level urbanistic plans were frequently required. Therefore, the new administrative organization led to a multiplication of required planning documents, with reduced administrative capacities.

The transition to democracy and a market economy necessitated the adoption of new legislation in the field of spatial planning and tourism. A new law defining land use [71], considering the war and changes in the PES, was adopted very quickly. This was followed by laws prohibiting privatization in 1996 [72], encouraging tourist activities in 1996 [73] and taking care of the environment in 1994 [74]. In addition to hasty adoption, relevant legislation suffered from a lack of intersectoral cooperation and sometimes provided contradictory solutions. It was not always clear which office had what duties, obligations and roles, and as a result, competences and coordination mechanisms between different policy sectors remained vaguely defined, if at all [75].

Legislation was also subjected to frequent changes. The 1994 Physical Planning Act was amended four times in the first ten years of its implementation. In 2007, it was substituted with the Physical Planning and Building Act 2007 [76], which similarly went through six rounds of changes before it was replaced with a new piece of legislation. The Physical Planning Act of 2014 [77] went through five rounds of changes until 2023. These laws attempted to guard the spatial planning legacy inherited from Yugoslavia—carefully analysing where tourism development could take place to save land as a valuable resource—with a new market-oriented push for more urbanization as close as possible to the seaside and at the lowest possible cost.

A lack of clarity in the laws about who was in charge of which aspect of the policy and frequent amendments also affected efforts to get the Kupari resort back into operation. The project required a multi-sectoral approach for its implementation, including four ministries—the State Office for Management of State Property and the municipality Župa Dubrovačka (where Kupari resort is located)—that were to jointly oversee the realization of the project. Despite their best intentions, the lack of intersectoral cooperation (a direct consequence of PES change as the administrative bodies kept changing) represented an obstacle to project implementation.

Relevant legislation was also fragmentated between spatial planning, regional development and strategic planning. As each of these fields required separate documentation, fragmentation led to a multiplication of strategies, programs and plans at state, regional and local levels, creating additional tasks and administrative hurdles [75]. The type and number of planning documents needed for tourism projects varied depending on the type of project and its location, introducing another layer of complexity for public administration, political officials and investors to deal with.

Compared to the period of socialism, there was also a lack of long term-oriented planning, which further complicated the investment process. Rather than analysing how

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certain areas could best be used for economic and human development and developing spatial plans reflecting these ideas, the planning phase often became a formality to be completed after an investment was already conceptualized. Investors could come up with their ideas, and spatial plans would then be prepared to reflect these ideas. As a result, at times, the plans at the regional level would need to be changed to accommodate newly planned investments at the local level, while at several lower levels, operational plans had to be made from scratch, leading to lengthy and complex political and bureaucratic procedures [78].

The case of Kupari illustrates these issues well. The Kupari redevelopment project required the development of county and municipal spatial plans, as well as a more specific, detailed urbanistic plan. The process of adopting these plans was marred by difficulties—the development of the plan started in 2016 but also required conservation entry data, the collection of which was completed in 2019. In addition, in 2018, the municipality of Župa Dubrovačka [79] acknowledged a procedural error in setting up a public discussion. The process included securing a location permit and subsequent contracts for the use of state-owned real estate and maritime property.

The introduction of a new PES led to significant legislative and structural changes. However, the established system allowed for a combination of change and continuity. The newly established system took over basic elements of the socialist spatial planning system—spatial plans were developed based on existent spatial planning solutions inherited from the socialist period [75]. In some cases, spatial plans adopted during socialism were in power even a decade after the PES change took place [80].

Some issues already present in the previous periods continued to affect spatial planning and tourism after capitalism and democracy were introduced. One such important issue was a lack of a unified cadastre and land registers in which data on land parcels and buildings permanently present on the land or beneath its surface, as well as the special legal status of the land surface, would be interlinked with data on legal real property status. In practice, this meant that legal transactions pertaining to real property were often not recorded in land registers—only in the cadastre—causing legal insecurity, as the land registers did not display the accurate legal status of properties [81].

This was another issue reflected in the case of Kupari. In 2011, following a tourism boom in Croatia, Kupari emerged in political discourse during the 2011 electoral campaign. However, concession rights over Kupari could not be established as, according to Darko Lorencin 2015 [82], the minister in charge of the tourism portfolio, the geodetic data necessary for the formation of cadastre records and land registry entries were missing. The lack of up-to-date information on property rights over the cadastral parcels resulted in legal insecurity and prevented the offering of a concession covering the resort.

For tourism-related spatial planning, other important issues that required regulation included the possibility of the sale of tourism units within tourism zones; the use of forest and agricultural land, as well as cultural and maritime domains, for tourism purposes; the setting of criteria regarding the locations of tourism zones; and the multi-level nature of spatial planning. All these issues were a result of the transition from social to private ownership and efforts to protect land, as well as cultural and maritime domains, as valuable resources.

