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Special Issue Reprint

Feature Papers for Land Systems and Global Change Section

2nd Edition

Edited by
Le Yu, Xin Chen, Zhenrong Du and Pengyu Hao

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This is a reprint of the Special Issue, published open access by the journal *Land* (ISSN 2073-445X), freely accessible at: https://www.mdpi.com/journal/land/special_issues/DN6N54893G.

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

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

ISBN 978-3-7258-6306-8 (Hbk)
ISBN 978-3-7258-6307-5 (PDF)
https://doi.org/10.3390/books978-3-7258-6307-5

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Article

Spatiotemporal Evolution and Driving Mechanisms of Urban Ecological Asset Utilization Efficiency from a "Technology-Scale-Structure" Perspective

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Abstract: This study focuses on Hohhot (the capital city of Inner Mongolia Autonomous Region, northern China), a representative arid-semi-arid town in northern China. Against the backdrop of concurrent rapid urbanization and ecological constraints, it undertakes a systematic investigation into the spatiotemporal evolution and driving mechanisms of ecological asset utilization efficiency, aiming to furnish scientific evidence for sustainable development in ecologically fragile urban areas. Employing a "technology-scale-structure" analytical framework and constructing an "input-output-benefit" evaluation system, this research integrates the super-efficiency slack-based measure (SBM) model with spatial analysis methodologies to conduct multidimensional assessments of ecological asset utilization efficiency across all administrative districts and counties from 2000 to 2020. Empirical results demonstrate an overall upward trajectory in Hohhot's ecological asset utilization efficiency, with comprehensive efficiency increasing from 1.132 in 2000 to 1.397 in 2020. However, pure technical efficiency and scale efficiency exhibit significant asynchrony, reflecting inherent tensions between technological advancement and scale expansion. Spatially, efficiency distribution manifests substantial spatial clustering and heterogeneity, with identified hotspots demonstrating temporal migration patterns. Peripheral counties exhibit distinct "technological isolation" phenomena and diseconomies of scale. Mechanism analysis reveals that industrial structure optimization constitutes the primary driver of efficiency enhancement, while the catalytic effects of economic development and governmental investment exhibit diminishing marginal returns. Urbanization maintains a moderate influence, transitioning from extensive spatial expansion toward intensive functional upgrading. This study recommends a synergistic enhancement of ecological asset utilization efficiency through strategic pathways, including the following: First, advancing green industrial transformation. Second, establishing regional technology-sharing platforms. Third, implementing systematic ecological compensation mechanisms. Fourth, adopting spatially differentiated governance approaches. These measures are projected to foster coordinated environmental and economic development. This research provides theoretical underpinnings and policy implications for urban ecological asset management in arid and semi-arid regions globally.

Keywords: ecological asset utilisation efficiency; spatial and temporal evolution; driving mechanism; Hohhot city

1. Introduction

Urban ecological assets represent the core components of urban ecosystems, providing essential material foundations and service functions for socioeconomic development and human well-being. Their utilization efficiency directly influences urban sustainability [1]. Recent accelerated urbanization has driven the rapid expansion of urban construction land, a prominent feature of China's land-use change [2]. Such expansion frequently occurs without orderly regulation, readily undermining ecosystem stability and service capacity [3]. China's economic development has entered a "new normal" phase, characterized by the "triple overlap" of (1) economic growth transition, (2) structural adjustment pains, (3) digestion of previous stimulus policies [4]. Within this context, resource and environmental constraints intensify significantly. Persistent reliance on traditional development pathways and entrenched conceptual paradigms necessitates urgent improvement in development quality and resource utilization efficiency [5].

Particularly in the arid and semi-arid regions of northern China, urban development encounters heightened ecological constraints. Taking Hohhot as a representative case, the region faces severe water scarcity and fragile ecosystems, where grassland degradation and soil erosion pose prominent environmental challenges. Concurrently, rapid urbanization progressively compresses ecological spaces, intensifying resource supply-demand imbalances and imposing significant constraints on regional ecological security and sustainable development. Consequently, research into the utilization efficiency of urban ecological assets within ecologically fragile regions possesses significant theoretical and practical urgency.

Research on the efficiency of urban ecological asset utilization constitutes a focal area within disciplines such as ecological economics, urban ecology, and sustainable development. This research aims to quantify the transformation efficiency between the supply capacity of urban ecosystems (ecological assets) and the actual services delivered for human well-being (utilization benefits). Its core objective is to identify strategies for maximizing socioeconomic benefits while minimizing ecological resource consumption and environmental impact, thereby propelling cities towards sustainable development [6–8].The conceptualisation of 'ecological assets' initially emphasized natural capital stocks (e.g., forest area, water resources, biodiversity) [9–11]. In recent decades, the focus has progressively shifted towards the dynamic flow and multidimensional value of ecosystem services. These services encompass provisioning services (e.g., food, water), regulating services (e.g., climate regulation, pollution purification), supporting services (e.g., soil formation), and cultural services (e.g., recreational tourism) [12,13]. This conceptual evolution underscores that the core value of ecological assets resides not merely in their static presence but fundamentally in their capacity to generate and deliver ecosystem services continuously.

Domestic research demonstrates strong policy-driven characteristics, being closely aligned with national strategies such as ecological civilization development, the dual carbon goals, new urbanization, and high-quality development [14–16]. Methodologically, energy-value analysis, ecological footprint assessment, material flow analysis, and geospatial technologies (including GIS, remote sensing, and satellite imagery) have been widely employed to map the spatial distribution of ecological assets and evaluate the alignment between ecosystem service supply and demand [17–20]. However, existing research predominantly focuses on humid eastern regions or basin scales, with limited systematic investigations conducted in arid and semi-arid urban areas, particularly the city of Hohhot. While studies within Inner Mongolia or the Yellow River basin have explored land-use changes, ecosystem service valuation, spatio-temporal evolution patterns, and driving factors, these investigations primarily emphasize ecological security assessments or single-

factor analyses [21–23]. Within Hohhot or comparable arid/semi-arid cities, three principal limitations persist: firstly, the absence of long-term dynamic efficiency evaluations; secondly, insufficient multi-scale analysis of driving mechanisms; and thirdly, inadequate depth in characterizing spatial heterogeneity and exploring its underlying mechanisms.

In contrast, international research prioritizes advancing theoretical frameworks and integrating interdisciplinary approaches. Applications of foundational theories—including ecosystem service assessment (MA, TEEB frameworks), urban metabolism theory, ecological economics, and sustainability science—demonstrate considerable maturity [24–26]. Furthermore, international scholars are pioneering the integration of diverse models (e.g., coupling ecosystem service assessments with economic models and land-use simulations), alongside leveraging big data analytics, artificial intelligence-driven forecasting, and multi-scenario simulation techniques [27,28]. Concurrently, research scales are becoming increasingly refined, with a growing emphasis on the efficiency of ecological asset allocation and environmental equity considerations at the neighbourhood and community levels [29–32].

In summary, recent domestic and international research has increasingly emphasized the need for systematic, comprehensive, and spatially explicit analyses, thereby fostering stronger interdisciplinary integration. Notable advances have been made, particularly in examining the interactions between ecological assets and socioeconomic factors. Nevertheless, ecological asset efficiency assessment continues to face persistent challenges, including inconsistent indicator systems and limited cross-study comparability. Moreover, investigations into the dynamic mechanisms governing utilization efficiency remain insufficiently developed.

To address these gaps, this study develops an analytical framework tailored to the ecological characteristics of Hohhot, integrating the "technology–scale–structure" perspective. We apply a super-efficiency SBM–DEA model to evaluate ecological asset utilization efficiency from 2000 to 2020. We employ global and local spatial autocorrelation techniques to characterize spatiotemporal patterns and identify key driving factors and their relative contributions using grey correlation analysis.

This work contributes by closing critical gaps in long-term assessment, multidimensional mechanism exploration, and spatial heterogeneity analysis in arid and semi-arid urban contexts. It provides a scientific basis for targeted ecological asset management, coordinated eco-economic development, and the formulation of sustainable regional policies.

The structure of this paper is as follows (Figure 1): The Section 2 outlines the study area, data sources, and analytical framework, including the super-efficiency SBM–DEA model, spatial autocorrelation methods, and grey relational analysis. Results detail the temporal dynamics and spatial differentiation of ecological asset utilization efficiency, elucidate its driving mechanisms, and highlight implications for ecological governance and policy. Discussion and Conclusions summarize the main findings, reflect on limitations, and propose directions for future research.

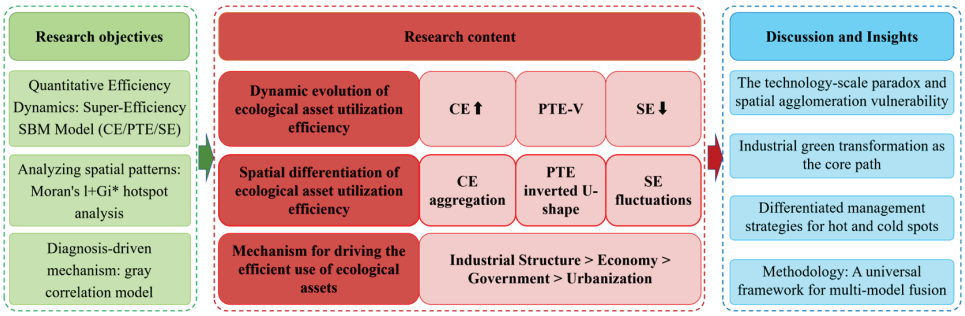


Figure 1. Flowchart of the research methodology. Note: CE, PTE, and SE denote comprehensive efficiency, pure technical efficiency, and scale efficiency within the urban ecological asset super-efficiency model, respectively.

The key contributions of this study are threefold: First, it provides a two-decade, county-level dynamic assessment and spatially explicit analysis of ecological asset utilization efficiency in an arid–semi-arid urban setting. Second, it establishes an integrated framework that couples the "technology–scale–structure" dimensions with spatial statistics and correlation analysis to identify multidimensional drivers systematically. Third, it offers differentiated, evidence-based policy recommendations, supplying actionable insights for ecological asset management and sustainable urban development in environmentally fragile regions.

2. Materials and Methods

2.1. Overview of the Study Area

Hohhot City (Figure 2) is situated in the western Inner Mongolia Plateau at the eastern terminus of the Yin Mountains. The region's topography is defined by the Daqingshan Mountains in the north, the Manhanshan Mountains in the southeast, and the Tumochuan Plain in the south, with elevations ranging from 875 to 2313 m and a general slope from northeast to southwest. The area has a temperate continental monsoon climate, characterized by mean annual temperatures of 2–6.7 °C and precipitation of 280–412 mm, increasing from north to south. Evaporation is highest from June to August, accentuating the region's pronounced aridity and water scarcity. Hydrologically, the area belongs to the Yellow River basin; its main rivers, including the Dahan and Hun, display strong seasonality and limited self-purification capacity. Hasu Lake, the largest freshwater body in the region (32 km^2), constitutes a critical habitat for migratory birds.

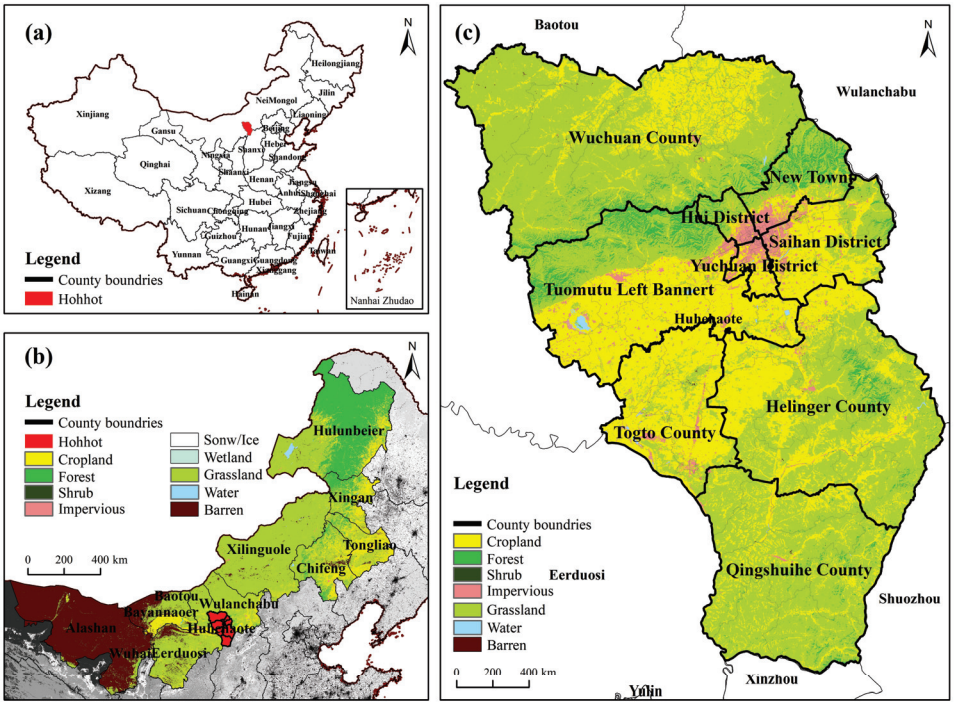


Figure 2. Map of the study area. Note: Geographical location of Hohhot in China (**a**); the land cover map of Inner Mongolia Autonomous Region and location of Hohhot in the region (**b**); and land-use types in Hohhot in 2020 (**c**).

In terms of ecological assets, Hohhot demonstrates both considerable natural endowments and marked vulnerabilities. Agricultural land dominates the land-use structure, accounting for 78.79% (with arable land comprising 43.31%), followed by woodland (23.68%, largely shrubland), grassland (18.54%, primarily natural grassland), and wetlands (1.03%, concentrated in the Hasu Wetland). Forest coverage is 21.4%, with a growing stock of

55.50 m^3/ha, reflecting relatively low vegetation carbon sequestration efficiency. Water scarcity is severe: per capita water availability is only 32.84 m^3, well below the regional average. Groundwater is heavily overexploited, covering 1031.84 km^2 with an annual overdraft of 38.92 million m^3. Mineral resources are dominated by niobium–tantalum and construction materials, mainly extracted using extensive methods with inadequate ecological restoration. Significant ecological challenges include soil erosion over 8207.63 km^2 (47.65% of the total area), driven by both wind and water processes; persistently poor water quality in the Dahan and Xiaohan Rivers (below Class V, primarily due to ammonia nitrogen and total phosphorus pollution); uneven distribution of urban green space, with tree-lined road coverage at only 67.15% compared to the national standard of 85%; and high ecological water consumption.

Socio-economically, Hohhot's GDP reached CNY 280.07 billion in 2020, with a tertiary-dominated industrial structure. The economy is led by the energy and dairy sectors, with energy consumption by large-scale industrial enterprises reaching 13.792 million tonnes of standard coal—well above the regional average. The urbanization rate stands at 70.5%. However, ecological efficiency is constrained by three interrelated challenges. First, regional disparities in pure technical efficiency persist, as peripheral counties (e.g., Tuoketuo) continue to lag in technological adoption. Second, construction land has expanded by 112% over the past two decades (from 547 km^2 to 1162 km^2), encroaching on ecological space and resulting in a decline in scale efficiency with an inverted V-shaped trajectory. Third, although industrial restructuring has become the primary driver of efficiency, energy-intensive industries still account for a substantial share, underscoring the urgent need for a more profound transition toward green development.

This regional overview provides a coherent framework that links ecological endowments, utilization conflicts, and socio-economic drivers, thereby laying the groundwork for subsequent dynamic assessments of ecological asset utilization efficiency and mechanism analysis.

2.2. Data Source

To ensure a comprehensive examination of the study area, this research draws on three main categories of data. (1) Socio-economic data were obtained from the *Hohhot Statistical Yearbooks* (2000, 2010, 2020), the *Inner Mongolia Statistical Yearbook*, the *Hohhot Hydrology and Environment* Bulletin, the *Hohhot Environmental Bulletin*, the *Hohhot Agricultural Economic Statistical Ledger*, and *Hohhot Territorial Spatial Planning*. (2) Geospatial data include land-use maps, elevation, slope, and aspect data for 2000, 2010, and 2020, derived from a Digital Elevation Model (DEM) provided by the Environmental Science Data Platform, Chinese Academy of Sciences (Environmental Science Data Platform Website: https://www.resdc.cn/). (3) Survey data were collected through multiple field investigations in Hohhot, supplemented by questionnaire surveys with local stakeholders and ecological experts familiar with the region.

To ensure data accuracy and reliability, all collected multivariate datasets underwent systematic pre-processing and quality control, comprising three key steps:

(1) Missing values: Isolated gaps in socio-economic data were corrected using time-series linear interpolation or averaging with adjacent counties/districts to preserve continuity. For geospatial datasets, gaps were addressed through cross-validation with remotely sensed image interpretation; records with >1% missing values were excluded.

(2) Outliers: Boxplot analysis was applied to detect anomalies across all indicators, with final assessments guided by Hohhot's local context. Values identified as statistical or entry errors were replaced with the corresponding annual mean or median.

(3) Standardization: To address differences in units, scales, and indicator orientations, all input–output variables and driving factors were normalized to the [0, 1] range using Min–Max normalization prior to DEA modelling and grey relational analysis. This ensured comparability and eliminated unit-dependent distortions. The normalization formula is the following:

$$R'_{ij} = \frac{R_{ij} - R_{j\min}}{R_{j\max} - R_{j\min}} \text{ (Positive indicator)}$$

$$R'_{ij} = \frac{R_{\max} - R_{ij}}{R_{j\max} - R_{j\min}} \text{ (Reverse indicator)}$$

In this formula, R'_{ij} denotes the normalized value of indicator j for City i; R_{ij} represents the observed value of indicator j for City i; and $R_{j\max}$ and $R_{j\min}$ correspond to the maximum and minimum values of indicator j, respectively.

(4) Data Reliability Assurance: Socio-economic data were primarily sourced from the *Hohhot Statistical Yearbook*, the *Inner Mongolia Statistical Yearbook*, and official bulletins and planning documents issued by government agencies, ensuring both authority and credibility. Geospatial datasets were derived from a Digital Elevation Model (DEM) and land-use remote sensing interpretations provided by the Computer Network Information Centre of the Chinese Academy of Sciences, with resolution and accuracy sufficient for mesoscale regional analysis. Critical datasets, including ecological land-use types and ecological asset valuations, were further validated using field surveys and expert interviews, enhancing the overall authenticity and reliability of the data.

2.3. Analytical Framework

(1) Selection of Evaluation Indicators for Urban Ecological Asset Utilization Efficiency

Drawing on ecological efficiency theory, urban ecological asset utilization efficiency is defined as the system-level transformation efficiency achieved through the combined deployment of ecological resources (e.g., land, water, and energy) and economic production factors (capital and labour). This efficiency reflects the synergistic optimization of both socio-economic outputs and ecological–environmental benefits. Its core attributes include the following: systemicity (coordinating the triadic relationship among resources, environment, and economy), dynamism (capturing spatiotemporal variations in factor allocation), and sustainability (incorporating ecological carrying capacity constraints). Accordingly, this study selects indicators that strike a balance between representativeness and data accessibility and constructs a Data Envelopment Analysis (DEA) framework encompassing both input and output dimensions. Input indicators include ecological resource inputs (e.g., ecological land area) and economic factor inputs (total fixed-asset investment, non-agricultural labour force). In contrast, output indicators cover economic outputs (e.g., value-added of secondary and tertiary industries, fiscal revenue) and ecological benefits (ecological asset value). This framework thus captures the dual objectives of economic growth and ecological conservation.

(2) Spatiotemporal Evolution Pattern Analysis Methodology

To examine the spatiotemporal dynamics of ecological asset utilization efficiency in Hohhot between 2000 and 2020, this study employs exploratory spatial data analysis (ESDA), integrating both global and local spatial autocorrelation metrics. The global Moran's I index quantifies overall spatial correlation, whereas the local Gi index* identifies spatial clusters, including hotspots and coldspots. This methodological approach minimizes

subjective bias and provides an objective depiction of agglomeration patterns and temporal evolution trends.

(3) Identification of Driving Factors and Mechanism Analysis

Multiple interacting factors, including urbanization, industrial structure, government regulation, and economic development, shape urban ecological asset utilization efficiency. Five key driving indicators are selected (Table 1): GDP per capita, share of secondary and tertiary industry output, fixed-asset investment per unit land area, fiscal revenue per unit land area, and urbanization rate. Grey relational analysis is then applied to assess the correlations between these factors and ecological efficiency across Hohhot's nine districts and counties for 2000, 2010, and 2020, thereby elucidating the principal driving mechanisms and their spatiotemporal evolution characteristics.

Table 1. Determinants of the utilization efficiency of urban ecological assets in Hohhot.

Independent Variable	Definition	Index Calculation	Type of Argument
Economic development level	GDP per capita	Total GDP/Total population	Continuous variable
	Per capita fiscal revenue	Total fiscal revenue/Area of urban ecological land	Continuous variable
Industrial structure level	The proportion of the output value of the secondary and tertiary industries	The output value of the secondary and tertiary industries/the total GDP	Continuous variable
Macro-regulation by the government	Fixed-asset investment per area	Total fixed-asset investment/urban ecological land area	Continuous variable
Urbanization level	The urbanization rate	Total non-agricultural population/Total population	Continuous variable

2.4. Methods

(1) Super-SBM Model Based on Data Envelopment Analysis [33]

This study adopts a nonparametric Data Envelopment Analysis (DEA) framework to evaluate the efficiency of urban ecological asset utilization. In particular, the super-efficiency Slack-Based Measure (Super-SBM) model is applied to calculate relative efficiency scores—comprehensive efficiency, pure technical efficiency, and scale efficiency—for each decision-making unit over the period 2000–2020.

The Super-SBM model effectively overcomes biases introduced by traditional radial and angular approaches, as it explicitly accounts for slack variables that capture both input redundancies and output shortfalls. To evaluate ecological asset efficiency across j regions, each inter-provincial region is treated as a distinct decision-making unit (DMU), with X_0 and Y_0 representing input and output variables, respectively. Each DMU is characterized by m input variables and r output variables: X_{jm} denotes the total quantity of the m input variables in region j, and Y_{jr} represents the total quantity of the r output variables across j regions. The weighting variable λ_j links all efficient points to construct the efficiency frontier, enabling the assessment of economies of scale across regions. The model is formally specified as follows:

$$\min\rho = \frac{1 + \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{ik}}{1 - \frac{1}{s}\sum_{r=1}^{s} s_i^+ / y_{rk}}$$

When $\rho > 1$ or when $\rho = 1$ and $s^+ = s^- = 0$, the ecological efficiency of the city reaches a strong state; when $\rho = 1$ and $s^+ \neq s^- \neq 0$, the ecological efficiency of the city reaches a

weak state; when $\rho < 1$, the ecological efficiency of the city is in an ineffective state. The ecological efficiency of the city ρ is equal to the product of pure technological efficiency (PTE) and scale efficiency (SE):

$$\rho = PTE \times SE$$

This model rests on three key assumptions:

a. Variable Returns to Scale (VRS): Decision-making units (DMUs) are assumed not to operate at an optimal scale, and scale effects influence their efficiency. This reflects the reality of Hohhot's districts and counties, where developmental stages vary and pronounced scale differences exist. Accordingly, a VRS-based model is more appropriate.

b. Input Orientation: Given the stringent ecological constraints in the study area—particularly regarding water resources and ecological land-use—the model assumes minimisation of inputs for a given output level. This orientation captures the potential for conserving ecological resources while maintaining current production levels.

c. Non-radial and Non-angular Specification: Unlike traditional DEA models, the SBM framework discards radial and angular assumptions by directly incorporating slack variables for input surpluses and output shortfalls. This formulation provides a more accurate representation of efficiency, particularly in contexts where undesirable outputs are present.