The Kupari project required solutions to multiple such issues stemming from legislative inconsistencies associated with the adoption of a new political and economic system based on existent socialist institutions. These included three types of inconsistencies in concession allocation and regarding conservation issues. First, the legislation regarding property rights over the land on which the resort is located (including the maritime domain) was lacking clarity. Staničić and Bogović [83] suggested the specific law defining

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concessions over the maritime domain remined unharmonized with the core Concessions Act 2017 [84], which led to case-by-case adjudications of which of the two laws should be applied. In the case of Kupari, a compromise solution was adopted, establishing property rights to the land in the state and municipal ownership through the right to build and the right of use for a period of 99 years. Second, Kupari resort includes the so-called maritime domain—including both a coastal part and a part on the sea. The Maritime Domain and Seaports Act 2003 [85] allowed for the allocation of concessions of national interest in the maritime domain for a period longer than 50 years only with the approval of the Croatian Parliament. Before offering a maritime domain for a concession for a period of 99 years, which that would ensure investors could get a return on their investment and be synchronized with the concession over Hotel Grand, it was necessary to ensure the approval of the Parliament. Third, issues related to the conservation of cultural domains arose. Hotel Grand, unlike other Kupari hotels, was under partial protection as a protected cultural heritage site. Therefore, any concession for the resort had to ensure its protection. In 2019, the Government of the Republic Croatia [86] decided it would be offered a 99-year-long concession under the condition of having the building renovated in the original style.

As a result of these issues, economic use of Kupari resort was "paused" in progress for over two decades. Once the conditions for allocation of concession were satisfied, a conceptual solution for a luxurious five-star resort was devised, showing that initial solutions devised by Czech investors at the beginning of the 20th century, reinforced by monarchical and socialist Yugoslav modernizations of the resort, would persist through the latest PES change.

In summary, the war resulted in significant damage to the resort, and military control over the resort complicated the ownership status. Once tourism took off again, the interest in putting it back into function also remerged. However, since 2011, Kupari has faced many issues resulting from the PES change. As a result of fragmented legislation, a lack of clear lines of responsibility and a lack of long-term planning before investment, a decade has passed, and the resort has neither been put in function nor has all documentation necessary for it been ensured. The following section summarizes the main arguments and outlines venues for future research.

5. Discussion

We analysed how PES changes affect spatial planning and land use in reference to the tourism sector. We focused on the territory of modern-day Croatia, using the case study of the Kupari tourism resort across four different PESs. Supporting the existing literature on path dependency [16,17], our analysis shows that formal and informal norms partially endure through PES changes. More specifically, the territory of modern-day Croatia has historically been characterized by an improvisational approach to spatial planning—plans follow investments rather than the other way around, as reflected in the case of the Kupari resort across all observed periods and PES changes. We also note that land use and planning have long-lasting effects—Kupari was conceptualized as an elite resort more than one hundred years ago and has, after four PES changes, maintained this same developmental vision. Most importantly, we show that the more drastic the PES change is, the more encompassing the changes in legislation and initial difficulties in implementation are.

Our contribution to the literature is a systematic analysis of the political, economic and territorial–administrative aspects of PES changes, followed by an overview of the aspects of path dependency—despite the changes, some important institutions and structural conditions tend to persist. We pay attention to how the adapted legislation reflected PES

https://doi.org/10.3390/land15010041

changes and path dependency. Finally, we describe how the case of Kupari exemplifies the patterns of change and continuity over a period of more than one hundred years.

Our analysis also delivers the following period specific findings. In the period of the Austro-Hungarian Monarchy, spatial planning and land use policies were just starting to develop. Tourism was also in its infancy. The first PES change we observed, from the Austro-Hungarian Monarchy to the Kingdom of Yugoslavia, led to slow and piecemeal changes in spatial planning—construction-related legislation persisted for a decade after the PES change, but once adapted, represented a step towards more detailed and better-defined spatial planning legislation.

With respect to socialism, our analysis showed a dramatic change. In the immediate aftermath of WW II, tourism spatial planning was marred by hasty repairs and the development of new capacities with the socialist ideology in mind—particularly the vacationing needs of the new working class. This was followed by an increase in demand for tourism-sector capacities, but better quality of tourism units became a relevant factor. As more data was collected to support the needs of better-quality spatial planning, mid-term regional plans were made, and local-level plans needed to follow these plans. In the last decade of socialism, planners started to slowly re-evaluate inflated tourism plans and showed a definite orientation to human health and environmental protection.

The Kupari development followed spatial planning and tourism trends in socialist Yugoslavia; initially, more hotels were built to host more visitors while keeping its status as a luxurious military resort; but then, a modernization phase transformed it into an area that demonstrated protection and smart use of the natural environment.

For the capitalist democracy PES, we focused on the effect the change in ownership of the means of production (from social to private ownership) had on spatial planning and tourism. We then emphasized how the need to adopt a new set of laws amidst a PES change led to a lack of intersectoral cooperation, frequent legislative changes, a lack of harmonization across policy fields and a lack of clear-cut borders in policy implementation competencies. Finally, we showed how some issues, such as the discord between land registers and the cadastre, which were inherited from the previous PESs, continued to affect spatial planning and tourism.

The results of the research on frequent changes in political–economic systems through spatiotemporal evolution are presented in Appendix A. For the example of the Kupari resort, continuity in the administration is visible, as well as how each regime change entailed new legislation (multiple sectors), as reflected in the tourist area. The results were analysed through the lens of continuity across regime changes, legislation and its application across PES changes, legislation and its effect, and the impact of PES changes on the Kupari tourist zone itself.

6. Conclusions

Focusing on the case of Kupari, we have shown how changes in the PES led to the cessation of the economic use of the resort despite its favourable geographical conditions and tourism heritage. Ownership problems, a lack of cross-sectoral cooperation and fragmented legislation, as well as insufficient administrative capacity at all levels of government, were direct consequences of changes in the PES and prevented the re-use of Kupari. However, some aspects of path dependence of use can still be observed, as luxury tourism remains the preferred development model for Kupari.

Key findings reveal that the recovery and resilience of tourism are closely tied to the stability of political and economic systems. Frequent changes in the PES (1) reduce the overall resilience of tourism and its institutions, (2) lead to recurring changes in legislation related to tourism spatial planning (e.g., ownership and land use) and (3) disrupt the

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positive correlation between space and tourism development. These frequent transitions are reflected in legislation, as well as in the challenges of negotiating compromises on issues closely linked to tourism and spatial management. We advocate for a stable political–economic system and the continuous, real-time monitoring of legislation and its spatial consequences. An integrated methodology for legislative monitoring, along with a spatial management framework, offers practical solutions for the sustainable management of tourist areas. These findings provide both scientific evidence and actionable strategies to better align legislation with tourism spatial planning resilience on the eastern coast of the Adriatic Sea.

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Abbreviations

The following abbreviations are used in this manuscript:

PES	Political and economic system
WW I	World War I
WW II	World War II
JNA	Jugoslavenska narodna armija/Yugoslav People's Army
SIZ	Self-governing interest community (so-called SIZ)
AH	Austro-Hungarian Monarchy
IUP	Institute of Urban Planning/Urbanistički institut
SFRJ	Socialist Federal Republic of Yugoslavia (SFRJ)

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Appendix A

Table A1. Challenges of political and economic system change.

PES Change	From AH Monarchy to Kingdom of Yugoslavia	To Socialism	To a Capitalist Democracy
Political change	Same type—from one monarchical autocracy to another.	New type of a political system—still an authoritarian regime, with monarchy as a ruler is replaced by single-party rule.	New type of a political system—single-party rule was replaced by a multi-party system with the introduction of democracy.
Economic change	Same type—capitalism.	New type of economic system—state and social ownership replaced private ownership, with a planned economy.	New type of economic system—private ownership dominates over social ownership and private interest towers over social interest in a market economy.
Administrative change	New territorial organization, as the centre of power shifted from Vienna to Belgrade. There were three administrative-territorial reforms.	Territorially largely the same but a new administrative organization.	New territorial organization, with much smaller local-level units.

Table A2. Continuity across regime changes.

PES Change	From AH Monarchy to Kingdom of Yugoslavia	To Socialist One-Party Autocracy	To a Capitalist Democracy
Path dependency	Issues regarding lack of suitable equipment and a qualified workforce persisted, and public administration still faced issues in providing infrastructure for tourism projects. Legislation took time to be adopted, and laws from the previous PES were in use a decade after the PES change. Investors pushed for informal solutions, permits from the AH Monarchy were used until administration could be reorganized. Legislation formally provided a relatively high level of consciousness regarding the need to save land as a valuable resource. Initial discord between the cadastre and land registries emerged.	Implementation capacities and education were initially poor, with equipment missing, but improvements occurred during the 1960s. Protection of land as a resource persisted among experts and in legislation, but implementation was haphazard—illegal construction spread.	Protection mechanisms aimed at preserving land as a valuable resource lapsed, but illegal construction persisted. Unharmonized cadastre and land registry books were inherited from the previous PES.
Change	As a result of administrative changes, an initial loss of implementation capacities occurred.	As a result of administrative changes, an initial loss of implementation capacities occurred. As a result of the new system of ownership, discord between the cadastre and land registries increased.	As a result of administrative changes, an initial loss of implementation capacities occurred.

Table A3. Legislation and its implementation across PES changes.