Based on these assumptions, this study applies the super-efficiency Slack-Based Measure (Super-SBM) model, implemented in MaxDEA, to estimate the comprehensive efficiency, pure technical efficiency, and scale efficiency of urban ecological asset utilization in Hohhot (Table 2). Spatial patterns of efficiency are subsequently examined using the spatial analysis module of ArcGIS 10.4.

Table 2. Ecological asset utilization efficiency and related explanations.

Ecological Asset Utilization Efficiency	Conceptual Connotation
Comprehensive efficiency	Eco-efficiency represents a holistic metric for evaluating the resource allocation and utilization efficiency of decision-making units. Mathematically, eco-efficiency can be expressed as the product of pure technical efficiency multiplied by scale efficiency.
Pure technical efficiency	Pure technical efficiency refers to the productive efficiency of a decision-making unit under managerial and technological constraints. In this study, it specifically denotes the capability to achieve maximal economic output while minimizing undesirable environmental outputs, given the resource inputs of each research unit.
Scale efficiency	Scale efficiency refers to production efficiency influenced by factors including the scale of decision-making units. In this study, this concept specifically denotes a city's capacity to maximize output through resource allocation and collaboration with other administrative units.

(2) Exploratory spatial analyses [34]

a. The global Moran's I index quantifies the degree of spatial autocorrelation, capturing both the similarity of neighbouring units and the extent to which adjacent regions exhibit comparable attribute values. It provides a statistical measure of spatial cluster-

ing or dispersion across the study area. The global Moran's I is calculated using the following formula:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{S^2\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}}$$

In the formula, n represents the total number of spatial units in the study area; X_i and X_j denote the observed values of units i and, j respectively; W_{ij} is the element of the spatial weight matrix, assigned 1 for adjacent units and 0 otherwise; S^2 corresponds to the variance of the observed values; and $\overline{X}$ represents their mean.

b. **Hotspot Analysis** G_i^* **Index** is used to identify clusters of high (hotspots) and low (coldspots) values across spatial regions, thereby capturing patterns of local spatial autocorrelation. Its formula is given as follows:

$$G_i^*(d) = \sum_{i=1}^{n} W_{ij}(d)X_j / \sum_{i=1}^{n} X_j$$

In the formula, W_{ij} denotes the spatial weight matrix, where adjacent units are assigned a value of 1 and non-adjacent units 0. A significantly positive G_i^* indicates that the values surrounding unit i are relatively high, forming a hotspot, whereas a significantly negative G_i^* implies that the values around unit i are relatively low, forming a coldspot.

In this study, exploratory spatial analysis employs the **Queen's adjacency rule** to construct the spatial weight matrix. Two districts are considered spatially adjacent (assigned a value of 1) if they share a common boundary or vertex; otherwise, they are non-adjacent (assigned a value of 0). This approach is justified by the spatial configuration of Hohhot's districts and counties, which form contiguous geographical units where ecological and economic interactions—such as resource flows, pollution dispersion, and technology spillovers—are most likely to occur between directly neighbouring units. Compared with distance-threshold-based weight matrices, the adjacency rule more accurately captures the effects of geographical proximity while avoiding subjective bias from arbitrarily defined distance thresholds.

(3) Grey correlation analysis model [35]

Grey Relational Analysis (GRA), rooted in grey system theory, provides a quantitative approach for characterizing system dynamics. It evaluates the degree of association between factors by measuring their geometric similarity. The method is robust to variations in sample size, computationally straightforward, and widely applicable. The procedure consists of the following steps:

a. The analysis begins by defining the reference sequence X_{ij} and the comparison sequence X_{0j} (i = 1, 2, 3,. . ., m; j = 1, 2, 3, . . ., n).

b. Apply the initialization method to normalize both the reference and comparison sequences using the following formula:

$$X'_{ij} = \frac{X_{ij}}{X_i}$$

c. Calculate the grey correlation coefficients:

$$\delta = \frac{1}{n}\sum_{j=1}^{n} \frac{\min\limits_{i}\min\limits_{j}\left|X'_{0j} - X'_{ij}\right| + \mu \max\limits_{i}\max\limits_{j}\left|X'_{0j} - X'_{ij}\right|}{\left|X'_{0j} - X'_{ij}\right| + \mu \max\limits_{i}\max\limits_{j}\left|X'_{0j} - X'_{ij}\right|}$$

In the formula, $\min_i \min_j \left|X'_{0j} - X'_{ij}\right|$ and $\max_i \max_j \left|X'_{0j} - X'_{ij}\right|$ denote the minimum and maximum range values, respectively, and μ is the resolution coefficient, conventionally set to 0.5.

In this study, the exploratory spatial analysis employed the **Queen's adjacency rule** to construct the spatial weight matrix. Two districts are considered spatially adjacent (assigned a value of 1) if they share a common boundary or vertex; otherwise, they are non-adjacent (assigned a value of 0). This approach is justified by the spatial configuration of Hohhot's districts and counties, which form contiguous geographical units where ecological and economic interactions—such as resource flows, pollution dispersion, and technology spillovers—are most likely to occur between directly neighbouring units. Compared with distance-threshold-based weight matrices, the adjacency rule more accurately captures the effects of geographical proximity while avoiding subjective bias from arbitrarily defined distance thresholds.

3. Results

3.1. Evaluation Results of Urban Ecological Asset Utilization Efficiency in Hohhot City

This study applies a super-efficiency SBM model to evaluate comprehensive efficiency, pure technical efficiency, and scale efficiency of ecological asset utilization across Hohhot's districts and counties in 2000, 2010, and 2020, with results reported in Table 3. Between 2000 and 2020, ecological asset utilization efficiency exhibited distinct evolutionary patterns: a steady increase in overall efficiency, a V-shaped recovery in pure technical efficiency, and an inverted V-shaped decline in scale efficiency. These trends highlight the asynchronous development of different efficiency dimensions under the constraints of limited ecological resources.

Table 3. Hohhot ecological asset utilization efficiency (2000–2020).

Region Name	The Year 2000			The Year 2010			The Year 2020		
	Combined Efficiency	Pure Technical Efficiency	Scale Efficiency	Combined Efficiency	Pure Technical Efficiency	Scale Efficiency	Combined Efficiency	Pure Technical Efficiency	Scale Efficiency
Horinger County	1.195	6.096	0.196	1.280	1.971	0.650	1.122	1.847	0.607
Hui Min District	1.223	7.072	0.173	1.137	1.284	0.886	2.376	3.018	0.787
Qingshuihe County	1.268	1.391	0.912	2.577	2.671	0.965	1.558	2.295	0.679
Saihan District	1.060	1.140	0.929	1.302	1.305	0.998	1.084	1.679	0.646
Tuomute Zuo Banner	1.117	1.279	0.873	1.369	2.616	0.523	1.495	7.930	0.189
Tuoketuo County	1.235	1.242	0.994	1.686	1.711	0.985	0.562	0.935	0.601
Wuchuan County	1.029	1.309	0.786	1.209	1.319	0.917	1.445	1.484	0.974
Xincheng District	1.325	1.241	1.068	1.291	1.158	1.115	1.872	3.692	0.507
Yuquan District	0.738	1.162	0.635	0.861	1.087	0.791	1.058	1.266	0.835
Mean value of Hohhot	**1.132**	**2.437**	**0.730**	**1.412**	**1.680**	**0.870**	**1.397**	**2.683**	**0.647**

(1) Comprehensive Efficiency: Steady Improvement with Marked Spatial Variations

Between 2000 and 2020, Hohhot's comprehensive urban ecological asset utilization efficiency exhibited an overall upward trend, with the citywide average increasing from

1.132 to 1.39, representing a 23.4% gain. Efficiency peaked at 1.4124 in 2010 before slightly declining, yet remained above initial levels, indicating enhanced ecological–economic synergy and resilience. Spatially, significant divergence persists and appears to be widening, as Xincheng District, Qingshuihe County, and Huimin District consistently maintain high efficiency, reflecting strong ecological endowments and synergistic advantages in economic, technological, and scale factors. In typical years, roughly 88.9% of districts and counties achieved DEA efficiency, primarily including Helingeer County, Huimin District, Qingshuihe County, Saihan District, Tumed Left Banner, Tuoketuo County, Wuchuan County, and Xincheng District. Conversely, Yuquan District exhibits persistent inefficiency, while Tuoketuo County shows periodic inefficiency, dropping to 0.562 in 2020. These patterns reveal structural constraints, including rapid urbanization and industrial agglomeration, which squeeze ecological land-use and lead to misalignments between resource allocation and ecological carrying capacity. High-efficiency zones correlate with superior ecological endowments and factor synergies, whereas low-efficiency zones follow a chain of "extensive scale expansion → ecological displacement → efficiency decline." Enhancing efficiency in underperforming areas, therefore, requires replacing scale-driven expansion with factor efficiency and structural optimization. Implementing strict ecological land protection, promoting green technologies, and controlling industrial intensity can break the "expansion–squeeze–inefficiency" feedback loop, narrowing inter-county efficiency gaps while maintaining an upward trajectory.

(2) Pure Technical Efficiency: V-Shaped Recovery Reflects Technological and Managerial Gains

Pure technical efficiency follows a pronounced V-shaped trajectory. From 2000 to 2010, it declined by approximately 31.1%, suggesting that urban expansion and management practices during this period failed to convert inputs effectively, thereby suppressing ecological asset utilization efficiency. Between 2010 and 2020, efficiency rebounded sharply by 59.7%, with the 2020 average rising to 2.683, exceeding the 2000 level of 2.439. This reflects substantial improvements in technology application and management optimization, enhancing resource conversion efficiency. Early declines were closely linked to extensive urban expansion and lagging ecological management.

In contrast, the subsequent recovery benefited from sustained ecological governance, accelerated adoption of green technologies, and progressive management reforms. Notably, Tuoketuo County's pure technical efficiency remained below 1, illustrating an "island effect" in peripheral technology absorption and application, highlighting persistent spatial barriers to interregional technology diffusion. Addressing these challenges requires cross-county technology-sharing platforms, differentiated technology support, a "technical efficiency–ecological compensation" linkage, alignment of industrial green transformation with technological capacity, spatial optimization of technology investment, and strengthened monitoring and talent development. Such measures can transition pure technical efficiency from "isolated breakthroughs" to "holistic coordination," supporting the sustainable enhancement of ecological asset utilization.

(3) Scale Efficiency: Inverted V-Shaped Decline Indicates Diseconomies of Scale

Time-series analysis reveals an inverted V-shaped trajectory for scale efficiency. After peaking at 0.87 in 2010, scale efficiency declined to 0.647 by 2020, a 25.6% reduction. Newly developed urban districts exhibited scale efficiency above 1 in 2000 and 2010, indicating an optimal ecological–economic scale. By 2020, however, most districts and counties recorded scale efficiency below 0.65, reflecting increasing diseconomies of scale. This pattern closely parallels Hohhot's 112% expansion of construction land over two decades, indicating that rapid urban growth failed to yield proportional ecological–economic efficiency gains.

Instead, excessive development led to ecological fragmentation and exceeded the carrying capacity of urban ecosystems.

3.2. Analysis of the Spatial and Temporal Variability of the Utilization Efficiency of Urban Ecological Assets in Hohhot

(1) Spatial autocorrelation analysis (Global Moran's I)

The spatial distribution of ecological asset utilization efficiency in Hohhot exhibits pronounced agglomeration, shaped by the interplay of policy interventions, resource endowments, and regional economic development stages.

The global Moran's I index for comprehensive efficiency steadily increased from 0.049 in 2000 to 0.320 in 2020, reflecting a strengthening positive spatial correlation and increasingly distinct clustering of high- and low-efficiency zones (Table 4). This pattern mirrors the trends observed in other rapidly urbanizing regions of China, such as the Yangtze River Delta and Pearl River Delta. Early efficiency disparities were driven by variations in resource allocation and pilot policy programmes, while subsequent infrastructure improvements and regional integration reinforced spatial interconnections. As a representative of ecologically fragile northern China, Hohhot's intensifying efficiency clustering is closely associated with initiatives such as the "Ecological Barrier Construction" and the Western Development Strategy. The notable post-2010 rise in Moran's I (0.289 → 0.320) likely reflects coordinated development of the Hohhot–Baotou–Ordos urban cluster and implementation of ecological compensation mechanisms, which, while optimizing cross-regional resources, may have amplified core–periphery polarization.

Table 4. Global Moran's I Index for the utilization efficiency of ecological assets in Hohho, 2000, 2010, and 2020.

Indicator	Comprehensive Efficiency			Pure technical Efficiency			Scale Efficiency		
	2000	**2010**	**2020**	**2000**	**2010**	**2020**	**2000**	**2010**	**2020**
Moran's I	0.049	0.289	0.320	0.166	0.518	0.117	0.210	0.286	0.159
Z	3.28	16.27	9.84	5.29	15.69	3.84	6.58	8.80	5.07
Variance	0.00034	0.00034	0.00113	0.00113	0.00114	0.00113	0.00114	0.00114	0.00114

For pure technical efficiency, the global Moran's I follows an inverted U-shaped trajectory, progressing through intensification, peak, and decline phases (Table 4). This evolution reflects how technological policies and infrastructure upgrades initially amplified spatial unevenness and the phased nature of technology spillovers. Efficiency peaked in 2010, coinciding with the expansion of Hohhot's High-Tech Development Zone and the concentration of innovative city initiatives, which reinforced core area advantages (e.g., Xincheng and Saihan Districts) and generated technological agglomeration hotspots. By 2020, however, pure technical efficiency declined markedly, indicating that, while technological diffusion disrupted prior agglomeration structures, peripheral counties (e.g., Tuoketuo and Wuchuan) remained unable to assimilate core technologies. Constraints, including talent shortages, inadequate infrastructure, and weak innovation ecosystems, produced a "technological island" effect, demonstrating that ecological fragility and developmental lags exacerbate barriers to technology diffusion.

Scale efficiency exhibits an inverted V-shaped trajectory (Table 4), characterized by rapid enhancement, a peak, and subsequent decline, highlighting its sensitivity to policy interventions while revealing sustainability limits. The 2010 peak corresponded to urban construction expansion policies, particularly the "new district development + land finance" model, which concentrated capital in central areas and temporarily boosted scale efficiency. By 2020, however, scale efficiency had fallen below initial levels, reflecting that

extensive urban expansion had exceeded the ecological carrying capacity. Emerging challenges—including the over-extraction of water (averaging 38.92 million m^3 annually) and grassland degradation affecting 47.65% of the total area—have intensified diseconomies of scale, constraining sustainable urban ecological development.

(2) Hotspot analysis (Getis-Ord Gi*)

Based on local spatial autocorrelation analysis using the Gi* index, Hohhot's urban ecological asset utilization efficiency exhibited pronounced hotspot and coldspot dynamics from 2000 to 2020. These patterns, however, reflect more than a simple "strong south–weak north" gradient or northward hotspot migration; they emerge from the combined influence of regional economic development models, policy orientations, and resource endowments.

The evolution of pure technical efficiency hotspots illustrates both technology diffusion and a persistent "island effect" (Figure 3). In 2000, hotspots were primarily concentrated in Helingeer County and southern Wuchuan County, whereas coldspots clustered in central urban areas, including the Xincheng and Saihan Districts. This distribution corresponded to Hohhot's prevailing "peripheral resources–core consumption" development model: peripheral regions benefited from stronger ecological foundations and lower input intensity, generating high-efficiency zones. In contrast, core urban areas exhibited lower efficiency due to rapid urban expansion and extensive industrial activity. By 2010, hotspots shifted southward to Qingshuihe County and Tumed Left Banner, and coldspots expanded into the central and northern regions. This transition closely aligned with regional and national policies—particularly the "ecological resettlement and grassland restoration" programme implemented after 2008—which facilitated the adoption of technology and ecological restoration in southern areas, producing new hotspots. By 2020, however, hotspots had contracted substantially, with only Tumed Left Banner maintaining a stable high-efficiency zone. The dissolution of other hotspots indicates that, despite improvements in technological efficiency, diffusion remained limited, producing a pronounced "technological island effect." Compared to eastern coastal cities, Hohhot continues to struggle in sustaining technological efficiency clustering, highlighting the absence of scalable mechanisms for technology dissemination.

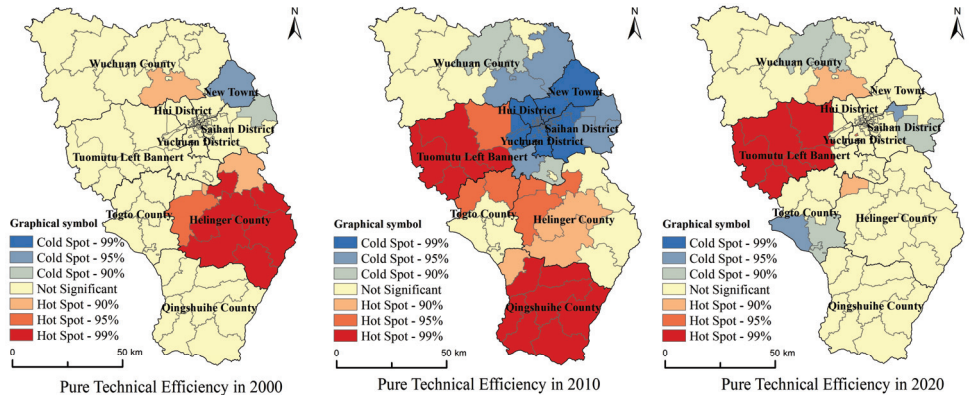


Figure 3. Hotspot analysis of pure technical efficiency of ecological assets in Hohhot city in 2000, 2010 and 2020.

The evolution of scale efficiency hotspots in Hohhot reveals alternating patterns of economies of scale and diseconomies of scale (Figure 4). In 2000, hotspots were concentrated in Xincheng and Saihan Districts, while coldspots clustered in Helingeer County, producing a "core advantage–peripheral inefficiency" pattern. By 2010, hotspots expanded further within Xincheng and Saihan Districts, reflecting the impacts of large-scale infrastructure development and new district expansion policies. By 2020, however, hotspots shifted

northward to Wuchuan County, and core urban areas experienced weakened or vanished scale efficiency. This trajectory suggests that initial expansion generated economies of scale; however, as urban land-use exceeded ecological carrying capacity, scale efficiency declined sharply, resulting in diseconomies of scale. Hohhot thus exemplifies an "expansion trap," where physical growth fails to enhance efficiency and instead precipitates decline due to constrained ecological space and structural industrial imbalances.

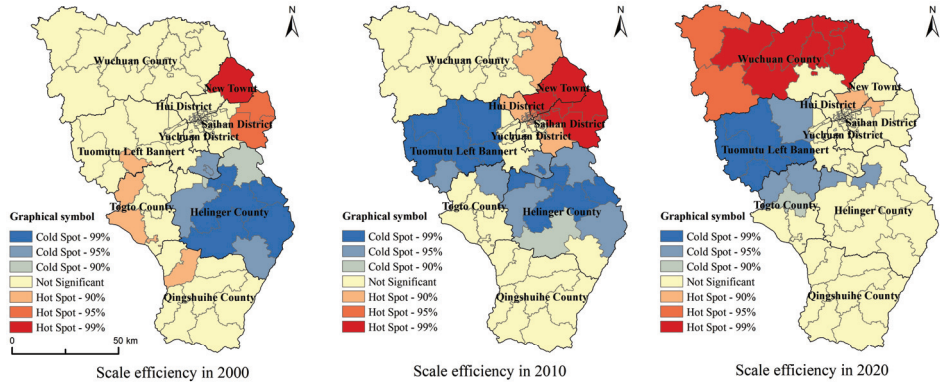


Figure 4. Hotspot analysis of the scale efficiency of urban ecological assets in Hohhot in 2000, 2010 and 2020.

The evolution of comprehensive efficiency hotspots in Hohhot demonstrates both synergistic effects and pronounced regional differentiation (Figure 5). Between 2000 and 2010, efficiency exhibited a stable "strong south–weak north" pattern, with the southern region gaining synergistic advantages through industrial upgrading and ecological restoration. By 2020, however, hotspots shifted markedly northward: former central coldspots became new high-efficiency zones, while southern advantages diminished. This spatial rebalancing reflects the dynamic interplay between ecological and economic factors. Synergistic effects in the south weakened due to overexploitation and population concentration. In contrast, northern regions benefited from policy interventions, such as the Grain-for-Green Program and poverty alleviation initiatives, as well as infrastructure improvements. The transition from a "single-core-driven" to a "multi-point balanced" development pattern aligns with theoretical expectations for ecological compensation and regionally balanced development in arid northern cities.

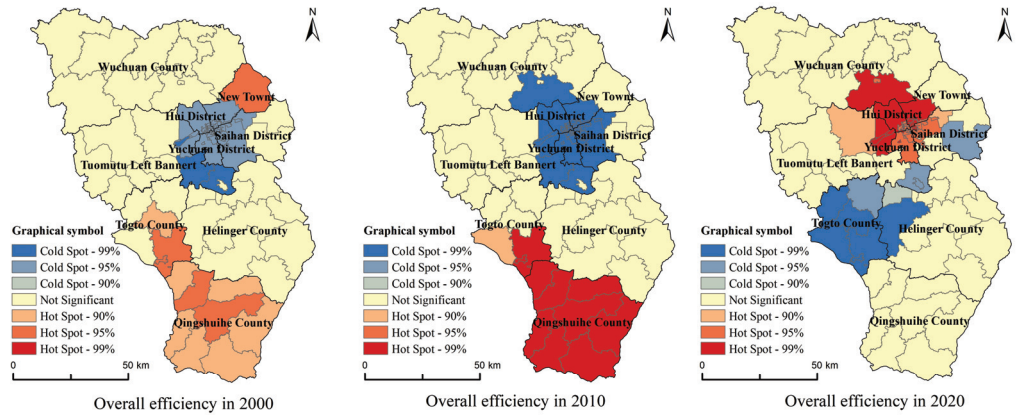


Figure 5. Hotspot analysis of comprehensive use efficiency of ecological assets in Hohhot in 2000, 2010 and 2020.

3.3. Analysis of Driving Factors for Changes in the Pattern of Utilization Efficiency of Hohhot's Urban Ecological Assets

Analysis of the spatiotemporal patterns of ecological asset utilization efficiency in Hohhot indicates that the complex interplay of multiple factors shapes its evolution. Prior studies suggest that urbanization directly affects the efficiency of ecological space allocation by altering land-use structures and landscape patterns. Economic development determines the intensity of factor inputs, thereby constraining the utilization of ecological assets. Optimization of industrial structure can enhance ecological efficiency by improving resource use and reducing environmental pressures. Meanwhile, market mechanisms and government regulation jointly influence resource allocation patterns. Additionally, China's demographic transition and the strategic shift in land policy from "incremental expansion" to "stock optimisation" provide a macro-level context for interpreting changes in ecological efficiency.

To identify key drivers, this study synthesizes existing research to construct a driver system centred on four core dimensions: economic development (per capita GDP, fiscal revenue per unit of land area), industrial structure (share of secondary and tertiary industries), government regulation (fixed-asset investment per unit of land area), and urbanization (urbanization rate). Grey relational analysis was applied to quantify the strength of each factor's association with ecological efficiency (Table 5). Results indicate that all factors exhibited correlation coefficients above 0.5 between 2000 and 2020, confirming the sustained influence of these variables and supporting the validity of the proposed driver model.

Table 5. Grey correlation degrees between driving factors and urban ecological asset utilization efficiency in 2000, 2010, and 2020.