PES Change	From AH Monarchy to Kingdom of Yugoslavia	To Socialism	To a Capitalist Democracy
Legislation and its effect	One new, more sophisticated law adopted 13 years after the regime change referred to the whole territory of the Kingdom of Yugoslavia, not just the Dalmatia area. It recognized tourism as land use and spatial planning categories. Territorial and administrative shifts slowed down the adoption and implementation of legislation—administrative centres changed, slowing down the ability of the administration to provide infrastructure and permits.	Legislation referred specifically to Croatia as one of the socialist states within Yugoslavia. A plethora of carefully planned laws and regulations aimed at social interest was introduced: 1960s—sophisticated guidelines for the development of spatial plans and increasingly data-driven long-term planning; 1970s—spatial planning became all-encompassing, looking into broader, cross-regional territory and planning how the best use for the social interest; 1980s—orientation toward natural protection and care for the environment. Spatial planners imposed expertise over politics and played a decisive role in defining legislation allowing for the protection of land. This was because tourism was used to demonstrate the success of socialism. Due to a lack of importance of private ownership, mismatches between land registries and the cadastre increased.	Frequent changes in legislation and fragmentation across policy fields occurred in an attempt to simultaneously keep protection mechanisms established during the earlier period and to ensure the functioning of the market economy.

Table A4. The tourist resort of Kupari through different political regimes.

PES Change	From AH Monarchy to Kingdom of Yugoslavia	To Socialism	To a Capitalist Democracy
Kupari	Kupari was transformed from an industrial zone to a luxurious tourism resort. Permits and legislation from a previous PES were used for project implementation.	The resort was initially renovated by Czech owners but then nationalized and handed over to the Yugoslav military. Following the trends of the 1960s, the number and quality of capacities were increased, while attention was dedicated to careful integration of the natural environment and sparing use of land as a valuable resource. Kupari remained a luxury resort.	War damage, property rights issues, mismatches between land registries and the cadastre, legislative fragmentation and a lack of intersectoral cooperation put the resort out of use. Plans were made to redevelop Kupari as a luxury resort.

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Notes

1 At the beginning of the twentieth century, the Habsburg public administration was quite inefficient (e.g., the costs of collecting taxes in the Kingdom of Dalmatia exceeded the taxes collected) [30].
2 As documented by Leček [36], illiteracy rates in the Kingdom of Dalmatia were very high, and an educated workforce was lacking for all sectors of the economy.
3 After WW I, the Kingdom of Dalmatia initially joined the State of Slovenes, Croats and Serbs, later called the Kingdom of Yugoslavia.
4 From 1918 to 1922, the Kingdom kept the subdivisions of predecessor states. In 1922, a new territorial organization divided the country into thirty-three provinces. In 1929, a system of nine regions was implemented. In 1939, a single Region of Croatia was formed from two existing regions (and from sections of others) [41].
5 The Act prescribed the content of spatial plans, as well as the method and manner of their adoption.
6 The South Adriatic Regional Plan (1964–1968) covered the territory of several now former republics, from Croatia and Bosnia and Herzegovina to Montenegro to the Yugoslav–Albanian border. The General Urban Plan for the Dubrovnik area was adopted in 1969 on the basis of a series of studies and expert reports on the historical factors of development, as well as the natural and socio-economic characteristics of the Dubrovnik region [53].
7 After a certain spatial-planning document was passed, the self-governing interest communities (so-called SIZs) financed the equipment and arrangement of land.
8 Unlike other sectors, the army was very well organized, including for the entire army's vacation.
9 This plan was authored by the Town Planning Institute and foresaw the construction of another hotel in Srebreno Bay, as well as the construction of a third villa in the separate residential zone.
10 The Facilities Construction Act 1975 [61] was passed in the same year; however, its provisions were not applied to the construction of facilities within the military compound for the purposes of JNA.