Influence Factor	Driving Force Indicator	The Year 2000		The Year 2010		The Year 2020	
		Grey Relational Degree	Associated Level	Grey Relational Degree	Associated Level	Grey Relational Degree	Associated Level
Economic development level	Per capita GDP	0.786	Strong	0.799	Strong	0.667	Medium
	Per capita fiscal revenue	0.781	Strong	0.767	Strong	0.617	Medium
Industrial structure level	The proportion of the second and third output values	0.884	Strong	0.889	Strong	0.788	Strong
Governmental macroeconomic regulation and control	Fixed-asset investment per area	0.605	Medium	0.712	Medium	0.553	Medium
Urbanization level	Urbanization rate	0.600	Medium	0.680	Medium	0.660	Medium

Note: Grey relational coefficients are classified into three levels: weak [0, 0.35], moderate (0.35, 0.75), and strong (0.75, 1.00).

Temporally, the driving strength of each factor exhibits an overall declining trend (2000 > 2010 > 2020), reflecting a structural shift in the mechanisms influencing ecological efficiency as development stages and policy contexts evolve. Industrial structure consistently emerges as the strongest driver, indicating that increasing the share of secondary and, particularly, tertiary industries exert a stable positive effect on ecological efficiency. This finding aligns with Hohhot's emphasis on green and high-end industrial transformation and underscores the general role of industrial upgrading in promoting ecological efficiency.

In contrast, the influence of economic development has weakened significantly: correlations for per capita GDP and fiscal revenue per unit area declined from 0.786 and 0.781 to 0.667 and 0.617, respectively. This suggests that traditional scale-driven economic growth is

gradually giving way to high-quality development, a shift reinforced by post-2010 restrictions on energy-intensive industries under China's ecological civilization initiatives and dual-carbon goals. Similarly, government regulation has shown a limited and diminishing impact, indicating that reliance on investment expansion alone cannot sustainably enhance ecological efficiency and may even exacerbate diseconomies of scale. Urbanization exhibits an "initial rise–subsequent stabilization" pattern, remaining an important driver. However, its mode has shifted from extensive expansion to intensive upgrading, consistent with Hohhot's compact urban development and green infrastructure strategies.

In summary, Hohhot's ecological asset utilization efficiency has transitioned from a primarily "scale-driven" model to a synergistic "technology–scale–structure" paradigm. Future policy priorities should focus on industrial green transformation, optimization of investment structures, and enhancement of urbanization quality to achieve high-level ecological–economic coordination. To further investigate the spatial heterogeneity and evolution of these drivers, and to fully capture their spatiotemporal dynamics, the analyses below were conducted.

(1) Influence of government economic regulation on the utilization efficiency of urban ecological assets

Government economic regulations, reflected by the intensity of fixed-asset investment per unit of land, mediates ecological asset management. Grey relational analysis indicates that this factor maintains a moderate correlation with ecological efficiency. Although it experienced a temporary increase in 2010, driven by the Western Development Strategy and ecological compensation policies, its influence declined below initial levels by 2020, reflecting limited driving effectiveness and diminishing marginal returns.

The spatial distribution of fixed-asset investment per unit area evolved from a "northwest high–southeast low" pattern to a centralized cluster (Figure 6). In 2000, high-value zones were concentrated in ecologically fragile areas such as Wuchuan County and Tumed Left Banner, reflecting their reliance on government ecological infrastructure. By 2010, high-value areas expanded to central districts, including Huimin and Xincheng, consistent with capital concentration under the "land finance" and new district development models. By 2020, high-value zones had contracted again to central regions, such as Helingeer County and Huimin District, indicating a spatial shift in policy-responsive sensitive areas. Notably, regions with lower ecological efficiency, such as Tuoketuo County and Yuquan District, exhibited higher correlations with government investment, highlighting both the dependence on external funding and the urgent need for ecological restoration in underdeveloped areas. This also suggests that single-source capital investment, without complementary technical and managerial measures, struggles to sustain improvements in ecological efficiency.

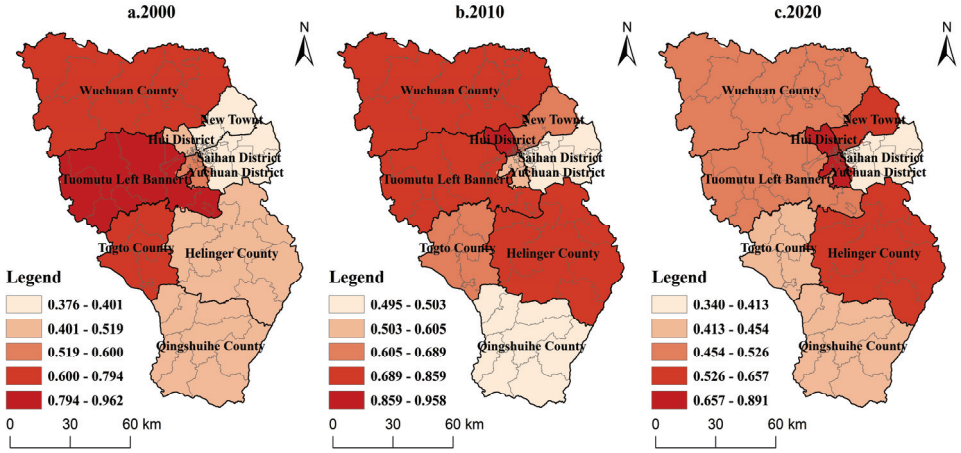


Figure 6. Distribution of grey correlation coefficients of land-averaged fixed-asset investment of eco-asset use efficiency in Hohhot city.

Government investment impacts ecological efficiency via dual pathways. Targeted investments in ecological infrastructure—for example, restoration projects in Qingshuihe County—directly enhance resource-intensive utilization. Conversely, extensive infrastructure expansion, such as road construction in new districts or industrial park development, can exacerbate ecological fragmentation and trigger diseconomies of scale. These findings suggest that regulatory strategies should shift from "scale expansion" to "structural optimisation," prioritizing green infrastructure and ecological technology deployment. Such an approach can mitigate diminishing returns while fostering synergistic gains in ecological benefits and capital allocation efficiency.

(2) Impact of economic development level on urban ecological asset utilization efficiency

Economic development, measured by per capita GDP and fiscal revenue per unit of land, exhibits a general weakening in its driving influence on ecological efficiency, reflecting Hohhot's gradual transition from a scale-oriented to a quality-oriented growth model. The correlation between per capita GDP and ecological efficiency has declined from strong to moderate. In contrast, the correlation with fiscal revenue per unit of land has decreased even more substantially, indicating the reduced impact of economic output per unit area on ecological outcomes.

High-value zones for per capita GDP have shifted spatially from resource-dependent counties, such as Tumed Left Banner and Tuoketuo County in 2000, to service-oriented core districts, including Huimin and Xincheng, by 2020 (Figure 7). This evolution mirrors Hohhot's industrial upgrading trajectory: early economic growth relied heavily on resource extraction and energy-intensive industries (e.g., Tuoketuo's thermal power cluster), which simultaneously expanded the economy and degraded ecological assets. In contrast, central urban districts have progressively decoupled economic growth from ecological impact through the development of service sectors such as finance and innovation. High-value areas of fiscal revenue per unit of land consistently align with ecological efficiency hotspots (Figure 8). For example, in 2020, Huimin and Saihan Districts—generating high fiscal revenues—also corresponded to high-efficiency ecological zones, confirming that economically concentrated areas with robust fiscal capacity can effectively support ecological management.

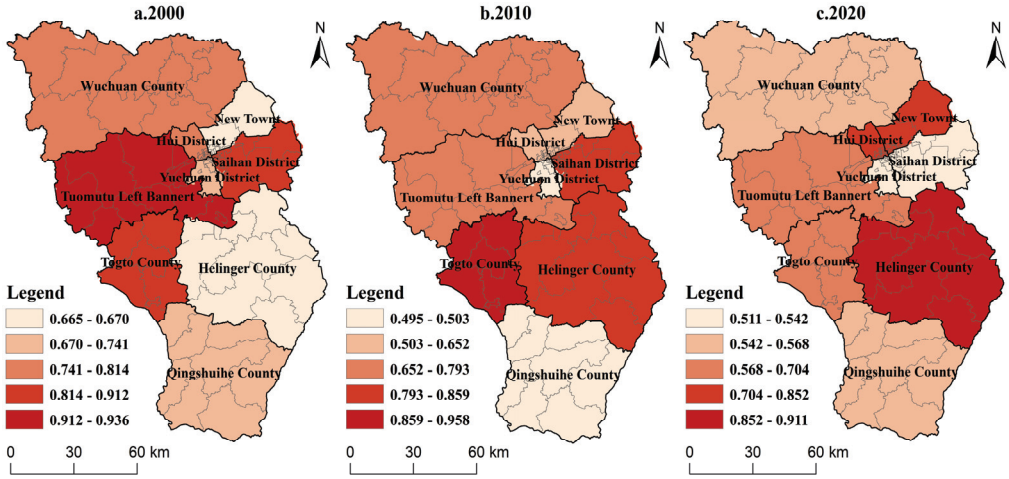


Figure 7. Distribution of grey correlation coefficients of per capita GDP of urban ecological asset use efficiency in Hohhot.

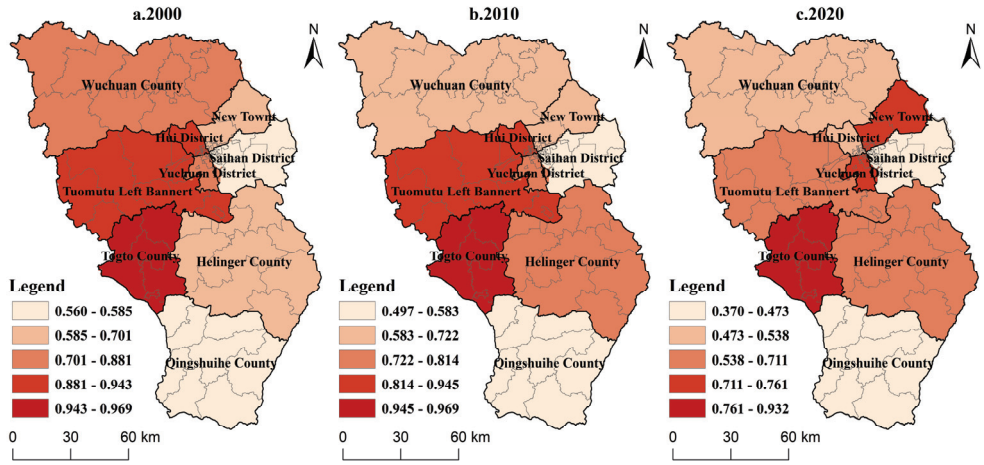


Figure 8. Distribution of grey correlation coefficients of land revenue per capita of Hohhot's ecological asset utilization efficiency.

Nevertheless, the overall decline in economic driver strength indicates that traditional GDP-focused growth models are insufficient to sustain improvements in ecological efficiency. In ecologically sensitive regions, such as Wuchuan and Qingshuihe Counties, continued reliance on resource extraction or energy-intensive industries risks exceeding ecological carrying capacities. Future development should prioritize a quality-driven economic pathway, leveraging green industrial innovation and ecological compensation mechanisms to achieve synergistic economic and ecological progress.

(3) Influence of industrial structure on the utilization efficiency of urban ecological assets

Industrial structure, measured by the share of secondary and tertiary industry value-added in GDP, emerged as the primary driver of urban ecological asset utilization efficiency, exhibiting the most stable and significant correlation from 2000 to 2020. Its influence shifted over time from an early "inverse suppression" effect to a consistent "positive promotion," confirming that industrial upgrading and optimization actively enhance ecological efficiency.

High-value zones of industrial structure–ecological efficiency correlation demonstrate pronounced spatial clustering. In 2000, these zones were scattered across regions such as Wuchuan County and Xincheng District; by 2020, they had consolidated into extensive clusters encompassing Huimin District, Yuquan District, Tuoketuo County, and others (Figure 9), largely overlapping with ecological efficiency hotspots. This pattern aligns with Hohhot's "industry in the south, tourism in the north" strategy: southern regions, including Tuoketuo and Helingeer Counties, improved ecological efficiency through industrial greening initiatives—such as wastewater recycling and clean production technologies—while northern areas, including Wuchuan and Qingshuihe Counties, enhanced ecological asset value via grassland eco-tourism and low-carbon agriculture.

Mechanistically, industrial structure enhances ecological efficiency through three main pathways: first, technological progress improves the utilization efficiency of ecological assets; second, capital and technology substitute for natural resource inputs, reducing ecological depletion; third, industrial agglomeration fosters circular economic development, optimizing the spatial allocation of ecological assets. Moving forward, Hohhot should further promote industrial greening and expand the ecological services sector, prioritizing the development of "ecology-plus" integrated industries and reinforcing the synergistic integration of industrial and ecological policies to achieve coordinated ecological–economic development.

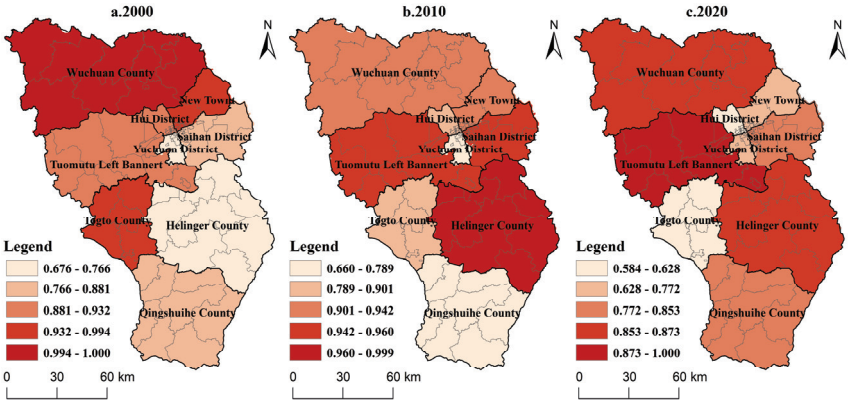


Figure 9. Distribution of grey correlation coefficients of industrial structure of eco-asset utilization efficiency in Hohhot city.

(4) The Impact of Urbanization Levels on the Utilization Efficiency of Urban Ecological Assets

The correlation between urbanization levels and ecological asset utilization efficiency has consistently remained moderate, following a pattern of "initial increase followed by stabilization." This reflects a transition in urbanization from extensive expansion toward quality-oriented development. The correlation peaked in 2010 (0.680), coinciding with a rapid phase of urbanization during which population concentration and land expansion for construction exerted significant pressure on ecological resources. By 2020, the correlation had declined slightly to 0.660, but remained above the 2000 levels, indicating that urbanization had entered a quality-driven phase, with compact urban construction and ecological restoration measures beginning to yield tangible benefits.

Spatially, high-value zones of the urbanization–ecological efficiency correlation evolved from northern regions to the south and finally to central areas (Figure 10). In 2010, low-value clusters emerged in the northeast, reflecting regional disparities during the period of rapid urban growth. By 2020, high-value zones were concentrated in central Hohhot, including Tuoketuo County, Helingeer County, Tumed Left Banner, Huimin District, and Xincheng District, forming a "high center–low north and south" spatial pattern closely aligned with ecological efficiency hotspots and coldspots. This evolution mirrors Hohhot's urbanization trajectory: early northern counties relied on ecological resettlement and village construction to drive urbanization but lacked industrial support, resulting in a co-occurrence of population growth and ecological degradation. In contrast, central urban areas later achieved synergistic development of urbanization and ecological efficiency through urban renewal and the deployment of green infrastructure.

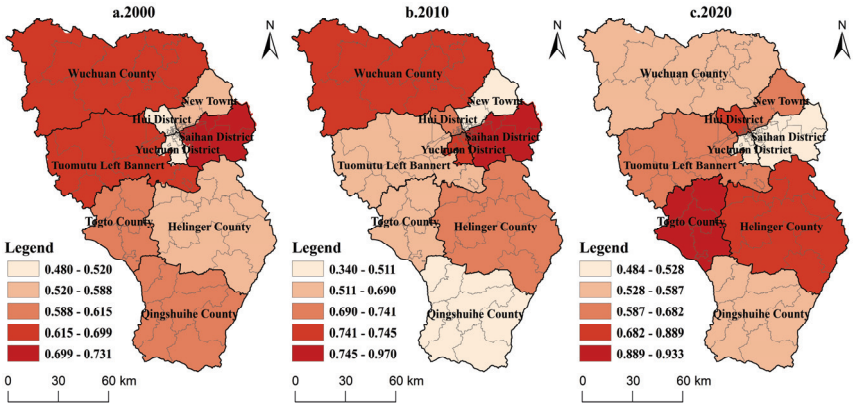


Figure 10. Distribution of grey correlation coefficients of urbanization rate of eco-asset utilization efficiency in Hohhot city.

Mechanistically, the initial urbanization phase involved extensive expansion that encroached on ecological space, producing significant diseconomies of scale. Subsequent stages effectively reversed efficiency losses by increasing development density, promoting mixed land-use, and implementing ecological restoration initiatives. Moving forward, the "compact city" development model should be maintained, with strict control over new construction land, to deepen coordination between urbanization and ecological conservation.

4. Discussion

Framed within the "technology-scale-structure" perspective, this study systematically examines the spatiotemporal evolution and driving mechanisms of urban ecological asset utilization efficiency in Hohhot between 2000 and 2020. Overall, comprehensive efficiency exhibited a sustained upward trend. Pure technical efficiency followed a V-shaped trajectory, initially declining before recovering, whereas scale efficiency displayed an inverted V-shaped pattern, rising before subsequently declining. Spatially, efficiency was markedly clustered and mobile, forming a distinct hotspot–coldspot structure. This "asynchronous-heterogeneous" evolution was particularly pronounced in arid and semi-arid regions characterized by limited ecological carrying capacity and strong resource constraints. Peripheral counties concurrently exhibited "technological enclaves" and scale diseconomies, reflecting the combined effects of barriers to technology diffusion and uncoordinated spatial expansion. Industrial structure optimization emerged as the most stable and decisive driver of efficiency gains.

In contrast, the marginal effects of economic growth and government investment diminished over time, while urbanization gradually shifted from extensive expansion toward intensive upgrading. These dynamics are consistent with the observed expansion of construction land from 547 km^2 to 1162 km^2 (a 112% increase) and the persistent dominance of energy-intensive industries, providing a coherent explanation for the inverted V-shaped evolution of scale efficiency under dual resource and spatial constraints. Meanwhile, the V-shaped recovery of pure technical efficiency closely corresponds to staged improvements in technology and management practices.

Based on these findings, the synergy mechanism of "technology-scale-structure" can be summarized as follows: technological progress acts as an endogenous driver, enhancing resource output efficiency; scale constraints, if overlooked during rapid construction, create a trade-off between short-term output gains and long-term efficiency losses; and structural upgrading sustains efficiency improvements by limiting energy-intensive industries and fostering green, service-oriented development. This mechanism not only systematically accounts for Hohhot's efficiency trajectory over the past two decades, but also provides a transferable framework for efficiency governance in arid and semi-arid urban clusters.

At the policy level, relying solely on expanded ecological investment is insufficient to sustain long-term efficiency gains. A multidimensional, systemic strategy is therefore required. First, accelerate the transformation of green industries to reduce path dependence on energy-intensive sectors. Second, establish cross-regional platforms for technology sharing and innovation diffusion to overcome the "technological isolation" of peripheral counties. Third, optimize fiscal expenditure by prioritizing investment in green infrastructure and ecological restoration. Fourth, implement spatially differentiated governance: enforce scale controls and ecological redlines in high-efficiency hotspots, while emphasizing technology empowerment and ecological compensation in low-efficiency coldspots to foster regional coordination and balanced efficiency improvements.

Despite rigorous methodological controls, several limitations of this study warrant careful consideration. First, the input-oriented super-efficiency SBM model has limited capacity to account for non-desired outputs. Second, grey correlation analysis is constrained

in capturing nonlinear interactions and lagged effects among multiple factors. Third, the county-level scale may obscure micro-level variations at the neighbourhood or community level, as well as potential environmental equity issues. Fourth, the findings are most directly applicable to arid and semi-arid cities; further validation is required for their application to other regions or highly industrialized urban contexts.

Future research could address these limitations by adopting network DEA or non-dominated sorting SBM models to differentiate dual outputs of economic gains versus environmental losses; integrating dynamic panel models or machine learning approaches to improve causal inference and predictive accuracy; leveraging remote sensing and social media data for more fine-grained neighbourhood-level analyses; and employing system dynamics or multi-agent simulations to assess the long-term impacts of policies under dual-carbon targets.

5. Conclusions

This study integrates the super-efficiency SBM model, global and local spatial autocorrelation analysis, and grey relational analysis to construct a multi-method evaluation framework. It systematically examines the spatiotemporal evolution and driving mechanisms of Hohhot's urban ecological asset utilization efficiency from 2000 to 2020, spanning both county and temporal scales. Key findings are as follows. First, comprehensive efficiency steadily increased from 1.132 in 2000 to 1.397 in 2020, yet exhibited pronounced spatial heterogeneity. Central urban areas and regions with favourable ecological endowments demonstrated higher efficiency, whereas peripheral and rapidly expanding zones formed efficiency depressions. Second, pure technical efficiency followed a recovery trajectory of initial decline followed by improvement, while scale efficiency displayed a long-term inverted V-shaped pattern, indicating that relying solely on scale expansion is insufficient for achieving sustainable efficiency gains; therefore, careful regulation of construction intensity and land expansion is essential. Third, industrial structure optimization emerged as the most stable and dominant driver. The marginal effects of economic growth and government intervention declined over time, while urbanization gradually shifted from extensive outward expansion to functionally driven, intensive growth. Fourth, differentiated governance strategies proved effective: high-efficiency hotspots should prioritize scale controls and ecological redlines, whereas low-efficiency coldspots should focus on technological enhancement and diffusion, complemented by ecological compensation and fiscal optimization to achieve synergistic development of efficiency and ecological security.

This study makes three primary contributions. First, it develops a replicable, multidimensional "efficiency–spatial–mechanism" evaluation framework by integrating super-efficiency SBM, spatial hotspot analysis, and grey relational analysis, tailored explicitly to arid and semi-arid regions. Second, it addresses a critical research gap by documenting the evolution of county-level ecological asset efficiency over a two-decade period in northern arid regions. Third, it proposes and validates a "technology–scale–structure" synergistic mechanism, clarifying the interactive effects among technological diffusion, scale constraints, and structural upgrading, thereby providing theoretical foundations and policy guidance for enhancing urban ecological efficiency.

Based on these findings, several policy implications are suggested to promote the high-quality development of regional ecological assets in Hohhot, as well as in other arid and semi-arid regions and similar contexts in developing countries. First, restructure green industrial systems by curbing energy-intensive sectors and promoting service- and ecology-oriented economies. Second, establish cross-city and cross-basin platforms for technology sharing and standardization to accelerate the diffusion of green technologies in peripheral areas. Third, optimize fiscal and investment structures to prioritize green infrastructure,

ecological restoration, and innovative governance capacity. Fourth, implement spatial zoning and differentiated controls to limit the expansion of disorderly construction while promoting stock renewal and intensive development. Fifth, establish regional ecological compensation and collaborative governance mechanisms to internalize environmental externalities and foster sustainable cooperation across watersheds and regions.

In summary, in ecologically fragile regions with stringent resource constraints, enhancing urban ecological asset utilization efficiency requires structural upgrading as the core driver, technological diffusion as the key lever, and scale constraints as the boundary to development. This integrated approach advances the principles of "fewer but better, intensive and efficient, and ecologically secure" urban development.

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

Funding: This research was supported by Fundamental Research Program of Shanxi Province (grant number 202403021222019).

Data Availability Statement: The data presented in this study are openly available (see Section 2.2).