References

1. Kytzia, S.; Walz, A.; Wegmann, M. How Can Tourism Use Land More Efficiently? A Model-Based Approach to Land-Use Efficiency for Tourist Destinations. *Tour. Manag.* **2011**, *32*, 629–640. [CrossRef]
2. Risteskia, M.; Kocevskia, J.; Arnaudov, K. Spatial Planning and Sustainable Tourism as Basis for Developing Competitive Tourist Destinations. *Procedia-Soc. Behav. Sci.* **2012**, *44*, 375–386. [CrossRef]
3. Bramwell, B.; Meyer, D. Power and Tourism Policy Relations in Transition. *Ann. Tour. Res.* **2007**, *34*, 766–788. [CrossRef]
4. Elliott, C.; Udovč, A. Nature Conservation and Spatial Planning in Slovenia: Continuity in Transition. *Land Use Policy* **2005**, *22*, 265–276. [CrossRef]
5. Williams, A.M.; Vladimir, B. *Tourism in Transition: Economic Change in Central Europe*; IBTauris: London, UK; New York, NY, USA, 2000.
6. Brooker, P. Authoritarian Regimes. In *Comparative Politics*; Oxford University Press: Oxford, UK, 2017. Available online: https://www.oxfordpoliticstrove.com/10.1093/hepl/9780198737421.001.0001/hepl-9780198737421-chapter-6 (accessed on 1 August 2025).
7. North, D. *Institutions, Institutional Change and Economic Performance*; Cambridge University Press: Cambridge, UK, 1990.
8. Hillier, J. *Shadows of Power: An Allegory of Prudence in Land-Use Planning*; Routledge: Oxfordshire, UK, 2002.
9. Alexander, E.R. Transaction-Cost Theory of Land Use Planning and Development Control. *Town Plan. Rev.* **2001**, *72*, 45–75. [CrossRef]
10. Rudbeck Jepsen, M.; Kuemmerle, T.; Müller, D.; Erb, K.; Verburg, P.H.; Haberl, H.; Vesterager, J.P.; Andrič, M.; Antrop, M.; Austrheim, G.; et al. Transitions in European Land-Management Regimes between 1800 and 2010. *Land Use Policy* **2015**, *49*, 53–64. [CrossRef]
11. Alexander, E.R.; Faludi, A. Planning and Plan Implementation: Notes on Evaluation Criteria. *Environ. Plan. B Plan. Des.* **1989**, *16*, 127–140. [CrossRef]
12. Thomas, D.; Minett, J.; Hopkins, S.; Hamnett, S.; Faludi, A.; Barrell, D. A Comparative Study of Local Planning and Development in the Netherlands and England. In *Flexibility and Commitment in Planning*, 1st ed.; Springer: Dordrecht, The Netherlands, 1983.
13. Capoccia, G.; Kelemen, R.D. The Study of Critical Junctures: Theory, Narrative, and Counterfactuals in Historical Institutionalism. *World Politics* **2007**, *59*, 341–369. [CrossRef]
14. Mahoney, J.; Thleen, K. Theory of Gradual Institutional Change. In *Explaining Institutional Change: Ambiguity, Agency, and Power*; Cambridge University Press: Cambridge, UK, 2010. [CrossRef]
15. Pierson, P. Increasing Returns, Path Dependence, and the Study of Politics. *Am. Political Sci. Rev.* **2000**, *94*, 251–267. [CrossRef]
16. Petursson, J.G.; Vedeld, P. The 'Nine Lives' of Protected Areas. A Historical-Institutional Analysis from the Transboundary Mt Elgon, Uganda and Kenya. *Land Use Policy* **2015**, *42*, 251–263. [CrossRef]

https://doi.org/10.3390/land15010041

17. Yakusheva, N. Managing Protected Areas in Central Eastern Europe: Between Path-Dependence and Europeanisation. *Land Use Policy* **2019**, *87*, 104036. [CrossRef]
18. Coral, C.; Bokelmann, W.; Bonatti, M.; Carcamo, R.; Sieber, S. Understanding Institutional Change Mechanisms for Land Use: Lessons from Ecuador's History. *Land Use Policy* **2021**, *108*, 105530. [CrossRef]
19. Andrić, N. Regionalni aspekti planiranja turizma. *Turizam* **1962**, *10*, 18–26.
20. Milić, B. Izrada prostornih planova za turistička područja. *Turizam* **1963**, *11*, 10–13.
21. Kranjčević, J.; Hajdinjak, S. Tourism Urbanization in Croatia. The Cases of Poreč in Istria and Makarska in Dalmatia. *Sudosteuropa* **2019**, *67*, 393–420. [CrossRef]
22. Bernhardt, C. Planning Urbanization and Urban Growth in the Socialist Period: The Case of East German New Towns, 1945–1989. *J. Urban Hist.* **2005**, *32*, 104–119. [CrossRef]
23. Drzewiecki, H.; French, R.A.; Ian Hamilton, F.E. (Eds.) The Socialist City: Spatial Structure and Urban Policy. *Town Plan. Rev.* **1980**, *51*, 3. [CrossRef]
24. Hall, D.R. Tourism Change in Central and Eastern Europe. In *European Tourism: Regions, Spaces and Restructuring*; Montanari, A., Williams, A.M., Eds.; Wiley: Hoboken, NJ, USA, 1995; pp. 221–244.
25. Hall, D.R. Tourism Development and Sustainability Issues in Central and South-Eastern Europe. *Tour. Manag.* **1998**, *19*, 423–431. [CrossRef]
26. Hall, D. From 'bricklaying' to 'Bricolage': Transition and Tourism Development in Central and Eastern Europe. *Tour. Geogr.* **2008**, *10*, 410–428. [CrossRef]
27. Krtalić, V. *Uređenje Građevnog zemljišTa: Analiza Inozemnih Propisa: Prilozi za Moguće Oblikovanje Hrvatskih Propisa/Arrangement of Construction Land: Analysis of Foreign Regulations: Contributions to the Possible Design of Croatian Regulations/*; Ministarstvo Zaštite Okoliša i Prostornog Uređenja: Zagreb, Croatia, 2000.
28. Krtalić, V. *Planiranje Korištenja Zemljišta—Usporedba Načina i Sustava Planiranja u Nekim Državama Članicama EU i Republike Hrvatske/Land Use Planning—A Comparison of Planning Methods and Systems in Some EU Member States and the Republic of Croatia*; Novi Informator: Zagreb, Croatia, 2009.
29. Bachvarov, M. End of the Model? Tourism in Post-Communist Bulgaria. *Tour. Manag.* **1997**, *18*, 43–50. [CrossRef]
30. MacMillan, M. *The War That Ended Peace: How Europe Abandoned Peace for the First World War*; Profile Books: London, UK, 2013.
31. Kranjčević, J. Transformation of Space for Tourism—Between Desire and Reality. In *Myths of Tourism*; Čavlek, N., Ed.; Department of Tourism and Communication Studies, University of Zadar: Zadar, Croatia, 2013; pp. 199–214.
32. Smrekar, M. *Priručnik za Političku Upravnu Službu u Kraljevinah Hrvatskoj i Slavoniji*; Knjiga Treća: Zagreb, Croatia, 1902.
33. Butorac, D. Jedinstvena Evidencija o Nekretninama—Objedinjavanje Podataka Katastra Zemljišta i Podataka Zemljišne Knjige—Da ili ne? *Geod. List.* **2017**, *71*, 143–162.
34. Kranjčević, J. Tourism on the Croatian Adriatic Coast and World War I. *Acad. Tur.* **2019**, *12*, 41–53.
35. Piplović, S. Rad na gospodarskom unaprjeđenju Dalmacije na prijelazu 19. u 20. stoljeće. *Godišnjak Njemačke Narodnos. Zajed.* **2011**, *18*, 199–228.
36. Leček, S. Pokušaji smanjivanja nepismenosti u Banskoj Hrvatskoj početkom 20. stoljeća. *Rad. Zavoda Za Hrvat. Povij. Filoz. Fak. Sveučilišta U Zagreb.* **1993**, *26*, 123–150.
37. Kranjčević, J. *Zanemarena Baštine—Prostorne Strukture Sela*; Srednja Europa: Zagreb, Croatia, 2018.
38. Gradjevni Pravilnik. Regional Parliament of the Kingdom of Dalmatia. 1886. Available online: https://alex.onb.ac.at/cgi-content/alex?aid=lda&datum=1886&page=33&size=45 (accessed on 1 August 2025).
39. Rudolf, P. Dobro Došli Na Českom Jadranu. *MCP Vestn.* **2004**, *7*, 2–24.
40. Perić, I. *Razvitak Turizma u Dubrovniku i Okolici od Pojave Parobrodarstva do 1941. Godine*; Zavod za Povijesne Znanosti Istraživačkog Centra Jugoslavenske Akademije Znanosti i Umjetnosti u Dubrovniku: Dubrovnik, Croatia, 1983.
41. Hrženjak, J. Napomene o lokalnoj i regionalnoj samoupravi u Hrvatskoj. *Hrvat. I Komparat. Javna Uprava Časopis Za Teor. I Praksu Javne Uprave* **2009**, *9*, 999–1010.
42. Građevinski Zakonik. *Službene Novine Kraljevina Jugoslavija*; Službene Novine: Beograd, Serbia, 1931.
43. Barić, N. Railway Lines in the Coastal Belt of the Independent State of Croatia until the Fall of Kindom of Italy. *Časopis Za Suvremenu Povij.* **2019**, *51*, 879–908. [CrossRef]
44. Kranjčević, J. Turizam u prostornim planovima makarskog primorja. In *Zbornik Makarsko Primorje Danas*; Mustapić, M., Hrstić, I., Eds.; Institut Ivo Pilar: Makarska, Croatia, 2012; pp. 211–230.
45. Kobašić, A. Osamdeset godina organiziranog turizma u Župi dubrovačkoj. In *Zbornik Župe Dubrovačke*; Ćosić, S., Ed.; Svezak III: Općina Župa Dubrovačka, Croatia, 2000; pp. 160–187.
46. Kranjčević, J. Turističko i prostorno planiranje u Hrvatskoj i Jugoslaviji 1960-ih. *Časopis Za Suvremenu Povij.* **2021**, *53*, 1183–1207. [CrossRef]
47. Ivković, M.; Džapo, M.; Lasić, Z. Jedan od načina obnove evidencija vlasništva i nekretnina. In *Treći Hrvatski Kongres o Katastru s Međunarodnim Sudjelovanjem*; Nikolić, P., Ed.; Hrvatsko Geodetsko Društvo: Zagreb, Croatia, 2005; pp. 137–145.