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

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Estimating Urbanization's Impact on Soil Erosion: A Global Comparative Analysis and Case Study of Phoenix, USA

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Abstract: Healthy soils are an essential ingredient of land systems and ongoing global change. Urbanization as a global change process often works through the lens of urban planning, which involves urban agriculture, urban greening, and leveraging nature-based solutions to promote resilient cities. Yet, urbanization frequently leads to soil erosion. Despite recognition of this tension, the rate at which the urban growth boundary accelerates soil erosion above natural background levels has not yet been determined. Our goal here is to provide a first broad estimate of urbanization's impact of soil erosion. By combining data on modern erosion levels with techniques for estimating long-term natural erosion rates through cosmogenic nuclide ^{10}Be analysis, we modeled the impact of urbanization on erosion across a range of cities in different global climates, revealing an acceleration of soil erosion ~7–19x in environments with mean annual precipitation <1500 mm; growth in wetter urban centers accelerated soil erosion ~23–72x. We tested our statistical model by comparing natural erosion rates to decades of monitoring soil erosion on the margins of Phoenix, USA. A century-long expansion of Phoenix accelerated soil erosion by ~12x, an estimate that is roughly at the mid-point of model projections for drier global cities. In addition to urban planning implications of being able to establish a baseline target of natural rates of soil erosion, our findings support the urban cycle of soil erosion theory for the two USA National Science Foundation urban long-term ecological research areas of Baltimore and Phoenix.

Keywords: urban soil; background rates of soil erosion; sustainable landscape pattern; urban agriculture; urban greening; urban nature-based solutions

1. Introduction

This Special Issue focuses on observation and modeling of land system changes, with the goal of presenting new data and models. We do both in this paper, focusing on the land system change in urban growth's impact on soil erosion. However, the reader should be cognizant that this is the first research designed to quantify just how much urbanization accelerates soil erosion above natural background rates. As such, our goal is not to provide a hard and firm rate of acceleration, but a first approximation.

Urban soils are part of global human-driven land use change [1–3]. Soils provide ecosystem services both within and outside cities, such as carbon storage and its association with global climate regulation [4,5], effective stormwater management [6,7], and regulation of the urban heat island effect [8,9]. Urban soils play an important role in urban

planning [10]. However, urban soils are sometimes an overlooked resource in human adaptation to global and local environmental changes [11].

Urbanization, while providing essential infrastructure and services for growing populations, has a profound impact. Urban growth alters temperature [12], vegetation [13], carbon emissions [14], and many other effects. The focus on this paper rests on the role of urban expansion on urban soils.

In this context, the process of urbanization directly impacts the erosion dynamics of urban soils. The modification of natural landscapes through construction and development accelerates soil erosion, shifting the location and magnitude of erosion patterns. A half-century ago, Wolman [15] proposed the "urban cycle of erosion" model for understanding how urbanization influences soil erosion, specifically for the Baltimore/Washington D.C. area, USA. His iconic schematic diagram illustrates how sediment yield changes over time as urban development transforms a humid, vegetated landscape, altering hydrologic flow paths and accelerating soil erosion (Figure 1). This model emphasizes the need to understand and address the impacts of urbanization on soil erosion to mitigate its consequences and protect vital ecosystem services provided by urban soils. It has not been possible to quantify the acceleration of soil erosion from urbanization until now.

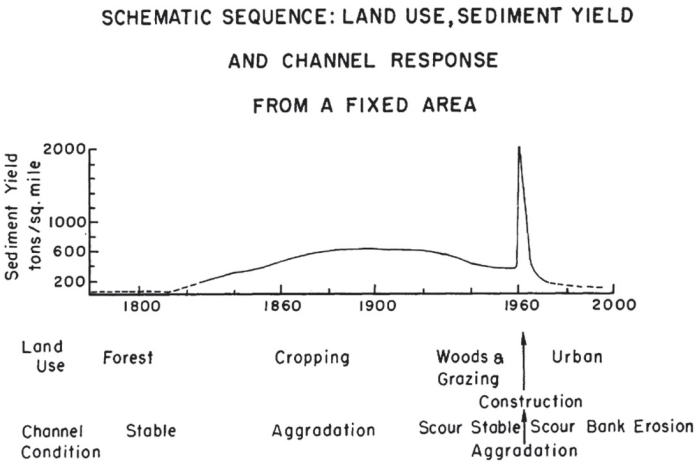


Figure 1. Wolman's [15] hypothesized cycle of erosion associated with urbanization. (Reproduced from [15]).

Thus, a significant research gap persists in determining specific criteria or thresholds for reducing soil erosion in urban areas. The reason why we focus on urban planning in this paper is that soil erosion might best be managed in an urban context by planners. Unfortunately, no data exists for the appropriate erosion reduction targets that should be established, nor on whether these targets should be tailored to the unique characteristics of different urban environments. Furthermore, it remains unclear whether the same erosion reduction values should be applied universally across cities or whether strategies should be adapted to the specific climatic conditions of each urban setting. Consequently, there is a lack of research that bridges the gap between scientific understanding of accelerated soil erosion due to urbanization and its practical implementation. This gap particularly pertains to providing evidence-based recommendations.

These unresolved issues give rise to several critical research questions: (i) How can the pre-Anthropocene (pre-human impact) erosion rate be quantified to provide target erosion rates for urban planners? (ii) How can urban planners effectively assess the current status of soil erosion acceleration in urban environments? (iii) How should erosion reduction targets be adapted to account for the unique characteristics of different urban environments?

Our approach to address this gap uses ^{10}Be (Beryllium-10) catchment-averaged erosion rates. The long half-life of ^{10}Be (1.387 million years) enables the calculation of long-term average erosion rates over periods ranging from 1000 to 100,000 years. These long-term erosion rates provide a natural baseline for understanding erosion dynamics in undisturbed landscapes. By establishing such a baseline, urban planners can use these values as reference points for setting target erosion rates [16,17], thereby informing the development of more effective strategies to manage and mitigate soil erosion in urban settings. In addition, comparing ^{10}Be-derived erosion rates, which represent the natural baseline, to current soil erosion rates can provide valuable insights into the extent of urbanization's impact on soil erosion. Expressed as a ratio (i.e., urban erosion rates relative to natural background levels), this comparison offers urban planners a practical framework for effectively managing and controlling soil erosion in urban areas.

To address the research questions outlined above and to meet the goal of this Special Issue by presenting both new observations and modeling, we designed our study in several steps (Figure 2). First, we analyze prior published compilations of ^{10}Be natural background erosion rates using the catchment-averaged denudation rate (CADR) method [18], alongside the compilation by Russell et al. [17] on modern urban soil erosion. This analysis involves developing a statistical model for global cities to estimate the acceleration of erosion in urban environments across different contexts. One limitation of our approach is that CADR data are not derived from the same global urban catchments as those compiled by Russell et al. [17]. To mitigate this, we use nearby catchments or estimates from similar climates. However, we acknowledge that more accurate estimates will be possible in the future through data sampled from the same urban sites.

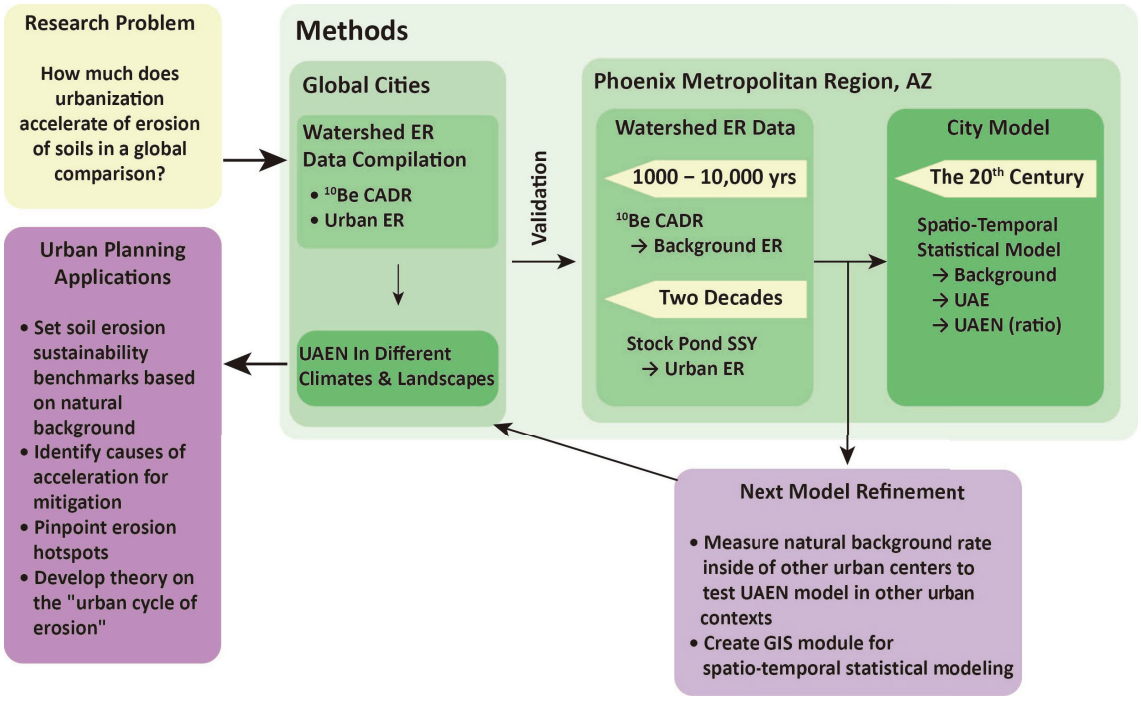


Figure 2. Overview of the research question, methods, scales, intended results, urban planning applications, and next steps for model refinement. ER: Erosion Rate; CADR: Catchment-Averaged Denudation Rate; SSY: Area-Specific Sediment Yield; UAE: Urban-Accelerated Erosion Rate; UAEN: Urban Acceleration of Erosion above Natural Background (ratio).

Our new data come from Phoenix, Arizona, USA. Located in the Sonoran Desert, Phoenix has been an icon of sprawl in urban planning [19], and more recently discussed in planning for urban heat resilience [20]. This urban sprawl, however, has been an important

aspect of our ability to measure CADR and monitor urban soil erosion using the same watersheds. Jeong et al. [21] provided CADR data for watersheds that have experienced over two decades of urban sprawl in Phoenix Metropolitan Region (PMR), and these watersheds were previously studied for urban soil erosion [22]. We utilize these watershed-specific results to develop a statistical model of natural background erosion rates for the entire PMR, based on the CADR data. Subsequently, we present the first approximation of a spatiotemporal statistical model for the rate of urban-accelerated erosion (UAE) in PMR, using two decades of soil erosion data. Finally, we combine the CADR and UAE models to present the first model of urbanization's acceleration of soil erosion above natural background (UAEN). Our Phoenix-wide statistical model serves as a test of the validity of the global cities model across both space and time.

Phoenix, thus, presents a particularly valuable case study for two reasons. First, the 2023 U.S. Census confirmed that Phoenix is now the fifth largest city in the United States [23], and it is the fastest growing of the major U.S. cities. Second, Phoenix is one of two urban centers selected by the U.S. National Science Foundation for long-term ecological research, representing an arid region, alongside the Baltimore/Washington D.C. area, which serves as a representative temperate humid region [24,25]. Therefore, our global comparative analysis and the specific results for Phoenix will contribute to urban soil sustainability by: (a) presenting a model to measure urban acceleration of erosion above natural background rates; and (b) offering a framework for understanding soil erosion across an important urban region using watershed-specific data.

In the Discussion section (Section 5), we return to how our approach to quantifying the impact of urban growth on erosion can be applied to promote sustainable urban landscape patterns. Our research strategy links spatial patterns of land use and land cover change in urbanizing cities to the processes and rates of soil erosion. By considering regional social-ecological elements, we attempt to work towards "sustainable development goals" (cf. [26], p. 1843), contributing to spatial environmental planning efforts aimed at fostering healthy urban soils.

2. Study Areas

We selected our sample of global cities (Figure 3) to understand soil erosion based on two very different published datasets: (i) urban areas where Russell et al. [17] compiled available data on urbanization's impact on soil erosion; and (ii) nearby watersheds where ^{10}Be CADR data are available [27,28], or watersheds with CADR data with similar slopes and climate to matching urban area [29]. Figure 3 also includes our case study urban area of Phoenix, Arizona, USA.

Table 1. Mean slope of different global cities. Supplementary File S1 presents the slope maps used to analyze the mean slope of these cities. The urban ID number corresponds with Figure 3, Table S1 in Supplementary File S2, and Supplementary File S1. Cities 1 through 8 (bold and *) in Table 1 are those we analyzed because they have both nearby/related ^{10}Be CADR data and low slopes. The other cities listed are ripe targets for future studies using ^{10}Be.

ID	City Name	Mean slope (°)	Std (°)
1	**West Fork, Arkansas, USA ***	**4.5**	**3.6**
2	**Washington D.C., USA ***	**3.7**	**3.0**
3	**Phoenix, Arizona, USA ***	**4.0**	**3.2**
4	**Fredericksburg, Virginia, USA ***	**3.4**	**3.2**
5	**Haean-myeon, South Korea ***	**7.1**	**4.5**
6	**Kuala Lumpur, Malaysia ***	**4.5**	**5.0**
7	**Tokyo, Japan ***	**2.4**	**2.7**

Table 1. *Cont.*

ID	City Name	Mean slope (°)	Std (°)
8	**Guwahati, India ***	**2.7**	**4.4**
9	Bogota, Columbia	2.8	3.7
10	Rome, Italy	3.8	3.4
11	El Alto-La Paz, Bolivia	5.1	6.8
12	Nairobi, Kenya	3.2	2.6
13	Addis Ababa, Ethiopia	4.7	3.6
14	Mexico City, Mexico	3.5	4.4
15	Quito, Ecuador	8.2	7.1
16	Santiago, Chile	1.8	1.9
17	Sana'a, Yemen	2.0	2.0
18	Tehran, Iran	3.3	3.1
19	Kabul, Afghanistan	2.7	4.9
20	Ankara, Turkey	5.9	4.9
21	Chongqing, China	7.8	6.7
22	Stockholm, Sweden	4.1	4.2
23	Zurich, Switzerland	4.8	4.4
24	Berlin, Germany	1.3	1.3
25	London, UK	2.2	2.3
26	Paris, France	2.5	2.6
27	Sydney, Australia	4.0	3.8
28	Toronto, Canada	2.3	2.4
29	Beijing, China	2.3	3.2
30	Seoul, South Korea	6.0	6.3

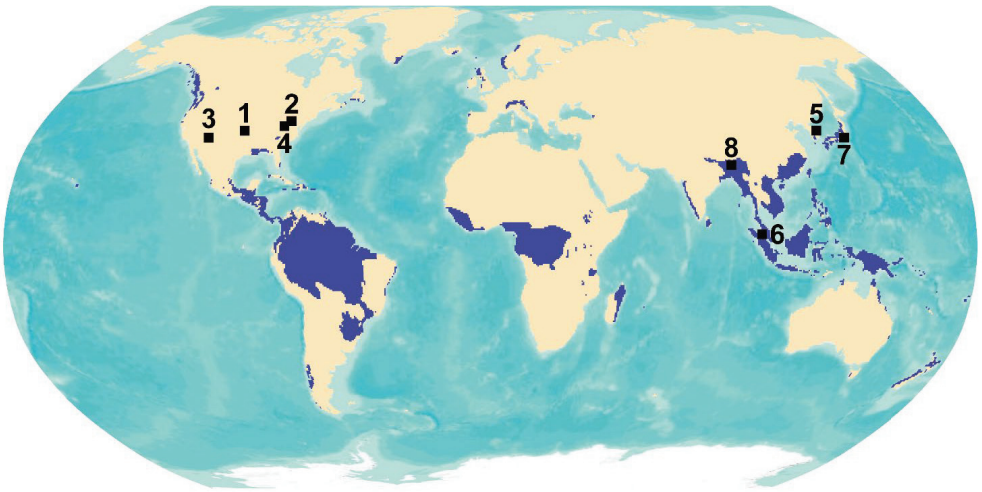


Figure 3. Locations of urban areas analyzed in this paper. Numbers correspond with the city ID in Table 1. The regions with mean annual precipitation >1500 mm [30] are blue-colored. The base map was imported from ESRI, producer of ArcGIS software 10.7.1 and public datasets—accessed through the Arizona State University license. Note—1: West Fork, Arkansas, USA; 2: Washington D.C., USA; 3: Phoenix, Arizona, USA; 4: Fredericksburg, Virginia, USA; 5: Haean-myeon, South Korea; 6: Kuala Lumpur, Malaysia; 7: Tokyo, Japan; 8: Guwahati, India.

The selection of appropriate cities had to be constrained by an urban slope. Cities with very steep slopes experience landslides and other mass wasting processes, as well as gullying. Since these processes can invalidate the ^{10}Be CADR method of determining natural rates of erosion, our selection of cities must exclude cities with mean slopes above 8.5° [31]. The ^{10}Be CADR method is based on erosion that happens first when rainfall generates rainsplash erosion [32]. Then, water that does not infiltrate continues to erode exposed ground via overland flow that picks up loose particles [33,34]. Thus, to compare

global cities with similar basic geomorphic conditions, we identified major global cities with mean slopes below 8.5° (see Supplementary File S1 for slope maps), which we present in Table 1.

The values presented in Table 1 go beyond this particular study, because they offer potential future urban regions that would be most amenable for further study using our methodological approach. Thus, Table 1 includes more cities than we analyze here, because (i) we needed to understand first what cities had average slopes below the key threshold of 8.5° that would indicate the dominant erosion processes on bare ground would be rain splash and overland flow; (ii) match these cities with existing data on modern urban erosion (e.g., [17]); and then (iii) match those cities that had nearby CADR data on background erosion rates [27,28], or had comparable natural watersheds in terms of slope and climate with CADR data [29]. Cities 1 through 8 in Table 1 and Figure 3 met these three conditions. Hence, the cities in Figure 3 are used in the development of a statistical model to compare existing urban erosion data with existing CADR background soil erosion rates.

For the PMR (Figure 4), we collected our own data on both modern rates of soil erosion due to urbanization [22] and ^{10}Be CADR [21]. This was necessary because we needed to measure modern urban soil erosion from the same watersheds as those used for CADR in order to assess the accuracy of the modeling conducted for other global cities (Figure 3).

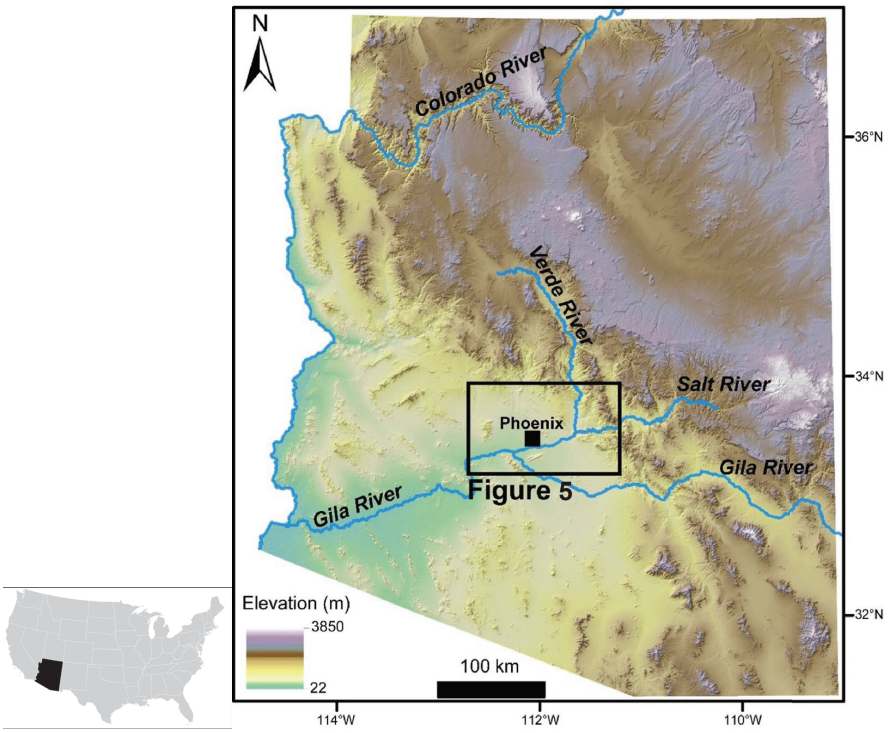


Figure 4. The metropolitan Phoenix region, identified by the rectangular box and the location of downtown Phoenix indicated by the solid square—placed with the context of the State of Arizona, USA. Phoenix could develop in such an arid, hot region because of its large drainage area that supplies gravity-fed water from mountains to the north and east.

Figure 5 contextualizes the locations of these watersheds monitored CADR and also erosion rates for over two decades, as the expanding PMR progressively encroached upon the surrounding Sonoran Desert. Soil erosion was monitored as it progressed through different stages, beginning with cattle grazing, followed by impacts from wildfire, and ultimately leading to the exposure of bare ground due to urbanization [22]. Subsequently, ^{10}Be CADR measurements were taken from the same watersheds [21], enabling the first direct comparison of urbanization-induced erosion to natural background erosion.

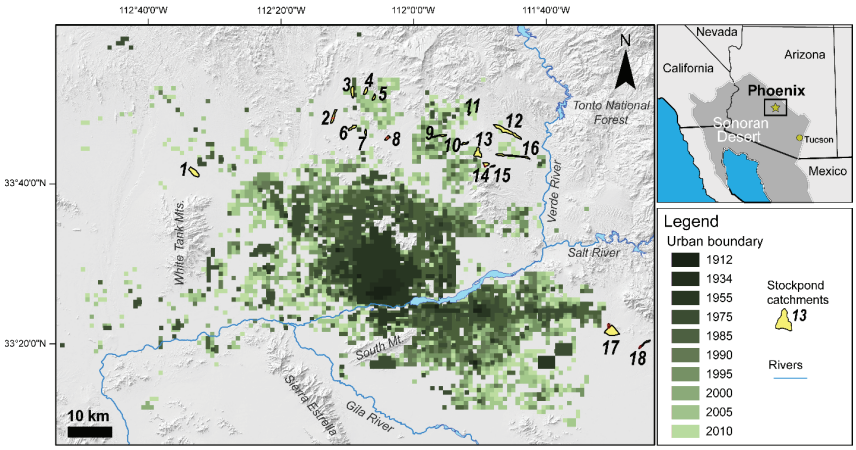


Figure 5. Urban sprawl of Phoenix metropolitan region contextualizing the scattered locations of 18 monitored stock pond catchments with urban sprawl from 1912 to 2010. Urban boundaries were extracted from land cover classification by Central Arizona–Phoenix Long-Term Ecological Research. Numbers refer to catchments identified prior research [21,22] and in Supplementary File S3 that presents all of these watersheds (by number and by name), their land use histories, precipitation, and erosion data.

Figure 6 illustrates how soil erosion was influenced by land use and land cover changes (LULCC) in one of these watersheds. For each watershed, we analyzed historical aerial photographic imagery to identify timelines of LULCC (exemplified by Figure 6A for one of the Phoenix-region watersheds). We then developed a method to quantify aerial changes in LULCC across different time periods for each watershed (Figure 6B). After completing the erosion data analysis, we compared LULCC to natural background erosion rates (CADR), as exemplified by Figure 6C. Supplementary File S3 provides this same analysis for all 18 monitored watersheds.

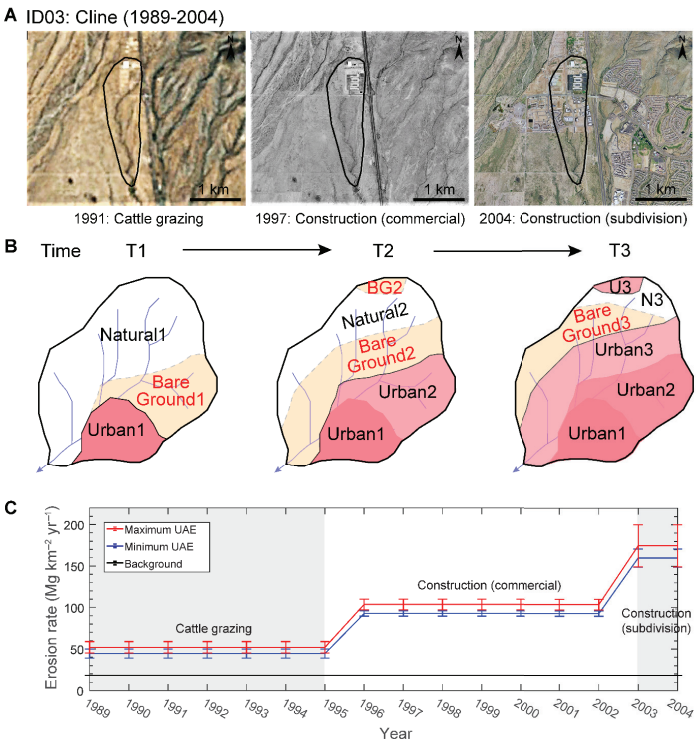


Figure 6. An example of how urbanization impacted a Phoenix-region watershed monitored for both natural background soil erosion (dark black line) and the influence of land use changes. The ID of this watershed is ID3 in prior research [21,22]. (**A**) LULCC of Cline stock pond catchment illustrated in

aerial photographs. (**B**) Idealized explanation of how we calculated bare ground exposure (modified from Jeong [35]). The dashed line is the imaginary line that does not exist on the land use/land cover classification map, which is to show the exposed bare ground. The exposed bare ground during the time period from T1 to T2 (Bare Ground1) can be calculated by the intersection of natural land cover in T1 (Natural1) and urban land cover in T2 (Urban2). The annual urban growth was calculated from dividing by the length of time period. (**C**) Comparison between CADR natural background soil erosion (lower flat line) with pre-urbanization cattle grazing and then urban development between 1989 to 2004.

3. Methods

Our approach to estimating the impact of urbanization on soil erosion above natural background (UAEN) differs topically from the air quality research of Yao et al. [36], but it shares methodological similarities, particularly in the use of a space-time regression model that explores physical geography data across an urban region. This section outlines six key steps, two of which we have been discussed in prior work: (i) measuring ^{10}Be CADR on timescales of 10^3–10^5 years from the PMR watersheds to obtain natural background rates of erosion [21]; and (ii) collecting and analyzing two decades of soil erosion data from the same PMR watersheds used for CADR [22]. Our data collection process spanned over two decades and incorporated significant LULCC, including transitions from cattle grazing to urbanization-induced bare ground exposure, as well as the impacts of wildfires.

This paper documents the four remaining tasks required to compare the CADR, which provides a sustainability target [21], with the impact of urbanization on soil sustainability. These four tasks are summarized in this section, with extensive details on data collection and methods provided in Supplementary File S2. The information in Supplementary File S2 offers a new set of tools for researchers aiming to further investigate urban soil sustainability.

The sequence of methods summarized here begins by modeling CADR for various global cities where urban soil erosion data have already been compiled. Next, we model natural background erosion rates for the entire PMR using the CADR data. Third, we present a model for the rate of UAE in the PMR, based on two decades of soil erosion data. Fourth, we compare UAE to CADR to develop a model of UAEN for the PMR. This Phoenix-specific case study enables us to test the accuracy of the global cities model.

Before delving into the details, we wish to stress that our findings are ultimately limited by the lack of data on background rates of soil erosion in global cities outside of Phoenix, Arizona, USA. The limitations of our methods expressed in the sections that follow also mean that our results are best interpreted as broad estimates of how urban growth increases soil erosion.

3.1. Comparison of UAEN to Global Cities in Different Environmental Settings

We compiled global scholarship from CADR research [27–29] to compare with modern sediment yields from urban centers undergoing substantial urban expansion [17]. This approach enabled the first comparison of sediment yields impacted by urban-accelerated erosion (UAE) and natural background erosion.

A significant challenge, however, is the lack of CADR data for the same watersheds studied for urban soil erosion. While CADR data may exist for nearby catchments or similar climatic regions, only one urban location—within the Potomac River basin of Chesapeake Bay, USA—had both CADR and modern urban soil erosion rates [28,37]. Importantly, neither of these studies was designed to compare natural and urban soil erosion.

Given this limitation, we focused on locations with reported median sediment yields from urbanizing catchments (as referenced in [17], and detailed Table S1 in Supplementary File S2). The scarcity of CADR data from the same catchments prevented direct comparison. Therefore, we utilized nearby CADR data or, in cases where such data were unavailable,

employed the median CADR values from multiple studies conducted in similar climate regimes [29]. Section S2 in Supplementary File S2 provides further details on how we addressed key discrepancies across studies.

To compare our findings in the PMR, we limited our analysis to cities with basic geomorphic conditions similar to Phoenix, specifically: (i) mean slopes below 8.5° [31] (Supplementary File S1 presents slope maps for 30 such global cities); and (ii) where eroded soil primarily results from overland flow processes, rather than gullying or streambed erosion. The 8.5° threshold is a reasonable one for the PMR, since gullying tends to occur on steeper slopes. While previous studies [16,17] emphasize that processes other than rainsplash and overland flow contribute to erosion in various urban contexts, we focused on low-slope cities to enhance the likelihood of comparing similar geomorphic erosion processes. We acknowledge that our global erosion assessment is subject to high uncertainty, due to the insufficient availability of CADR data for urbanizing catchments.

3.2. Natural Background of Soil Erosion Rates

Controlled experiments have previously determined that CADR is insensitive to urbaniza tion-induced soil erosion in the PMR [21]. Jeong et al. [21] collected active-channel sediment samples from 18 stock pond watersheds that had undergone urbanization over the past two decades. The CADRs of each stock pond watershed is presented in Jeong et al. [21]. To compare CADRs with modern sediment yields, bedrock density was used for conversion from length unit to mass unit (e.g., m My^{-1} × bedrock density, 2.7 t m^{-3} = Mg km^{-2} yr^{-1}).

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3.3. Modern Rates of Soil Erosion

To understand erosion associated with different LULCC over time in the PMR (Figure 5), sediment accumulation depths were measured from 18 stock ponds during the expansion of Phoenix's urban fringe between 1989 and 2013 [22] (Figures 4 and 5). Since dust storms are common in the Phoenix region, the silt and clay accumulating in the stock ponds could potentially originate from aeolian dust deposition, weathered bedrock or, more likely, a combination of these sources. Consequently, two area-specific sediment yields (SSY) (and erosion rates) are presented in Table S5 in Supplementary File S2. The maximum SSY calculation assumes no aeolian dust deposition, while the minimum SSY calculation assumes that all silt and clay are derived from aeolian deposition. SSY was calculated as follows [38]:

$$SSY = SM_{max\ or\ min}/(A_D \times TE \times Y) \times 10^6 \quad (1)$$

where SSY (Mg km^{-2} yr^{-1}) is the area-specific sediment yield, SM (Mg) is sediment mass, A_D (km^2) is drainage area of the watershed of each stock pond, TE (%) is the sediment trap efficiency (100% for each stock pond) and Y (years) is the measurement period. The maximum sediment mass (SM_{max}) and minimum sediment mass (SM_{min}) were calculated as follows:

$$SM_{max} = SV \times dBD = A_P \times D_{avg} \times dBD, \quad (2)$$

$$SM_{min} = SM_{max} \times (1 - percent\ silt\ and\ clay) \quad (3)$$

where SV (m^3) is the measured sediment volume in the stock pond during the given time period Y (years), dBD (t m^{-3}) is average dry bulk density of the sediment, A_p (m^2) is

sedimentation area and D_{avg} (m) is the averaged depth of the sediments measured from nine grid points. The error term of two sediment yields derives from the standard deviation of nine depth measurements for each time slice. This standard deviation of the average depth then translates as a ± percentage of the reported sediment yield.

We followed previous studies in comparing CADR and modern SSY [39,40], using the bedrock density (~2.7 g cm^{-3}) for CADR conversion and sediment bulk density for modern SSY calculation (see Table 1 in [21]).

3.4. Modeling Background Rates of Erosion for the Entire Phoenix Metropolitan Region

Jeong et al. [21] demonstrated that natural background rates of erosion were significantly and positively correlated with mean slope (r = 0.75, $p < 0.05$) and mean elevation (r = 0.63, $p < 0.05$) in the 18 monitored watersheds in PMR. Given that mean slope and mean elevation are significantly correlated and endogenously related [21], we omitted mean elevation as a predictor for natural background sediment yield to mitigate multicollinearity issues. Therefore, mean slope was finally adopted as a proxy for background erosion, as explained in Section S3 of Supplementary File S2.

The final model to predict background erosion for bare ground exposed during the PMR urban expansion from 1912 to 2010 within a regression framework as follows ($R^2 = 0.57$):

$$\textit{Background erosion} = 47.677 \times (\textit{mean slope}) - 0.075 \quad (4)$$

Full details are provided in Table S2 in Supplementary File S2.

3.5. Modeling Urban Acceleration of Erosion for the Entire Phoenix Metropolitan Region

There are different approaches to modeling soil erosion over a region. The Revised Universal Soil Loss Equation (RUSLE) within a GIS environment usually yields accurate results for watersheds [41–44] and urban landscapes [45–47]. However, given the nature of our historic and cosmogenic nuclide datasets, which exhibit spatiotemporal heterogeneities, we determined that a nested spatiotemporal statistical regression model—similar to those used to study urban air pollution [36,48]—would be more suitable for investigating soil erosion at the urban growth boundary [49].

To model urban acceleration of erosion for bare ground exposed during PMR urban expansion from 1912 to 2010, we examined relationships between modern SSY from the 18 stock ponds, LULCC, and catchment geomorphological factors (i.e., initial urban cover, annual urban growth rate, drainage area, mean slope, relief, and drainage density) (Figure S3 and Table S6 in Supplementary File S2). Through the correlational analysis, we selected annual urban growth rate (AUGR2, in km^2 yr^{-1}) and mean slope as proxies for urban acceleration of erosion (Table S7 in Supplementary File) (rationale explained in Section S4 of Supplementary File S2). The final model predicts the urban acceleration of erosion (UAE) within a multiple regression framework as follows (adjusted $R^2 = 0.17$):

$$\textit{Urban acceleration of erosion} = 783.92 \times (\textit{AUGR2}) + 8.8 \times (\textit{mean slope}) + 96.52 \quad (5)$$

Full details are provided in Table S7 in Supplementary File S2.

3.6. Urban Cycle of Erosion for an Arid Environment

Wolman [15] proposed the first and only conceptual model illustrating how LULCC associated with urbanization impact soil erosion. He introduced the concept of the "urban erosion cycle" for the Maryland piedmont, USA, where deforestation and agriculture at the urban growth boundary accelerated erosion. However, this acceleration was not as significant as the erosion observed during the construction phase of urbanization. After

the completion of urbanization, erosion rates decreased substantially with the paving of surfaces [50]. Two critical components of Wolman's model were based on assumptions due to data limitations: Wolman lacked the ability to measure natural background erosion rates, and he did not account for the urban acceleration of erosion due to surface sealing, such as the application of asphalt and concrete.

While Wolman's model focused on a humid-region city, we are in a unique position to examine whether a similar "cycle" exists in an arid-region city. To investigate this, we compiled all previously published SSY data in the Köppen–Geiger BWh climate (hot desert climate) setting, as well as data from the PMR [21,22,51]. We categorized the SSY data according to LULC types, including natural, grazing, agriculture, wildfires, construction, and surface sealing. Using these data, we created box-and-whisker plots for each LULC type in arid settings and compared the results with Wolman [15]'s erosion cycle in humid regions.

Table S1 in Supplementary File S4 provides the data on the stock pond catchments necessary for calculating soil erosion, along with other watershed characteristics used in modeling soil erosion in the PMR. Additionally, Table S1 presents the LULC categories. Table S2 in Supplementary File S4 presents summary statistics of compiled SSY data used for the box-and-whisker plot, along with their corresponding references.

4. Results

4.1. Modeling of UAEN for Global Cities in Different Environmental Settings

The global cities UAEN model indicated a similar range of soil erosion acceleration in urban areas, spanning from 200 mm to approximately 1300 mm of mean annual precipitation (MAP). Figure 7 illustrates this range, showing UAEN values between 7x and 19x for cities with MAP <1500 mm. The acceleration of erosion in urban areas increases significantly in cities with MAP >1500 mm, where the modeled UAEN values range from 23x to 72x (Figure 7). These results suggest a three- to four-fold increase in urban-accelerated erosion in wetter climates compared to drier ones.

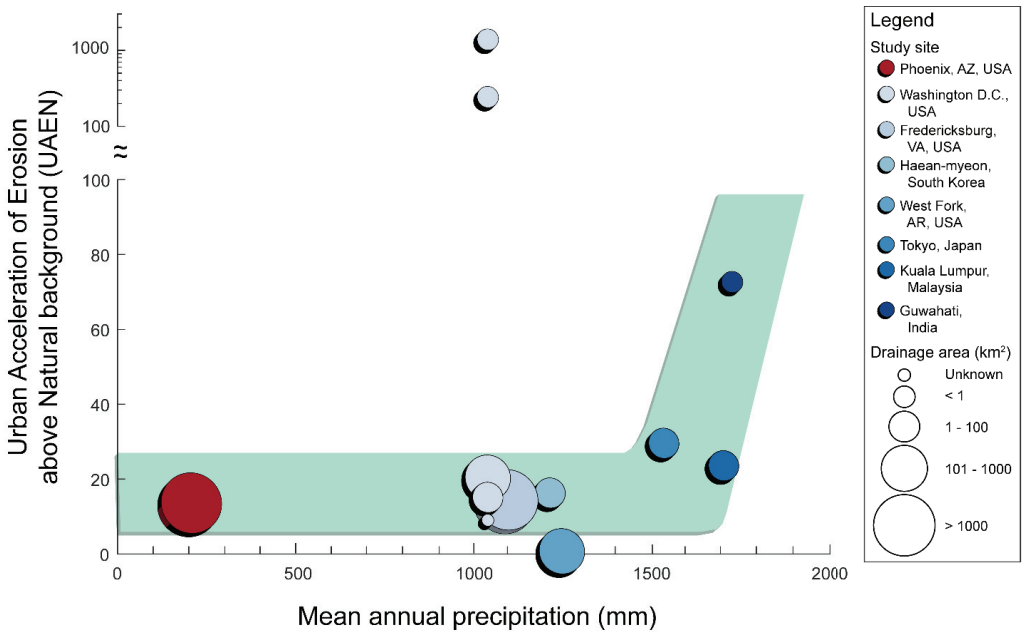


Figure 7. Modeled urban acceleration of erosion above natural background (UAEN) of global cities plotted against mean annual precipitation (MAP). The green shaded area is a visual guide and does not represent a statistically fitted line or confidence interval. The vertical scale is linear up to 100 UAEN and log afterwards. Colors reflect MAP, and size indicates the size of the drainage area.

We offer speculative explanations for the three outliers in Figure 7. The two Washington D.C. subcatchments, which exhibit significantly higher UAEN, may be influenced by gullying, a process known to greatly accelerate erosion. The notably lower UAEN for West Fork, Arkansas, USA, could be attributed to rapid vegetation regrowth at construction sites. These hypotheses are based on an examination of low-resolution historical aerial photographs and would require confirmation through historical ground rephotography.

4.2. Modeling Natural Background and Urbanization-Related Erosion in the Metropolitan Phoenix Region

Figure 8 situates our estimates of background and urbanization-accelerated erosion in both spatially and temporally. Figure 8A displays the development history of the PMR, as shown in Figure 5. Figure 8B (Table S4, Supplementary File S2) presents our estimated background erosion rates for the entire PMR. A comparison with Figure 8A reveals that background erosion is typically higher in areas of the PMR that have been developed more recently and have historically been less urbanized. This is because background erosion tends to be higher in locations with steeper slopes, which are traditionally less favorable to construction and urbanization.

In contrast, Figure 8C shows that areas with lower background erosion rates tend to exhibit higher rates of urban-accelerated erosion. This is particularly evident in the central and earlier developed areas of the metropolitan region (see Figure 5). A likely explanation for this discrepancy is that the earliest phases of urbanization were concentrated in lower-lying, flatter areas, conditions that naturally favor lower rates of background erosion. Taken together, Figure 8B,C suggest that urbanization has the potential to accelerate erosion in areas that would otherwise be prone to low levels of background erosion, as well as in areas already experiencing higher levels of background erosion.

Figure 8D provides a temporal perspective by illustrating the annual urban growth rate (AUGR) and our estimate of urban-accelerated erosion in the PMR from 1912 to 2010. As expected, the acceleration of erosion by urbanization closely tracks the broader magnitude of urbanization over time. Prior to 1950, both urbanization and the erosion induced by urbanization were minimal. From the mid-1950s to 2000, both urbanization and erosion progressively increased decade by decade. The most striking increase in both metrics coincided with the widespread build of the early 2000s. These patterns of expansion and acceleration tapered off between 2005 and 2010, likely due to the slowdown in building and expansion following the USA's Great Recession. Erosion, and consequently soil sustainability, is closely linked to human development activities over time. Furthermore, erosion can occur in areas that deviate from typical background spatial patterns, highlighting the influence of urbanization on soil processes.

Figure 9 integrates our perspectives of time and space, as well as the interplay between natural background and urbanization-accelerated erosion processes. Figure 9A presents our estimates of the UAEN, indicating the degree to which urbanization accelerated the natural erosion process across the twentieth century.

A UAEN of "1" indicates that the level of erosion attributable to urbanization is equivalent to the level of natural background erosion. From 1912 to 1955, the UAEN ranged between 2.4 and 3.5, suggesting that urbanization during this period accelerated erosion by no more than 3.5 times the natural background rate. This acceleration increased significantly in subsequent decades, peaking during the 1985–1990 period, when urbanization accelerated erosion by approximately 23 times the background. The period following 1985 witnessed significant construction in the southeastern (e.g., Tempe, Gilbert, Chandler) and northwestern (e.g., Peoria) region of the PMR (see Figure 9B). Despite slight declining since the 1985–1990 peak, UAEN has remained high in the PMR.

Table 2 presents the transitions of UAE, background erosion, and UAEN in PMR from 1912 to 2010, derived from regression analysis. Sediment yield estimates from the bare ground layers exposed by urban expansion in PMR from 1912 to 2010 were 9 Mg km^{-2} yr^{-1} for background erosion and 111 Mg km^{-2} yr^{-1} for UAE. This analysis reveals an acceleration of soil erosion by a factor of 12.2 times above the natural background rate as Phoenix expanded over a century (Table 2).

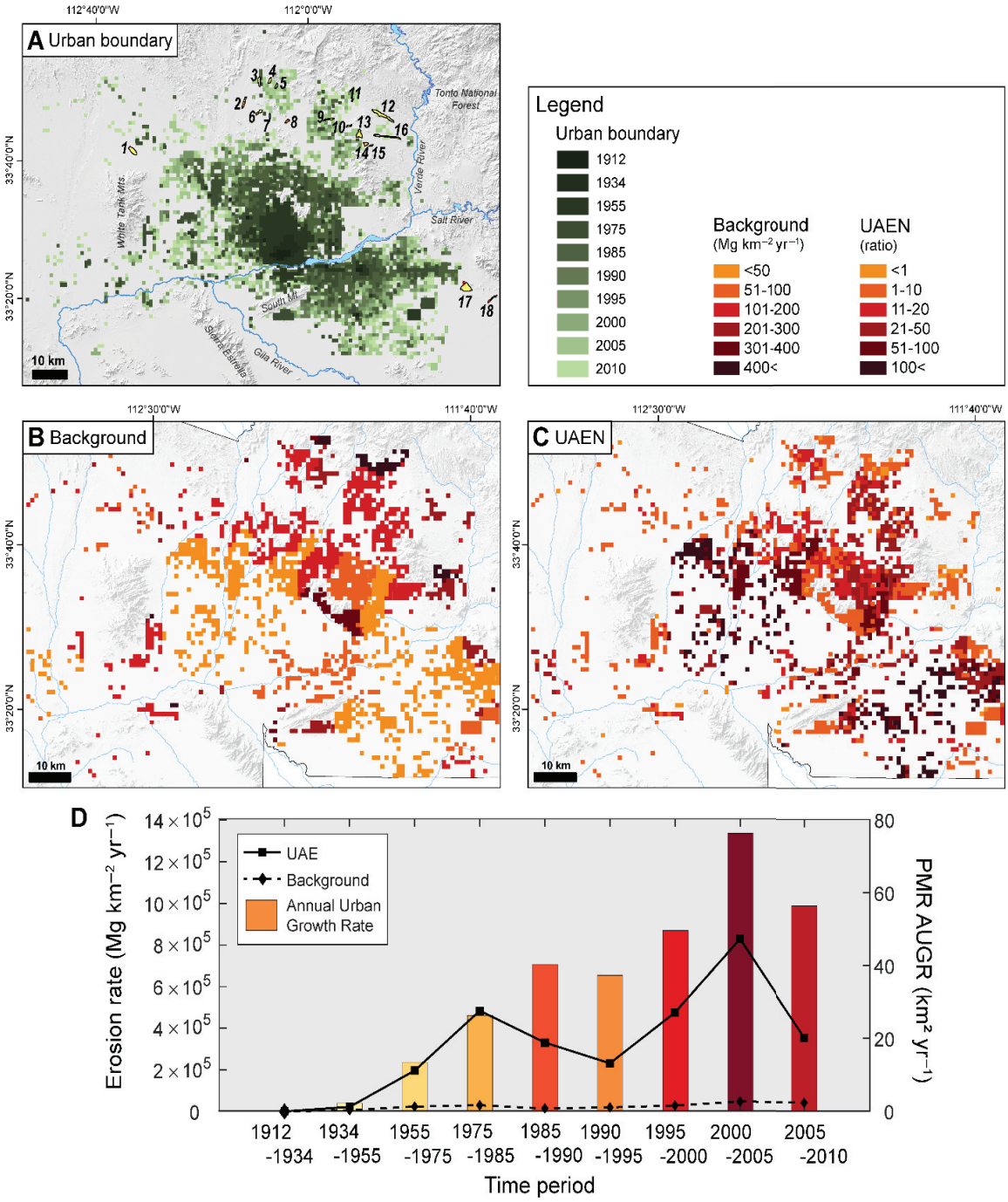


Figure 8. Spatial and temporal variability in natural and urbanization-generated soil erosion for metropolitan Phoenix, USA. (**A**) Urban sprawl of Phoenix metropolitan region from 1912 to 2010. (**B**) Spatial distribution of the modeled background erosion rate using CADR measurements, and (**C**) UAEN. (**D**) Temporal change in background erosion and UAE in PMR from 1912 to 2010 associated with PMR's annual urban growth rate.