https://doi.org/10.3390/land15010041

48. Mihić Lj, J. *Kupari Kod Dubrovnika—More, Klima, Vegetacija i Njihov Uticaj na Ljudski Organizam*; Vojno-Ugostiteljska Ustanova za Odmor i Rekreaciju "Kupari": Dubrovnik, Croatia, 1973.
49. Urbanistički Institut SR Hrvatske. *Urbanistički Institut SR Hrvatske 1947–1987*; Salaj, B., Ed.; Monografija; Urbanistički Institut SR Hrvatske: Zagreb, Croatia, 1988.
50. Narodne Novine (NN). *Zakon o Nacionalizaciji Najamnih Zgrada i Građevinskog Zemljišta (Sl 51/1958, 52/1958, 3/1959, 24/1959, 24/1961, 1/1963) [Nationalisation of Private Companies Act, Official Gazette 51/1958, 52/1958, 3/1959, 24/1959, 24/1961, 1/1963]*; Narodne Novine (NN): Zagreb, Croatia, 1958.
51. Petrović, B.; Žuljić, S. *Metodologija Regionalnog Planiranja Methodology of Regional Spatial Planning*; Urbanistički Institut Narodne Republike Hrvatske: Zagreb, Croatia, 1956.
52. *Metodologija i Uputstva za Izradu Dugoročnog Programa Razvitka Turizma. Primorska Turistička Područja*; Komisija za Turizam Odbora za Privredu Izvršnog Vijeća Sabora Narodne Republike Hrvatske: Zagreb, Croatia, 1959.
53. Benić, B.; Žunić, A. Turistički sklop nekadašnjega vojnog odmarališta u Kuparima. *Prostor* **2019**, *27*, 284–297. [CrossRef]
54. Narodne Novine (NN). *Zakon o Urbanističkom i Regionalnom Prostornom Planiranju, (Narodne Novine 21/1961) [Urban Planning and Regional Spatial Planning Act]*; Narodne Novine (NN): Zagreb, Croatia, 1961.
55. United Nations Development Programme. Regionalni Plan Južnog Jadrana/The South Adriatic Regional Plan. Vlada SFRJ Jugoslavije, Urbanistički Institut Sr Hrvatske, Republički Zavod za Urbanizam SR Crne Gore, Urbanistički Zavod SR Bosne i Hercegovine, Institut za Ekonomiku Turizma, MeđUnarodni Konzultativni Konzorcij Tekne Milano i Cekop Warszawa. Available online: https://books.google.co.jp/books/about/Regionalni_prostorni_plan_Ju%C5%BEnog_Jadran.html?id=0D9mnQAACAAJ&redir_esc=y (accessed on 1 August 2025).
56. United Nations Development Programme. *Koordinacioni Regionalni Prostorni Plan Gornjeg Jadran: Koordinacijski Regionalni Prostorski Načrt Gornjega Jadrana*; Projekt Gornji Jadran: Čiovo, Croatia, 1972.
57. Yugoslavia; UN; UNDP. *Project of Protection of Human Environment of Yugoslavia's Adriatic Region: Project Findings and Recommendations*; United Nations: New York, NY, USA, 1979; Available online: https://digitallibrary.un.org/record/17932?ln=en (accessed on 1 August 2025).
58. Petrović, B. Pojmovni okvir projekta Zaštita čovjekove sredine Jugoslavenske jadranske regije. *Turizam* **1973**, *21*, 2–4.
59. Narodne Novine (NN). *Zakon o Prostornom Uređenju I Korištenju Zemljišta (NN 14/1973) [Physical Planning and Land Use Act, Official Gazette 14/73]*; Narodne Novine (NN): Zagreb, Croatia, 1973.
60. Narodne Novine (NN). *Urbanistički Plan Sportsko Rekreacijske i Turističke Zone Župe Dubrovačke—Kupari. Dubrovnik, 1976 [Urban Plan of the Sports, Recreation and Tourism Zone of Župa Dubrovačka—Kupari, Dubrovnik, 1976]*; Narodne Novine (NN): Zagreb, Croatia, 1976.
61. Narodne Novine (NN). *Zakon o Izgradnji Objekata (NN 20/1975) [The Facilities Construction Act]*; Narodne Novine (NN): Zagreb, Croatia, 1975.
62. Arsenić, T. *Aspekti Programiranja Centra za Odmor i Rekreaciju Aktivnih Vojnih Lica*; Magistarski Rad, Sveučilište u Zagrebu: Zagreb, Croatia, 1989.
63. Ustava Socijalističke Republike Hrvatske. *Social Planning Act, Official Gazette, Official Gazette 40/1978 [Social Planning Act, Official Gazette, Official Gazette 40/1978]*; Predsjednik Predsjedništva SR Hrvatske: Zagreb, Croatia, 1990.
64. Narodne Novine (NN). *Zakon o Udruženom Radu (Službeni List SFRJ 53/1976) [Associated Labour Act, Official Gazette SFRJ 53/1976]*; Narodne Novine (NN): Zagreb, Croatia, 1976.
65. Narodne Novine (NN). *Zakon o Prostornom Planiranju i Uređivanju Prostora (NN 54/80, 16/86) [Spatial Planning and Physical Planning Act]*; Narodne Novine (NN): Zagreb, Croatia, 1980.
66. Narodne Novine (NN). *Zakon o Građevinskom Zemljištu (NN 54/1980) [Construction Land Act]*; Narodne Novine (NN): Zagreb, Croatia, 1980.
67. Narodne Novine (NN). *Zakon o Izgradnji Objekata (Official Gazette NN 52/1981) [Law on Construction of Buildings]*; Narodne Novine (NN): Zagreb, Croatia, 1981.
68. Bičanić, I. Privatization in Croatia. *East Eur. Politics Soc.* **1993**, *7*, 422–439. [CrossRef]
69. Franičević, V. Privatization in Croatia: Legacies and Context. *East. Eur. Econ.* **1999**, *37*, 5–54. [CrossRef]
70. Borić Poljanec, S. Privatizacija Hrvatske Hotelske Industrije: Reforma i Anomija. *Društvena Istraživanja* **2004**, *13*, 27–48.
71. Narodne Novine (NN). *Zakon o Prostornom Planiranju (NN 30/1994) [Physical Planning Act, Official Gazette 30/1994]*; Narodne Novine (NN): Zagreb, Croatia, 1994.
72. Narodne Novine (NN). *Zakon o Privatizaciji (NN 21/1996) [Laws, proscribing privatization Official Gazette 21/1996]*; Narodne Novine (NN): Zagreb, Croatia, 1996.
73. Narodne Novine (NN). *Zakon o Turističkoj Djelatnosti (NN 8/1986) [Law on Tourism Activities Official Gazette 8/1986]*; Narodne Novine (NN): Zagreb, Croatia, 1986.
74. Narodne Novine (NN). *Zakon o Zaštiti Okoliša (NN 82/1994) [Environmental Protection Act, Official Gazette 82/1994]*; Narodne Novine (NN): Zagreb, Croatia, 1994.