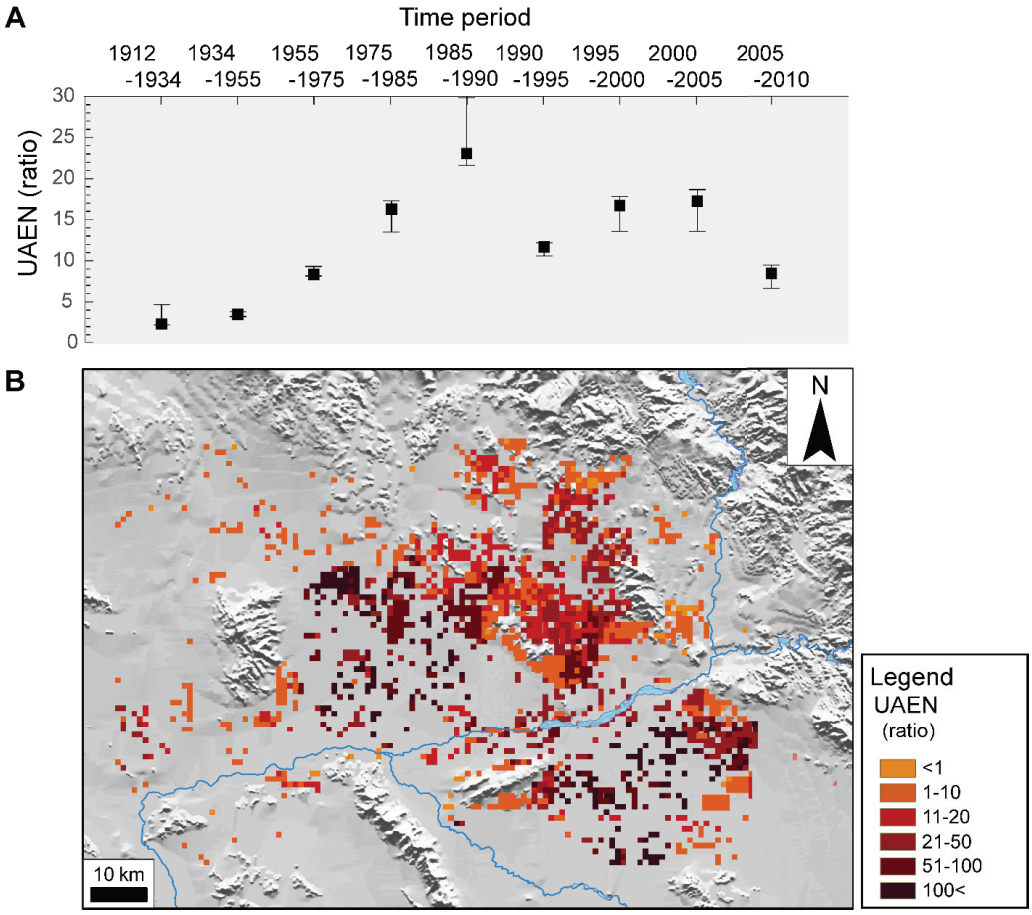


Figure 9. (**A**) Temporal change in the urban acceleration of erosion above natural background (UAEN) in PMR from 1912 to 2010. (**B**) Spatial distribution of the UAEN.

Table 2. Transition of UAE, background erosion, and UAEN in PMR from 1912 to 2010 derived from regression analyses.

Time Period	LT [1] (yr)	ABG [2] (km^2)	AUGR [3] (km^2 yr^{-1})	Background ± 1σ (Mg)	UAE ± 1σ (Mg)	Background ± 1σ (Mg km^{-2} yr^{-1})	UAE ± 1σ (Mg km^{-2} yr^{-1})	UAEN [4] Mean	(−1σ)	(+1σ)
T1: 1912–1934	22	0.46	0.02	503 ± 404	1219 ± 789	49 ± 40	119 ± 77	2.4	2.2	4.3
T2: 1934–1955	21	44.81	2.13	10,318 ± 51,516	459,435 ± 208,082	138 ± 55	488 ± 221	3.5	3.2	3.7
T3: 1955–1975	20	266.79	13.34	468,878 ± 250,184	3,925,647 ± 1,916,566	88 ± 47	736 ± 359	8.4	8.1	9.2
T4: 1975–1985	10	262.39	26.24	296,872 ± 131,363	4,838,963 ± 2,589,339	113 ± 50	1844 ± 987	16.3	13.6	17.3
T5: 1985–1990	5	200.89	40.18	71,732 ± 45,628	1,655,341 ± 878,108	71 ± 45	1648 ± 874	23.1	21.6	29.8
T6: 1990–1995	5	186.06	37.21	98,353 ± 45,885	1,156,408 ± 596,934	106 ± 49	1243 ± 642	11.8	10.7	12.2
T7: 1995–2000	5	247.13	49.43	142,376 ± 61,607	2,377,551 ± 1,273,757	115 ± 50	1924 ± 1031	16.7	13.7	17.9
T8: 2000–2005	5	380.37	76.07	240,941 ± 99,622	4,147,279 ± 2,235,257	127 ± 52	2181 ± 1175	17.2	13.5	18.7
T9: 2005–2010	5	281.70	56.34	211,366 ± 79,733	1,779,401 ± 916,481	150 ± 57	1263 ± 651	8.4	6.6	9.3
T1–T9: 1912–2010	98	1870.61	19.09	1,661,338 ± 765,942	20,341,242 ± 10,615,315	9 ± 4	111 ± 58	12.2	10.9	12.8

[1] LT: length of time period. [2] ABG: area of exposed bare ground during urbanization. [3] AUGR: annual urban growth rate calculated as ABG/the length of time period. [4] UAEN: urban acceleration of erosion above natural background erosion calculated as UAE/background.

4.3. Urban Cycle of Erosion for Arid Environments

The rocky desert landscape of the Phoenix, Arizona, USA, region exhibits significant sensitivity to soil erosion resulting from anthropogenic disturbance [22,52] (Table S2 in Supplementary File S4 and Figure 10). A comparison of sediment yields from the 1st and 3rd quartiles of each major LULCC category for the PMR reveals the following trends: (i) grazing increased sediment yields typically 0.5 to 6.6 times the natural background rates; (ii) human-set wildfires [53] elevated sediment yields by a factor of 1.9 to 10.6 times the natural background rates; (iii) the exposure of bare ground due to residential and commercial development resulted in sediment yields 7.5 to 61.8 times higher than natural background rates; and (iv) the sealing of urban surfaces led to sediment yields ranging from one-tenth to one-half of those associated with natural background erosion rates.

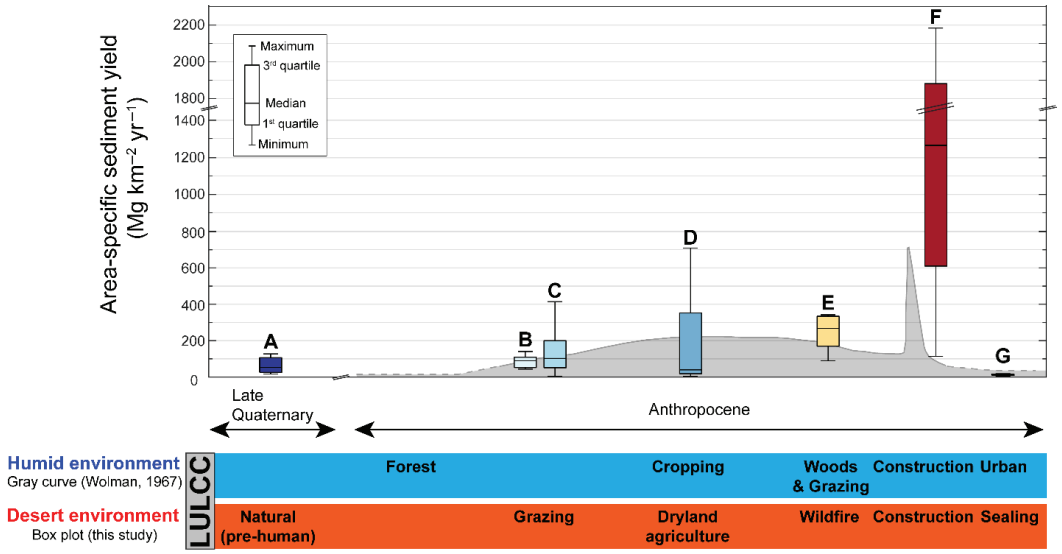


Figure 10. Box and whisker plots of area-specific sediment yield associated with LULCC in a warm desert environment compared with the humid-region prior model. The gray curve presents the classic cycle of land use change and sediment yield behavior developed for LULCC in Maryland [15]. Dashed lines in the gray curve indicate unmeasured but predicted lower erosion due to urban sealing effect [15]. Letters (A–G) correspond to different land uses associated LULCC in the PMR, with their associated area-specific sediment yield (SSY) data. Specific land use categories and associated sediment yields: (A) Background sediment yield: Derived from CADR from stock ponds in the PMR using ^{10}Be [21]. (B) Grazing Period SSY: Collected from stock ponds in PMR during grazing period [22]. (C) Published grazing SSY: Collected from published grazing data in BWh catchments [22,51]. (D) Dryland agriculture SSY: Collected from published data from BWh catchments experiencing dryland agriculture [22,51]. (E) Wildfire SSY: Collected from stock ponds in PMR after wildfires [22]. (F) Construction period SSY: Estimated from our model for entire PMR from 1912 to 2010. (G) Urban sealing SSY: From the PMR in stock pond and other watersheds after urbanization sealed surfaces.

5. Discussion

The methods (Section 3) and Results Section (Section 4) provides detail about the observations and modeling used to obtain a first broad quantification of just how much urban growth accelerates soil erosion. It is crucial to acknowledge, however, that the models for estimating UAEN presented here are largely based on indirect comparisons across diverse catchments and data sources. Given these inherent limitations in data availability and modeling detail, there are also limits to their interpretation and, importantly, their transferability and general applicability to other regions. For example, this initial estimate suggests a potential climatic inflection point around 1500 mm of mean annual precipitation

(Figure 7), where the acceleration rate appears to change significantly. However, the rough nature of our modeling efforts, coupled with the limited dataset, renders it inappropriate to model how global changes might alter broader patterns of soil erosion, or to establish a rigid threshold. Indeed, the UAEN concept, while promising, remains insufficiently validated by independent data outside our Phoenix case study, especially for more humid climatic regions (MAP > 1500 mm) where output variability is considerable (ranging from 23× to 72×). This underscores a key limitation of our current model and the need for further verification. Therefore, despite our broader interest in global change, we focus this discussion on local applications for urban planners. We have sufficient confidence in the direction and approximate magnitude of soil erosion acceleration to recommend these findings for effective erosion management in urban contexts. Future research must explicitly address the degree of uncertainty, the model's limiting assumptions, and potential biases that may arise when transferring this model to regions with substantially different climatic, hydrological, and urbanization characteristics.

5.1. Sustainable Landscape Pattern and Urban Soil Sustainability

The provision of ecosystem services by soils makes their preservation a critical consideration in urban planning [10]. Widely recognized improvements to the urban environment include replacing impervious land surfaces with healthy soils and green groundcover and trees [54,55]. Thus, soil erosion, especially its potential for off-site movement and subsequent impacts, has emerged as a key concern in urban planning [55]. It is often the downstream consequences, such as degraded water quality or increased flood risks from transported sediment, that underline this significance.

It is important to recognize that the value and challenges of urban soils differ significantly from natural or agricultural contexts. While the ecological functions of urban soils are paramount, their perceived importance in planning can also be influenced by esthetic considerations, perceived quality of life in urban gardens and farms, or even the practical ability of clients or developers to import or 'manufacture' soil for specific purposes. Therefore, urban soil management often involves a more balanced view of soil dynamics, where the focus shifts from preventing all erosion to effectively managing its undesirable consequences.

Soil erosion is the opposite of soil retention—an important conservation priority for urban ecological land [56] (p. 3). Achieving sustainable landscape pattern (SLP) in cities requires soil retention [2] in order to carry out such activities as sustainable urban agriculture and urban greening [57] and associated resilience to urban heat islands [20]. Some argue that the carbon-storing function of urban soils could play a role in helping to control anthropogenic global warming [5]. Recognition of the importance of urban soils prompted a variety of soil-related sustainability strategies, including the artificial creation of soil [58], the unsealing of soils [59], or focusing more on natural soils that survived the urban sealing processes [59]. Irrespective of the scholar's preferred sustainability strategy, urban soils provide a wide variety of ecosystem services that are vital to sustaining our cities into the future [60–62]. Therefore, in the context of sustainable development, we hope to help spatial planners explore this practical dimension of SLP [49].

Specifically for spatial planning, natural background rates of soil erosion as measured by ^{10}Be CADR provide a useful "planning target" (cf. [49], p. 37) for sustainable rates of soil erosion. This is because soils maintain a dynamic equilibrium when rates of soil formation are equal to natural erosion rates [63]. Thus, the urban acceleration of erosion above natural background of 1 or below permits soil retention [64]. The overwhelmingly clear finding of this research is that all modeled global cities had urban accelerations above natural background rates of erosion (UAEN) much higher than 1 (Figure 7), including our

focused study region of metropolitan Phoenix (Figure 8). Historic rates of urban soil erosion greatly exceed rates of soil formation. In other words, no modeled or directly observed city had sustainable urban soils, because all analyzed cities experienced an anthropogenic acceleration of physical soil erosion far above natural values.

One piece of this sustainable future involves the post-industrial trend of urban agriculture efforts that enhance the sustainability of cities of the future [65]. Urban agriculture is part of urban greening [66], a way to cool cities [67] and better air quality [68]. Urban greening is also a nature-based strategy to mitigate the impact of urban flooding on urban soils [69]. Our basic finding of a non-sustainable UAEN much higher than 1 (Figures 7 and 8) does not directly influence the resilience of the remaining urban soils; shocks to soil health are an entirely different issue, typically involving such issues as heavy metal pollution or removal of organic carbon [70].

5.2. Testing Global Cities Model with Phoenix-Region Case Study

The largest problem with our global cities UAEN model is that there is no "apples to apples" comparison of the same watersheds studied for urbanization impacts and natural erosion rates. All of the natural rates we have available to compare with urbanization's impact derive from the proxies of nearby drainages or samples collected from a similar climate region, introducing inherent uncertainty in these broader estimates. Thus, our detailed case study for the PMR, Arizona, USA (Figures 7–10) provides the first "apples to apples" comparison that we use to test the general accuracy of the global cities modeling results (Figure 7). While this case study strengthens our confidence, it also highlights the critical need for similar direct validation in other diverse urban settings to enhance the model's robustness and transferability.

Our Phoenix case study reveals a ~12.2x acceleration of erosion; this resides in the middle of 7x–19x for drier global cities (Table 1; Figure 7). The natural question to ask is whether Phoenix is truly representative of an arid region in terms of its erosion rates and in terms of its soil production. Prior scholarship [71] does indicate that arid-region soil production is about the same as the long-term erosion rates we modeled for the Phoenix region (Figure 7).

This means that the next test of our approach to modeling the acceleration of soil erosion above sustainable natural background values should come from wetter global cities above 1500 mm precipitation with a UAEN envelope of 23x–72x (Figure 7). While it is beyond the scope of this study to replicate our Phoenix-region results for another urban area, our next step is to obtain samples from urbanizing watersheds on the perimeter of wetter cities (e.g., Table 1) for CADR analysis. Such a study would provide enhanced confidence that CADR offers clear "targets" for sustainable rates of urban soil erosion.

5.3. Spatial and Temporal Variability in Soil Sustainability

Our strategy to model soil erosion across the history of the metropolitan region of Phoenix reflects what Dong et al. [49] refer to as "frontier theory" supporting SLP development. While there is growing recognition that the field of urban sustainability lacks a firm scientific foundation for understanding critical sustainability processes [72] over the long durée, soils are particularly challenging, as their relevant spatial scale for analysis is often extremely fine. The construction of structures and roads can have an impact on the health of proximate soils. Our analysis therefore complements other recent sustainability research by integrating settlement and environmental data over long periods of time and at high spatial resolution within a land-based perspective [73].

The overall picture that we present suggests that the PMR lacks sustainable soils. This regional conclusion, however, may not be accurate for all places or times. The Phoenix-wide

modeling results presented here (Figure 8) indicates that there are periods of time and locations where urbanization's impact on soil erosion is less severe (e.g., UAEN < 1 in Figure 8C,D). For example, the Phoenix region experienced sustainable soil erosion prior to about 1975 (Figure 8C) and also in developments on lower slopes (Figure 8B).

Certainly, the spotty nature of Phoenix's sustainable soil erosion seen in Figure 8B,C might not be a pattern observed in other cities. However, the trend over time (Figure 8D) towards greater offsets between sustainable rates of soil erosion and urbanization's impact might be similar to other urban areas that are expanding their perimeter out towards steeper slopes. What our Phoenix model offers to other cities is the ability to model where accelerated soil erosion might occur and enhance efforts to mitigate this erosion. The mitigation might be as simple as allowing the growth of some vegetation cover [74,75] or not exposing piles of bare ground during a rainy season [76–78].

5.4. Why Precipitation Falling on Urban Construction Sites Is Different from Natural Watersheds: Implication for SLP Serving Spatial Planning

Our research on urban soil erosion operates within the "frontier theory" in Sustainable Landscape Planning (SLP), which necessitates placing soil erosion in a broader theoretical context [49]. For over six decades, the scientific discipline of geomorphology has debated the precise impact of precipitation on natural rates of soil erosion [79–82]. A prominent perspective from this debate is the model by Langbein and Schumm [83], which posited a skewed distribution of erosion rates with climate—specifically, lower rates in arid regions, maximum rates in semi-arid environments, and a subsequent decline in wetter places attributed to increased vegetation cover. However, this view is not universally accepted, as many studies in non-urban and non-agricultural settings show a low correlation between precipitation and erosion, largely due to the mitigating role of dense vegetation cover [79–81].

Our global cities modeling results, however, present a strong and distinct precipitation signal in urban environments, often characterized by a step function where erosion rates double or triple above ~1500 mm of mean annual precipitation (Figure 7 and Table 2). This striking contrast to natural settings reignites aspects of the long-standing debate within a new urban context, and is likely attributable to the widespread exposure of bare ground during urban construction. Unlike natural landscapes where vegetation acts as a primary buffer [79–81], urban construction processes frequently remove this protective cover entirely. In such disturbed urban settings, the basic drivers of erosion—rainfall intensity, surface runoff, and the inherent energy from slope—become dominant.

Specifically, the pronounced increase in erosion above 1500 mm precipitation can be explained by the fundamental process of rainsplash. While initial surface crusts can form on newly exposed bare ground and offer some temporary protection [84], the constant intensity and cumulative volume of precipitation typical of rainy seasons in wetter cities likely overwhelm this natural soil-crusting effect. Without the robust protection of vegetation, it is geomorphologically plausible that erosion rates would accelerate significantly once the limited protective capacity of soil crusting is exceeded by abundant rainfall.

This analysis underscores a critical point for spatial planning solutions to manage urban soil erosion problems and promote SLP. For example, construction projects can be strategically planned to expose bare ground predominantly during dry seasons, while carrying out other activities during wet periods. Another effective strategy is to protect soil piles under covers for their later use in urban agriculture or greening, after testing for lead and other contaminants [85]. Such solutions may seem obvious in retrospect and are easier to propose than to implement.

5.5. The Urban Cycle of Erosion and Soil Sustainability

The U.S. National Science Foundation supports long term ecological research (LTER) in two urban regions of the USA: Baltimore/Washington D.C. Maryland metropolitan region [25] and the Phoenix metropolitan area [24]. Wolman [15] proposed an urban cycle of erosion for the Baltimore/Washington D.C. area (Figure 1). We reinterpret here Wolman's broader thinking now in terms of SLP for more settings than Wolman's Baltimore/Washington D.C. setting.

The various spatial patterns of erosion across urban growth boundaries are space and time transgressive, something we were able to assess for the PMR. Thus, Wolman's general model can be interpreted in terms of urban soil sustainability (Figure 10). The Sonoran Desert setting of PMR experienced a sequence of LULCC different than the Maryland piedmont (Figure 10). Late Quaternary conditions in the PMR had low rates of soil erosion. Then, instead of deforestation, the studied watersheds underwent a period of grazing slightly increasing erosion above natural background rates. While the Phoenix area did have both prehistoric and historic agriculture [86], no data exists on soil erosion for either period. Thus, we plot global dryland agricultural data [22,51] for illustrative and comparative purposes. The PMR watersheds then experienced a spike in erosion from human-set wildfires [53] on the urban fringe [22]. Then, the largest effect on soil erosion came from a century of urbanization, as predicted in Wolman's model [15]. Soil erosion in the PMR then returned close to natural background levels after paving these urban surfaces.

Thus, both of the LTER urban areas of the USA National Science Foundation went through a long phase of accelerated soil erosion related to LULCC preceding urbanization. Both LTER urban areas experienced a massive spike in elevated urban soil erosion associated with construction. However, what we learned in the case of PMR, the ^{10}Be CADR method offers a target for urban planning; hence we were able to quantify exactly how much enhancement occurred from such processes as grazing and wildfire that preceded urbanization (Figure 10) and that urban sealing drops soil erosion below natural CADR-quantified erosion rates.

5.6. Broader Impacts of Urban Soil Erosion for Urban Planning

It is important to highlight issues that extend beyond our focus on sustainable soils [2], given their significance for urban planning and SLP. Figure 2 in Dong et al. [49] present a ternary theoretical basis of a SLP. One leg of Dong et al.'s [49] ternary diagram involves a feedback loop between biodiversity and ecosystem processes. In the context of urban patterns, we view this ternary leg as truly involving soils. Consider the importance of soils as key to urban agriculture as part of urban greening [57], cooling cities [67], and aiding air quality [68]—especially in the global urban south that is a key for global sustainability [87].

We acknowledge that the rate, manner, and regulatory frameworks of urbanization vary significantly across the globe. This includes diverse approaches to managing and mitigating environmental impacts, such as 'biodiversity offsetting,' a mechanism through which urban development's impact on green open space assets is counterbalanced by their creation or enhancement elsewhere [88]. For instance, in Germany, particularly in cities like Berlin, urban development projects often include requirements for developers to provide compensation for environmental benefits or mitigate negative landscape impacts, formalized through mechanisms like eco-accounts [89]. Similarly, in the UK, specifically London, such compensation is facilitated through instruments like Section 106 agreements [88]. Beyond Europe, countries like the USA also have established requirements for mitigation and compensation, prominently for wetland losses, often involving concepts such as wetland mitigation banking. Other nations like the Netherlands and Sweden have also

implemented various forms of environmental compensation within their planning systems, showcasing a diversity of approaches adapted to different legal and environmental contexts globally [90]. These varied policy measures underscore a global trend towards acknowledging and attempting to compensate for the environmental costs of urban growth.

The stakes associated with urbanization-enhanced soil erosion tend to be spatially variable, as tends to be for all soil erosion [60,91–93]. Beyond direct erosion impacts, urbanization fundamentally alters natural hydrology through increased impervious surfaces and modified drainage systems. This altered hydrology, in conjunction with soil erosion, leads to significant impacts on water quality. Involving SLP to help aid in urban planning (cf. [49]) naturally incorporates issues such as urban soil erosion impacting reservoirs [35], degraded water quality [94–96] and related health effects from heavy metals [97,98]. This is particularly critical as once urbanized areas stabilize, concerns may shift from soil quality itself to the overarching implications for water resources.

Moving forward into the twenty-first century demands that "urban sustainability, urban resilience and urban transformation" involves Earth System dynamics [99], such as soil erosion processes. These processes can also cause other urban sustainability complications such as eutrophication of freshwater systems due to the increased delivery of sediment containing P and N from fertilizers [100,101]. Soil erosion also impacts urban poverty in a variety of ways [102], including negative health impacts [103] and compromised water quality [104]. Enhanced urban soil erosion might remove carbon stored in city soils [5,105], or it might end up in a setting where it can be more stable such as a reservoir [106].

6. Conclusions

Our research on how urbanization accelerates soil erosion links to this Special Issue on land systems pertaining to global change by presenting new observations and new models of urban soil erosion. For the first time, we provide a comparison of natural long-term rates of soil erosion obtained through cosmogenic nuclide ^{10}Be analysis with direct observations of urban soil erosion over a century. This unique dataset exists only for the city of Phoenix in the Sonoran Desert of North America, where urban expansion accelerated soil erosion by about 12x. Unfortunately, no cosmogenic nuclide ^{10}Be data exist for other cities across different global climates. Thus, we had to model existing ^{10}Be data, and this led to only being able to provide a broad estimate that cities with mean annual precipitation <1500 mm experienced soil erosion acceleration of ~7–19x, similar to Phoenix. A jump in urban acceleration of soil erosion occurred for cities with mean annual precipitation >1500 mm. The next step in this research requires obtaining new data on cosmogenic nuclide ^{10}Be for global cities in different climates, instead of using modeled data.

The loss of soils in urban landscapes remains an understudied topic in global change and with likely long-term consequences for ecosystem services derived from urban landscapes [107]. In this first insight into quantifying the offset between urban soil erosion and sustainable rates of erosion, we offer new research strategies for urban planners to better understand urban soil sustainability, as follows: (i) a way to obtain sustainable rates of soil erosion via measurement of ^{10}Be cosmogenic nuclides from watersheds before they undergo urbanization; (ii) how to estimate natural background rates of soil erosion if ^{10}Be cosmogenic nuclide analyses were not feasible; and (iii) a strategy to statistically model rates of soil erosion across an urban area. Furthermore, the combination of our approach coincides with the emergence of new data pertaining to long-term urbanization patterns (e.g., [108]). The list of urban areas in Table 1 that were beyond the scope of our research design would be ideal candidates for ^{10}Be measurements to provide a natural baseline and a basic target of sustainable rates of soil erosion to aid spatial planners in promoting sustainable soils for urban planning.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14081590/s1, Supplementary File S1. Slope map for global cities; Supplementary File S2. Detailed methods (e.g., [15,17,21,22,27–29,31,35,109–120]); Supplementary File S3. The change changes in land use, precipitation and erosion rates for each of the 18 stock ponds catchments (e.g., [21]); Supplementary File S4. Supplementary data for validation of Wolman (1967) model (e.g., [15,21,22,51]).

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

Funding: This research received no external funding.

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

Acknowledgments: We thank B.L. Turner II, T. Dunne, M.W. Schmeeckle, I.J. Walker, and K. Seto for suggestions at different stages of manuscript preparation, and the School of Geographical Sciences & Urban Planning of Arizona State University for support.

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

Abbreviations

The following abbreviations are used in this manuscript:

CADR	Catchment-averaged denudation rate
PMR	Phoenix Metropolitan Region
UAE	Urban-accelerated erosion
UAEN	Urbanization's acceleration of soil erosion above natural background
LULCC	Land use and land cover changes
SSY	Area-specific sediment yields
MAP	Mean annual precipitation
SLP	Sustainable landscape pattern

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Land-Use Changes Largely Determine the Trajectory of Plant Species Distributions Under Climatic Uncertainty in a Mediterranean Landscape

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Abstract: We investigated the combined effects of climate and land-use change on plant diversity in northwestern Greece, a region representative of broader European trends in land abandonment. We based our study on comprehensive field data on plants' distribution and modelling of land-use changes based on socio-economic trends. We build distribution models for 358 taxa based on current (2015) and future (2055) conditions according to the combinations of three climate and three land-use change scenarios. We compared species distribution changes between current and future conditions for each scenario, and we investigated species trends concerning their ecological indicator values and strategies. Additionally, by analyzing the distribution changes in aggregated differential taxa representing the various plant communities in the study area, we identified patterns of distribution shifts at the community level. Our results indicated more pronounced differences between land-use scenarios than between climate ones, which was attributed to the local scale of the study area, its climatic and physiographic characteristics, and its complex land-use legacy. Both climate and land-use changes drastically reduced the distribution of some species, with species distribution loss exceeding 80% under certain combinations of socioeconomic and climate change scenarios. Species ecological indicator values and strategies showed a buffering effect of forest microclimate against climate change, which, however, may favor only species of forest communities. At the community level, land-use change had again a stronger impact than climate change, with consistent patterns within major vegetation types (forests and open habitats) but contrasting trends between them. Our results highlight the need for appropriate conservation plans to counteract the negative impacts of land abandonment and to take advantage of its positive impacts.

Keywords: biodiversity; climate change; ecological indicator values; land-use change; ecological strategies; socioeconomic scenarios; species distribution modelling

1. Introduction

We live in a rapidly changing world, where native species are being threatened by several factors. According to the global assessment report on biodiversity of IPBES, the factors with the greatest negative influence on biodiversity, listed in descending order of importance, are habitat loss or change (due to land-use changes), direct exploitation of

organisms, climate change, pollution, and invasive species [1]. Climate change drastically threatens biodiversity by affecting species distributions [2,3], while it is expected that habitat loss caused indirectly by climate may exacerbate the negative impacts of other biodiversity threats [1].

Land-use change has posed the highest negative impact on biodiversity loss to date, mainly due to loss or degradation of species habitats [1,4]. The importance of habitat loss because of land-use change is highlighted when considering that wildland covers around 22% of the ice-free land on earth, with only about 3.3% being retained in biomes other than the cold and dry ones [5,6]. The impact of land-use change that has been covered in the bibliography so far mainly concerns habitat loss or degradation due to the intensification of land uses. However, the growing trend of farmland and pastureland abandonment worldwide, especially in mountainous areas and areas of low productivity, results in significant habitat loss for many species [7].

In Europe, land abandonment is currently the most prominent cause of landscape changes [8], with 20% of European agricultural land being under a high or very high risk of abandonment until 2030 [9]. On the one hand, land abandonment is considered an opportunity for the natural restoration of ecosystems and recovery or re-introduction of many species (ref. [10] and many articles therein). On the other hand, it has been considered a biodiversity threat, having a negative impact on species of open or seminatural habitats that have been formed by traditional human use of ecosystems for millennia [11–13]. Specifically, natural succession, which follows land abandonment, causes replacement of open and seminatural habitats with scrubs and, finally, forests [14].

Although climate change and land-use change are probably the most widely studied biodiversity threats globally [4], it is only recently that an assessment of their combined impact has been thoroughly studied, as has been shown by the significantly more studies appearing in the bibliography (search in Scopus database on 20 January 2024). Nevertheless, there is still a lot of research to be undertaken towards a better understanding of the combined effect of these two threats on biodiversity, for different biomes or ecosystems, environmental conditions, groups of taxa, etc. [15–17].

Indicators of species' ecological or habitat preferences can significantly enhance our understanding of how climate and land-use change affect species diversity by revealing distributional shifts among groups of species with distinct ecological characteristics or life strategies. On one hand, plant species' ecological characteristics are available through the concept of ecological indicator values, which represent their preferences in relation to light availability, temperature, continentality, soil moisture, soil reaction, soil fertility, and salinity [18]. On the other hand, species' habitat preferences can be captured by incorporating functional diversity metrics, such as trait syndromes, including Grime's Competitor, Stress-tolerator, Ruderal (CSR) model of plant life strategies [19,20]. Competitive species may thrive under reduced disturbance regimes linked to land abandonment, whereas ruderal species depend on frequent disturbances and may decline as traditional land uses are abandoned. Stress-tolerant species often exhibit greater resistance to climatic extremes but may be constrained by changing land cover. Identification of groups of species with distinct ecological optima or life strategies and investigation of their distribution patterns under future climate and land-use conditions can significantly assist biodiversity conservation and efforts towards the monitoring of climate and habitat change.

In Greece, and especially towards the northern and central parts of the country, high landscape changes have been recorded due to land abandonment, especially in (sub)mountainous areas, concerning a high decrease in farmlands and seminatural grasslands and forest increase (e.g., [21–24]). In the present study, in such a sub-mountainous area, representative of the landscape changes caused by land abandonment in northern and

central Greece, we assessed the combined effects of land abandonment and climate change on vascular plant species distribution at a local scale. For this area, Kiziridis et al. [22] found an increase in forests from 22% to 63% in the period from 1945 to 2015, and a decrease in farmland from 30 to 3%. For assessing the impact of climate and land-use change in this area, we incorporated combinations of three land cover and three climate scenarios referring to the year 2055. For current conditions, as well as for the nine combinations of the land cover and climate scenarios, we predicted and compared species' potential distribution. Through the above-described rationale, we addressed the following questions: (a) What are the patterns of losses and gains of species per future climate and land-use change scenarios? (b) Do these patterns vary among the plant communities found in the study area? (c) Are there any "winners" and "losers" among taxa with different ecological preferences and life strategies in relation to future scenarios?

2. Materials and Methods

2.1. Study Area

The study area comprised five circular sites with a total area of 141.4 km^2, located at the north-western sub-mountainous region of the Pindus Mountains in Greece (Figure 1). Historically, this area had extensive farmlands and grasslands traditionally exploited via low-intensity farming and transhumance, but land abandonment after the 1940s has led to significant landscape changes [22]. Elevation ranged from 248 to 1203 m, while the area is characterized by gentle slopes (0–10°), reaching a maximum of 55°. The geological substrate of the study area is constituted by 50% limestone, 25.4% deposits, 18.9% silicate, and 5.7% flysch [25]. According to Köppen–Geiger climatic classification, the area belongs to the Csa type [26], since it has a temperate climate, with hot and dry summers, as well as mild and wet winters. Additionally, the study area belongs to the vegetation formation of thermophilous deciduous oaks [27], which represents the climax vegetation of the study area.

2.2. Vegetation Sampling and Plant Communities

The field data used in the present study to determine species occurrences across the study area are described in detail in Mastrogianni et al. [28]. In brief, vegetation sampling of 250 plots was conducted in 2020, with 125 plots located in grassland or shrubland habitats (50 m^2 each) and 125 in forest habitats (200 m^2 each). Within each plot, all vascular plant taxa and their cover were recorded by using the 9-grade Braun–Blanquet scale [29,30]. Following vegetation classification of these plots, 11 floristically and ecologically distinct vegetation communities were identified in the study area [28]. These communities represented different stages of a secondary vegetation succession gradient. The grassland communities along the successional stages included (a) two communities at the early successional stage, namely, hay meadows with *Alopecurus rendlei* and old-fields with *Hordeum bulbosum*; (b) one community at the advanced and ongoing successional stage, namely, wet meadows with *Cynosurus cristatus*; (c) two communities at the advanced but stable successional stage, namely, semi-natural grasslands with *Chrysopogon gryllus* and semi-natural grassland with *Phlomis fruticosa*; and (d) one retrogressive community of *Pteridium aquilinum* stands. Regarding forests, the five identified communities included (a) two advanced and stable communities, namely, *Carpinus orientalis* forests and xerothermophytic oak forests (*Quercus pubescens–Q. trojana*); and (b) three late forest communities, *Quercus frainetto* forests, *Quercus cerris–Q. frainetto* mixed forests and riparian forests. For more details on these communities, please see Mastrogianni et al. [28].

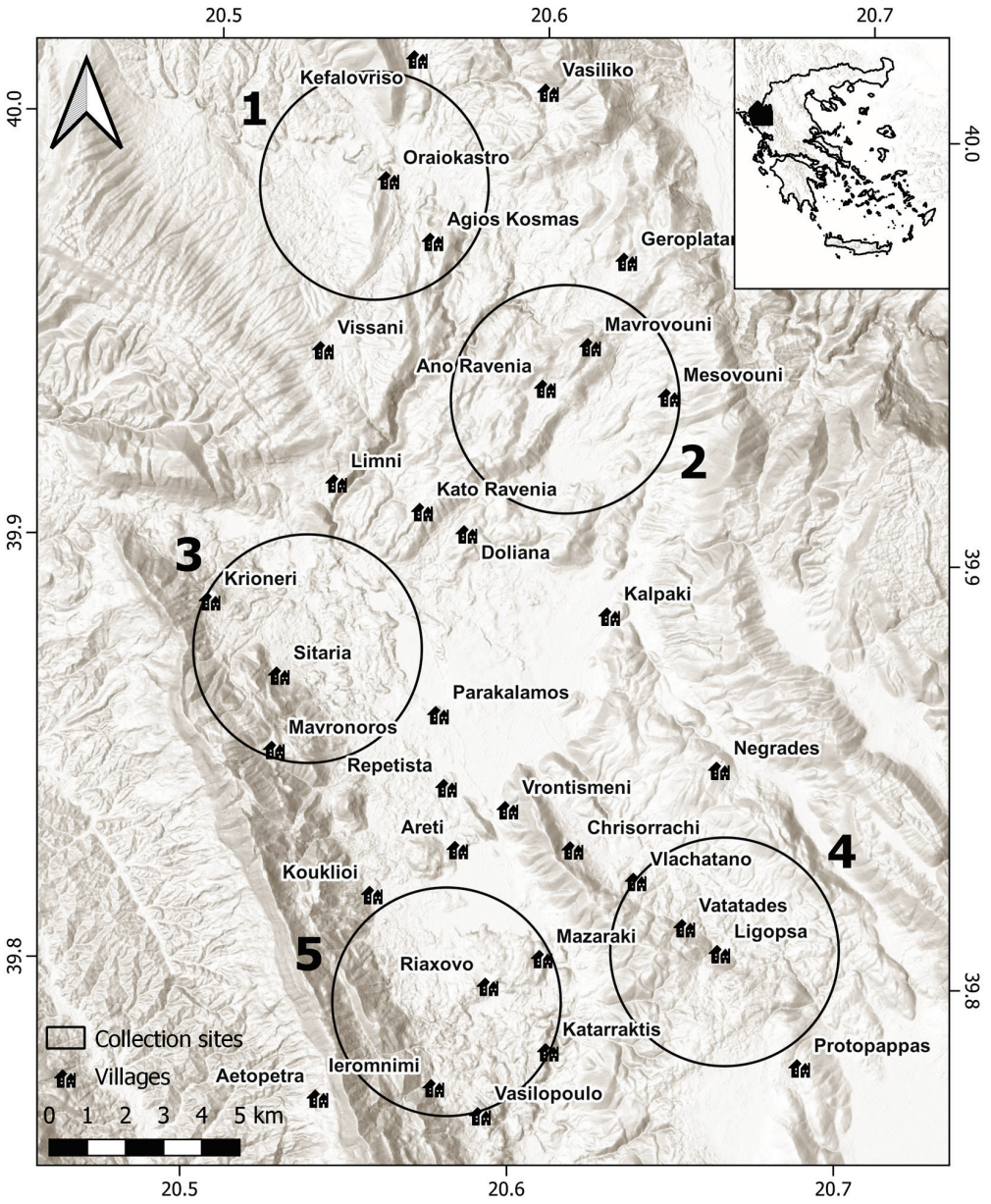


Figure 1. Map of the study area, depicting the five circular collection sites and their location in Greece depicted as a black-filled rectangle (top right). Numbers (1–5) outside the circular collection sites refer to the code names of each collection site.

2.3. Land Cover Mapping

For the determination of the distribution of land-use classes in the study area, we mapped land cover into five land types, namely, farmland, grassland, open-scrub, closed-scrub, and forest, by using natural-color orthophotos for 2015, obtained from the Hellenic Cadastre. From the total study area, we excluded settlements and water bodies as unsuitable for species distribution modelling within the context of the present study, leading to a final study area of 138.4 km^2. Farmlands represented areas with evidence of agriculture and land management practices. Grasslands represented natural habitats with cover of trees and shrubs ranging between 0 and 10%, open-scrubs with respective cover of trees and shrubs ranging between 10 and 40%, closed-scrubs with cover of trees and shrubs ranging between 40 and 70% and, finally, forests with cover of trees and shrubs ranging between 70 and 100%. Mapping was achieved by the visual interpretation of orthophotos, vectorization of the land-type boundaries, and subsequent rasterization of the maps at 25 m

resolution [22]. The land-use change projections and associated validation data employed in this study were derived from Kiziridis et al. [31], where the full methodology and model performance metrics are described in detail. In brief, the future land cover was predicted for 2055 according to three socioeconomic scenarios: business-as-usual (USU), preservation of intensive farming (INT), and extensification of farming (EXT) [31]. The three scenarios were developed after taking into account the study area's land-use cover in past years (1945, 1996, and 2005), combined with the changes in the trends of socioeconomic variables in our study area among these years, as well as climate change. More specifically, in the USU scenario, the trend in demand for land cover is the same as the trend observed for the period 1996–2015. The INT scenario is similar to the USU scenario but preserves the farmland of low elevation and slope, whereas the EXT scenario is characterized by an inverse transitioning to the demands of 1970. More details on the demand scenarios can be found in Kiziridis et al. [31]. The total area of the different land-use types under each scenario is given in Table 1, while the patterns of substitution among these land-use types can be found in Kiziridis et al. [31].

Table 1. Total area (in km^2) of each land-use type (farmlands, grasslands, open scrubs, closed scrubs, and forests) across the ten land-use and climate change scenarios, namely, SSP126, SSP370, and SSP585, as well as the three socioeconomic scenarios, namely, extensive farming (EXT), intensive farming (INT), and business-as-usual (USU). Data are derived from Kiziridis et al. [31].

Scenario	Farmlands	Grasslands	Open Scrubs	Closed Scrubs	Forests
2015	4.49	21.24	11.26	14.75	86.66
SS126-EXT	30.02	23.58	17.49	21.58	45.72
SS126-INT	3.89	7.88	6.93	10.86	108.84
SS126-USU	0.58	9.4	7.63	11.26	109.53
SS370-EXT	30.02	23.58	17.49	21.58	45.72
SS370-INT	3.89	7.88	6.93	10.86	108.84
SS370-USU	0.58	9.4	7.63	11.26	109.53
SS585-EXT	30.02	23.58	17.49	21.58	45.72
SS585-INT	3.89	7.88	6.93	10.86	108.84
SS585-USU	0.58	9.4	7.63	11.26	109.53

The floristic character of each land-use type can be inferred by matching them with the plant communities identified within the study area. Specifically, grasslands include areas occupied by semi-natural grasslands with *Chrysopogon gryllus*, semi-natural grasslands with *Phlomis fruticosa*, old fields with *Hordeum bulbosum*, hay meadows with *Alopecurus rendlei*, wet meadows with *Cynosurus cristatus*, and stands of *Pteridium aquilinum*. Open and closed scrubs encompass areas occupied by all plant communities identified in the study area, differentiated primarily by tree cover density. Finally, forests correspond to areas occupied by *Quercus frainetto* forests, *Carpinus orientalis* forests, xero-thermophytic oak forests (*Quercus pubescens–Q. trojana*), *Quercus cerris–Q. frainetto* mixed forests, and riparian forests.

2.4. Species Distribution Modelling

For the evaluation of the potential effects of climate and land-use changes on species' distribution across the study area, we applied the species distribution modelling (SDM) technique for 358 out of the 629 plant taxa recorded in the study area. Specifically, we applied modelling only for taxa recorded in at least seven localities (n = 7–129 occurrences) within the study area [32], to allow reliable modelling results. Occurrence data of these species were collected through the vegetation sampling in 250 plots, representative of the different plant communities, ecological conditions, and land cover types found in the study area (see Section 2.2). Current and future potential distribution of species

were predicted by applying the MaxEnt algorithm [33,34], which is known to have high predictive performance, even in the case of very small sample sizes [35,36].

The employed predictive variables were representative of the area's climate, physiography, geological substrate, soil attributes of the topsoil, as well as land cover, at a spatial resolution of 25 m. CHELSAcruts and CHELSAfuture V2.1 datasets were used for the construction of 19 bioclimatic variables, for current conditions and for three future climate scenarios, namely, the Shared Socioeconomic Pathways of sustainability (SSP126), regional rivalry (SSP370), and fossil-fueled development (SSP585) from the CMIP6 framework [37] (see Kiziridis et al. [31] for more details). We checked for multicollinearity between them, by using Pearson's correlation coefficients for all pairwise combinations, and kept those bioclimatic variables with a higher percent contribution and training gain among any pair with a correlation coefficient $|r| > 0.70$: annual precipitation, precipitation of the warmest quarter, mean temperature of the coldest quarter, and mean temperature of the warmest. The geological substrate was obtained from the map of Nakos [25], and the soil variables (pH, nitrogen, proportion of silt and clay, soil organic carbon) were obtained from the global gridded soil information, SoilGrids [38]. For altitude, we used the Digital Elevation Model over Europe at a 25 m resolution [39], based on which the ground's slope raster was also generated by the R package "raster" [40]. Geological substrate and soil variable data were assumed to remain unchanged and were applied identically across current (2015) conditions and all nine future socioeconomic scenarios.

To make more accurate predictions for models produced with the MaxEnt algorithm based on presence-only distribution data, and to capture the variability of the study area's environmental conditions, we incorporated 10,000 random background points [36]. This is the default number of background points and was selected because it ensures a broad and representative sampling of the environmental space (e.g., different land uses and environmental gradients), as well as stable and reliable estimates of the environmental distribution across the study area. MaxEnt models were run using 5-fold cross-validation, and default settings as suggested by Phillips and Dudík [33]. This process was repeated ten times, and the average prediction was then calculated for each plant taxon. We ran MaxEnt models under current conditions (2015) and projected them to future conditions (2055), using nine combined scenarios of climate and land-use change. This resulted in a total of ten potential distribution maps for each taxon. We used the Maximum Sensitivity plus Specificity (MaxSSS) to convert habitat suitability rasters into presence/absence maps [41]. We selected this threshold as it is known to provide better results independently of the type of the employed data (presence/absence or presence-only) [41], leading to resulting binary maps characterized by balanced commission and omission errors. All SDM analyses were conducted with the R package "dismo" [42].

2.5. CSR Life Strategies and Ecological Indicator Values of Species

We used taxa ecological indicator values [43] and their ecological strategies according to Grime's CSR theory [44] to explore the distribution changes in taxa with different ecological characteristics, under future climate and land-use scenarios. Ecological indicator values of light, temperature, soil moisture, nitrogen, and reaction were obtained from Dengler et al. [45]. For 11 taxa not included in Dengler et al. [45], we calculated indicator values by averaging the indicator values of the five taxa with the highest percentage of co-occurrence with the taxon under question in the vegetation dataset. The taxa ternary coordinates in Grime's triangle of ecological strategies were calculated based on extensive sampling of plant traits in the study area [28,32] and the methodology of Pierce et al. [46]. Three coordinates were produced for each taxon, each ranging from 1 to 100, representing the three main dimensions in Grime's triangle, namely, competition (C), stress-tolerance (S),

and ruderality (R). Four taxa were omitted from the dataset for the analysis of ecological strategies because of a lack of data. Finally, we calculated linear regressions between the percentage of change in the distribution extent of the modelled plant taxa among current conditions and future scenarios, and their indicator values as well as taxa ternary coordinates in Grime's triangle of ecological strategies.

2.6. Vegetation Communities' Distribution

In order to identify any differences in the patterns of distribution changes among species that occur preferentially in specific plant communities, we investigated the trends of distribution changes in differential taxa per community under the future climate and land-use scenarios. Specifically, we determined the differential taxa for each plant community by applying the indicator species analysis proposed by De Cáceres et al. [47], though the package "indicspecies" in R (ver. 1.7.12) [48]. Then, we selected all taxa having a statistically preferential occurrence in any of the 11 plant communities, leading to a subset of 233 out of the 358 studied taxa, and determined the minimum number of indicator taxa per plant community according to the vegetation plot data (Table S1). Based on the predicted current and future potential distribution of the 233 differential taxa, we calculated the number of cells with at least the minimum number of differential taxa per community. The number of cells per plant community with an equal or higher number of indicator species than the minimum number per plot within each community is herein used as a surrogate for the investigation of a possible differentiation in species distribution changes between the plant communities.