https://doi.org/10.3390/land15010041

75. Krtalić, V. Planiranje razvoja države, regionalno i lokalno planiranje. *Pravo I Porezi* **2019**, *28*, 18–27.
76. Narodne Novine (NN). *Zakon o Prostornom Planiranju i Izgradnji Objekata (NN 76/07) [Physical Planning and Building Act, Official Gazette NN 76/07]*; Narodne Novine (NN): Zagreb, Croatia, 2007.
77. Narodne Novine (NN). *Zakon o Prostornom Uređenju 2013 (NN 153/13, 65/17, 114/18, 39/19, 98/19, 67/23) [Physical Planning Act, Official Gazette 153/13, 65/17, 114/18, 39/19, 98/19, 67/23]*; Narodne Novine (NN): Zagreb, Croatia, 2013.
78. Hajdinjak, S. *When Bureaucrats Constrain the Grabbing Hand*; Central European University: Vienna, Austria, 2017.
79. Župa Dubrovačka Zaključak o Ispravci Tehničke Pogreške u Odluci o Donošenju Izmjena i Dopuna Prostornog Plana Uređenja Općine Župa Dubrovačka 2018 (Službeni Glasnik 2/2018). Available online: https://zupa-dubrovacka.hr/Dokumenti/SluzbeniGlasnik/SG_2018/Sluzbeni%20glasnik%2018-02.pdf (accessed on 1 August 2025).
80. Radeljak, P. Spatial Planning in the Area of Šibenik-Knin County Since the Second Half of the 20th Century. *Sociol. I Prost.* **2012**, *50*, 345–377. [CrossRef]
81. Kontrec, D. Land Registration System of the Republic of Croatia. 2010. Available online: https://www.elra.eu/land-registration-system-of-the-republic-of-croatia/ (accessed on 1 August 2025).
82. Lorencin, D. Kreće Zadnja Faza Velikog Projekta Kupari Upotpunjenog u Privlačan Investicijski Paket. 2015. Available online: https://vlada.gov.hr/vijesti/ministar-lorencin-krece-zadnja-faza-velikog-projekta-kupari-upotpunjenog-u-privlacan-investicijski-paket/16708 (accessed on 1 August 2025).
83. Staničić, F.; Bogović, M. koncesije na pomorskom dobru—Odnos zakona o koncesijama i zakona o pomorskom dobru i morskim lukama. *Prav. Vjesn.* **2017**, *33*, 73–104. [CrossRef]
84. Narodne Novine (NN). *Zakon o Koncesijama (NN 69/2017) [Concessions Act, Official Gazette 69/2017]*; Narodne Novine (NN): Zagreb, Croatia, 2017.
85. Narodne Novine (NN). *Zakon o Pomorskom Dobru i Morskim Lukama (NN 158/03) [The Maritime Domain and Seaports Act, Official Gazette 158/2003]*; Narodne Novine (NN): Zagreb, Croatia, 2003.
86. Odluka o Namjeri Davanja Koncesije za Realizaciju Turističkog Projekta Kupari. Vlada Republike Hrvatske Zagreb. 2019. Available online: https://mmpi.gov.hr/more/vijesti-337/vlada-rh-usvojena-odluka-o-namjeri-davanja-koncesije-za-realizaciju-turistickog-projekta-kupari/17492 (accessed on 1 August 2025).

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