3. Results

The SDMs built for the 358 taxa had Area Under Curve values always higher than 0.75, indicating good predictive accuracy. The results concerning the distribution changes in all investigated taxa among the current (2015) and the different future scenarios are presented in Table S2 (Supplementary Material). Based on models' predictions, no taxon is expected to disappear from the study area. Nevertheless, the overall distribution extent of the great majority of taxa is going to be subjected to significant changes (Figure 2; Table 2). Specifically, for 13–16% of taxa, a severe reduction (>80%) in their current distribution was predicted (Figure 2) for the INT and USU scenarios and the two worst climate scenarios. The corresponding percentages for the above land-use scenarios and the mildest climate scenario were reduced by approximately 50%. Many taxa (27 to 44% of total examined taxa) were predicted to have a reduction in their distribution extent by 40 to 80% under the INT and USU land-use scenarios, independently of the climate scenario. The EXT scenario presented the lowest numbers of taxa with a significant reduction in their distribution extent (e.g., >40%), especially for the case of the SSP126 scenario. The same land-use scenario also resulted in the highest number (i.e., increased by 43 to 71%) of taxa with a significant gain (40 to >100%) in their distribution compared to the remaining two land-use scenarios and for all the climate scenarios.

The coefficients and statistical significance of the regression analyses are presented in Table S3 (Supplementary Material). Statistically significant association ($p < 0.05$) was found concerning the percentage change in taxa distribution between current and future conditions and their indicator values for light, temperature, and soil moisture (Figure 3a–c), but not for soil reaction and soil nitrogen content (Table S2). The type of association between percentage change in taxa distribution and indicator values was similar between climate scenarios, while it followed an opposite trend among the EXT scenario and the other two land-use scenarios (Figure 3a–c). Regarding the light indicator values, a high increase was found in the distribution of the shade-loving taxa compared to current conditions, as

well as a decrease in a similar magnitude of the light-loving taxa, for the INT and USU scenarios. For the EXT scenario, a very high decrease in the distribution of shade-loving taxa and a moderate increase in light-loving taxa were found. Regarding the temperature indicator values, no change in distribution extent (or very small increase) was predicted for the cold-adapted, while a high decrease was found for the most thermophilous taxa (heat-loving plant species), for the INT and USU scenarios. For the EXT scenario, this trend was opposite, showing a small decrease for the cold-adapted taxa, and no changes for the most thermophilous taxa. Finally, for the INT and USU scenarios, there was a high decrease in the distribution of drought-tolerant taxa and a moderate increase for taxa preferring moister soil conditions. For the EXT scenario, the drought-tolerant taxa had a stable distribution, while the more hydrophilous taxa had a small decrease.

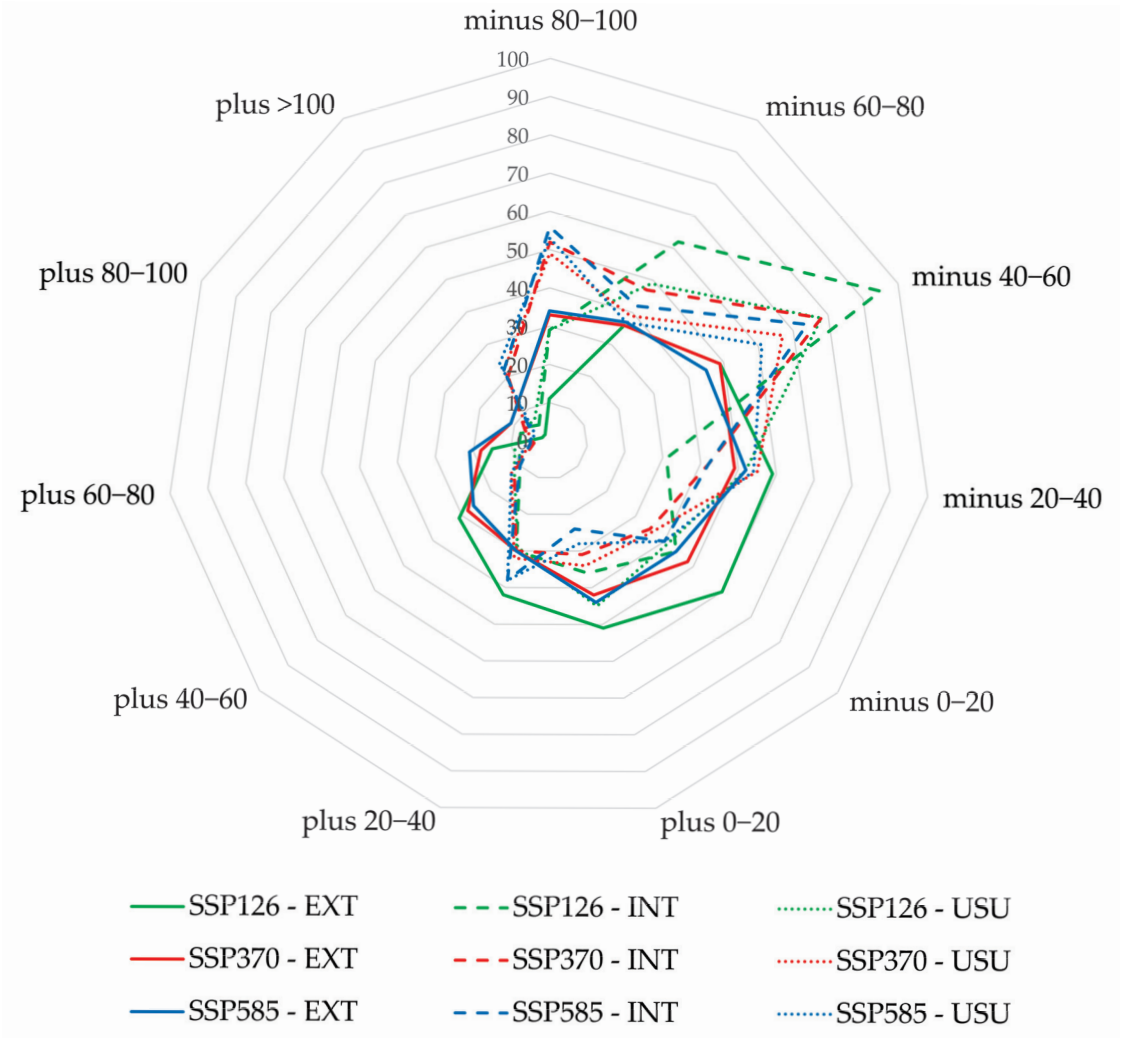


Figure 2. Number of species per category of percentage changes in their distribution extents in comparison to present conditions and the nine scenarios employed. The terms "minus" and "plus" indicate reduction and increase in species distribution (e.g., minus 80–100 means reduction in a species from 80 to 100% in terms of distribution extent). Percentages are presented for the combinations of the three climatic scenarios, namely, SSP126, SSP370, and SSP585, as well as the three socioeconomic scenarios, namely, extensive farming (EXT), intensive farming (INT), and business-as-usual (USU).

Table 2. Number of species per category of percentage change in distribution extent across the three climate (SSP126, SSP370, and SSP585) and three land-use (business-as-usual; USU, intensive farming; INT, and extensive farming; EXT) scenarios.

	SSP126 EXT	SSP126 INT	SSP126 USU	SSP370 EXT	SSP370 INT	SSP370 USU	SSP58 EXT	SSP585 INT	SSP585 USU
minus 80–100	11	29	29	33	52	49	34	56	53
minus 60–80	36	62	49	36	47	39	37	42	37
minus 40–60	49	95	78	49	78	67	45	74	61
minus 20–40	59	31	52	49	42	55	52	42	54
minus 0–20	60	44	41	48	35	36	44	40	40
plus 0–20	51	36	45	42	31	34	44	24	28
plus 20–40	42	30	29	30	30	32	30	38	38
plus 40–60	31	10	12	28	12	13	26	10	13
plus 60–80	15	8	9	18	4	5	21	5	6
plus 80–100	2	8	7	11	7	6	11	5	4
plus >100	2	5	7	14	20	22	14	22	24

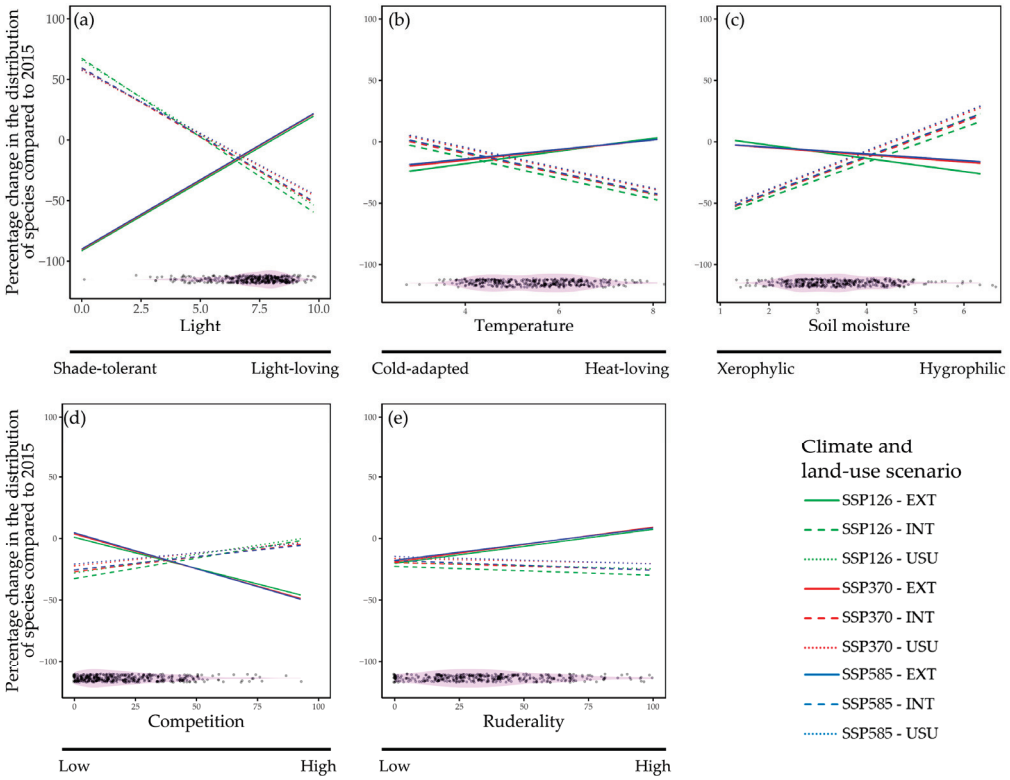


Figure 3. Associations between the percentage of change in the distribution extent of the modelled plant taxa and their indicator value for (**a**) light, (**b**) temperature, and (**c**) soil moisture, as well as their ecological strategies (**d**) competition, and (**e**) ruderality among the different scenarios and the current conditions (2015). For the abbreviations of climate and land-use scenarios, see Figure 1. Violin plots at the bottom of each plot illustrate the distribution of species values for each respective indicator.

The relation between the percentage change in taxa distribution extent under current and future conditions and the three plant ecological strategies was found statistically significant ($p < 0.05$) for competition and ruderality (except for the combinations of SSP370-INT and SSP585-INT scenarios), but not for stress tolerance (Table S2). Similar to the indicator values, the type of association between taxa distribution and ecological strategies was the same between climate scenarios but differed between land-use scenarios (Figure 3d,e). The current distribution extent of taxa of low competitiveness was predicted to decrease, while

the most competitive taxa had almost unchanged distribution, under the INT and USU scenarios. Under the EXT scenario, the distribution extent of taxa of low competitiveness remained almost unchanged in relation to current conditions, but competitive taxa showed a high decrease (Figure 3d). Regarding ruderality, a slightly decreasing trend in the current distribution extent of ruderals under the INT and USU scenarios was observed. In contrast, the current distribution extent of non-ruderal taxa was predicted to decrease, while the current distribution extent of ruderal species was expected to slightly increase under the EXT scenario (Figure 3e).

Regarding the distribution changes in taxa in relation to their preferential occurrence in plant communities, for all the communities, the differences in change trends between the climate scenarios were minor, while a striking difference in this trend was found between the EXT scenario and the other two land-use scenarios (Figure 4). The trends concerning land-use change were similar within the species of the two main groups of plant communities, namely, open habitats and forests, and opposite among them. Specifically, the distribution of the species differential of all open habitat communities was decreased according to the USU and INT scenarios and relatively to the EXT scenario, while those of the forest communities showed the opposite trends between the above-mentioned scenarios. Species distribution of all the forest communities was slightly increased (from 5 to around 25% in comparison with the current conditions) on the basis of the USU and INT scenarios, but was more sharply decreased (around 50%) according to the EXT scenario. The species of the riparian forest community (Figure 4K) showed an exceptionally high decrease (around 80%) for the EXT scenario. Concerning the species of the open-habitat communities, their distribution in four out of six communities showed a moderate increase (from around 25 to 50% in comparison with the current conditions) for the EXT scenario and a more pronounced decrease (about 50%) for the other two scenarios. As an exception, the species of the *Phlomis fruticosa* community (Figure 4B) showed a small decrease in the EXT scenario compared to current conditions and a high decrease (around 75%) for the other two scenarios. Species of the *Pteridium aquilinum* community (Figure 4F) were predicted with a high to very high decrease in their distribution for the extensive farming scenario and the remaining two land-use scenarios, respectively.

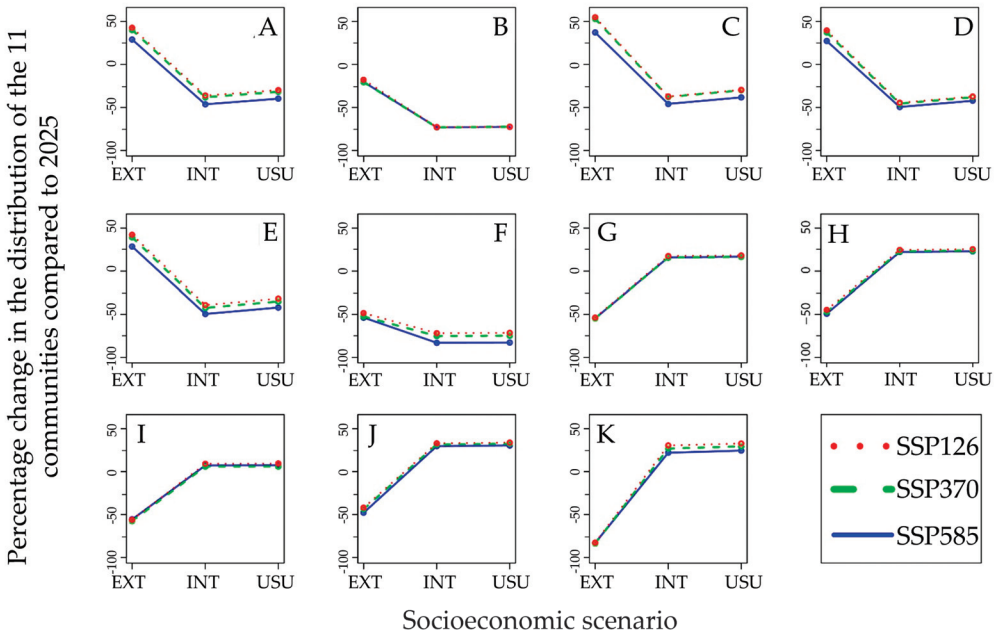


Figure 4. Percentage of change in the distribution of the species of the 11 communities, distinguished in the study area, for between the different scenarios (socioeconomic and future climate) and that of

2015 in relation to the current conditions. The different communities are indicated with capital letters ((**A**): *Chrysopogon gryllus* community; (**B**): *Phlomis fruticosa* community; (**C**): *Hordeum bulbosum* community; (**D**): *Alopecurus rendlei* community; (**E**): *Cynosurus cristatus* community; (**F**): *Pteridium aquilinum* community; (**G**): *Quercus frainetto* community; (**H**): *Carpinus orientalis* community; (**I**): Xero-thermophytic oak forests; (**J**): *Quercus cerris–Q. frainetto* community; (**K**): Riparian forests). The terms "ext", "int", and "usu" presented on the X-axes of the graphs indicate the three socioeconomic land-use scenarios (extensive farming, intensive farming, and business-as-usual, respectively).

4. Discussion

4.1. Characteristics of Our Case Study

In this study, we explored the combined effects of climate change and land-use change due to the abandonment of traditional agricultural activities. Ecosystems with particularly high levels of species diversity and endemism [49], complex historical legacies of human management, as well as biogeographical and ecological identity [7], such as those occurring in the wider Mediterranean biogeographic region, provide great opportunities for exploring such an effect. Our study area, namely, a sub-mountainous region in northern Pindus, is highly representative of such ecosystems, mainly concerning the land abandonment trends, despite its relatively small geographical extent. The spatial scale of studies exploring the combined effects of climate and land-use changes is occasionally considered a limitation, since these two biodiversity threats operate on different scales, whereas land-use changes are difficult to quantify on wide or global scales [4,17,50]. Our small-scale study area included only part of the total environmental variation, and it mainly allowed inferences about local-scale extinctions, since it did not include the full distribution of species. Nevertheless, we consider that such limitations are far outweighed by the following advantages of this study area. Firstly, this small scale allowed more precise quantification of the ecological and socioeconomic factors affecting nature and its management. Secondly, the local scale of the study area allowed the application of SDMs that would allow comparable inferences of impacts of climate change and land-use change. Although SDMs constitute the most common approach for studying the impacts of climate change on biodiversity [3], this is also not the case for the impacts of land-use change, which are usually studied through the space-for-time substitution approach [4], potentially obscuring the investigation of their combined impacts [15,51]. Finally, local-scale studies, which allow inferences on local-scale biodiversity, ecosystem functions, and services, have been found to be particularly important for management and conservation purposes [52,53].

Newbold et al. [53] argued that, in changing environments, local biodiversity determines many ecosystems' functions and services, and management at that scale may have a strong impact on biodiversity at higher scales. Furthermore, conservation targets should be set also at the local scale (i.e., protected area level), and conservation measures as well as the monitoring of their effectiveness should be implemented starting from this scale towards an effective conservation policy [52], whereas according to Sodhi et al. [54], "habitat and species preservation epitomize microscale conservation projects".

4.2. Impact of Climate and Land-Use Change on Species Distribution

During the last decade, the debate concerning whether climate or land-use change exerts a higher impact on biodiversity and how such impact may be differentiated across spatial or temporal scales and among different biogeographical regions or categories of organisms has been investigated in an increasing number of studies. On the one hand, recent reviews of such studies show that most of them resulted in a similar effect size of climate and land-use change [17,55]. On the other hand, in studies on a global scale, in which the combined effect of land-use and climate changes was predicted for the future,

results showed that climate change effects surpass by far those of land-use, especially after the year 2050 or 2070 [50,56].

Here, we found that a significant fraction of taxa (13–16%) will have a more than 80% reduction in their current distribution under some climate and land-use change scenarios, with approximately 9% of taxa having an even more than 90% reduction. According to the literature, such percentages of distribution reduction are used as thresholds to consider a species "committed to extinction" [2,3]. In our case, such reductions cannot be interpreted as extinctions, since our study area does not correspond with overall species distributions, and because newly occurring habitats (e.g., because of natural disturbances) may have been recolonized from neighboring areas through direct seed dispersal [57]. Limitations related to seed dispersal are unlikely to influence our results, given the high spatial resolution of the study area. Nevertheless, taking into account the substantial loss of species' habitats and that the herein recorded land-use change trends are similar across a much greater geographical extent, it would be reasonable to consider that such species will be locally represented by hardly viable sub-populations (i.e., locally extinct).

Our results indicated that land-use change had a more pronounced impact on species distribution than climate change in the investigated spatial and time scale. The impact of land-use change within our study area has already been highlighted at the landscape level over the past years, and significant changes have also been predicted for future conditions [22,31]. Specifically, a reduction in land cover diversity and an increase in habitat fragmentation were observed for the period 1945 to 2015, with these trends projected to continue under the USU and INT scenarios. The accompanying significant forest expansion, along with a reduction in farmland and open or semi-open habitats, is predicted and likely explains the high or moderate distribution decrease observed for a large number of species under these scenarios. In contrast, under the EXT scenario, open and semi-open habitats were predicted to expand and cover almost half of the landscape [31], justifying the percentage of species with significantly increased distributions under future conditions. On the other hand, the intensity of climate change, as imposed by the different climate change scenarios, was also found to affect changes in species distributions. This was indicated mainly by the high increase in the number of taxa that were predicted to lose more than 80% of their current distribution extent, under the two more extreme climate change scenarios, independently of the consideration of the land-use change scenario. Rathore et al. [58] also found a declining extent of species bioclimatic envelopes in the western Himalaya because of climate change, while Newbold et al. [53] noted that climate change may exacerbate losses caused by land-use changes. Our results suggest that both climate and land-use changes drastically affect the distribution of some species, with the latter also affecting a much higher number of species at a moderate level. Here, we assess the relative impact of climate and land-use change by comparing the differences in the impact of land-use change scenarios within the same climate scenario and vice versa. However, as the interactions between these two threats may be very complex [59], further investigation is needed to quantify their unique and joint impact, which is planned to be conducted on the basis of the data of this study.

Recent research has highlighted that the impact of each threat alone, as well as their combined effect, varies significantly according to location, biome, latitude, altitude, taxonomic group, land-use history, climate type, and spatial and temporal scales [2,4,16,17,58,60]. For instance, Newbold et al. [16] found that land-use changes will have a more severe impact on tropical areas than temperate ones (Mediterranean) and on areas with only a recent history of human management disturbances, but climate change will have a higher impact on areas with low climatic seasonality and on species in areas near their warmest distribution limit. Santos et al. [17] reported that climate and land-use

changes were found to affect different biodiversity attributes and to operate at different spatial and temporal scales, with climate change being more important in longer-term and broader-scale cases. A lot of studies report different relative effects of climate and land-use changes among categories of taxa, as well as among taxa [50,61,62]. According to Bellard et al. [60], the relative effect of different biodiversity threats depends on the local context (i.e., location, habitats, taxa) and methods and metrics used for its assessment, and thus the ranking of biodiversity threats is not always applicable for conservation prioritization purposes. Therefore, we can attribute the predominance of land-use effects in our results to the following reasons: (a) the small scale of the study area, which renders the effect of land-use changes as more important due to its higher variability compared to climate change [17]; (b) the temperate climate of the study area (Csa type according to Köppen–Geiger climatic classification) in which land-use change impacts usually prevail [16,60]; (c) the long history of traditional land-use of the study area, which has favored the adaptation of species in such use [16]; (d) the relatively short altitudinal gradient of the study area, which does not include high-altitude alpine areas, where climate change has a stronger influence on species appearing in the borders of their geographical and/or ecological space [58,60]; and (e) the highly significant changes in the landscape from 1945 to the predicted ones in 2055, according to the USU and INT scenarios [16,31], which render some land cover types as very rare, thus leading to a great habitat loss, especially for the species of open habitats. The last reason is expected to be the most influential, and it also explains the great difference in the results between the EXT and the other two scenarios (see also below).

4.3. Ecological Characteristics of Species Distribution Changes

Ecological indicator values of species are semi-quantitative estimates of environmental conditions and comprise a very useful tool for monitoring purposes [63–65]. The pattern of decrease in thermophilous species and the increase in the more soil moisture-demanding species for all climate change scenarios under the USU and INT scenarios indicated an opposite response of species in relation to what would be expected because of temperature rise and precipitation reduction, predicted especially for the SSP370 and SSP585 scenarios [37]. Specifically, it showed an antagonistic effect of land-use changes because of abandonment in relation to that of climate change, caused by the progressive establishment of shrub and tree species due to the reduction or cessation of disturbances in the landscape. Therefore, for as long as secondary succession proceeds, the micro-environment (microclimate) within the vegetation stands becomes more shaded and thus cooler and moister, as it is also supported by the simultaneous significant increase in shade-tolerant species and the corresponding decrease in light-loving species for the USU and INT scenarios.

Microclimate can differ greatly from climatic averages [66], since vegetation canopy and, especially, the canopy of tree species affect photosynthetically active radiation, soil water content, air humidity, and soil and air temperature in the understory layer [67]. It has been found that forest habitats function as a "thermal insulator" against global warming due to anthropogenic climate change, as well as extreme climate events [68,69]. Our results indicate indirectly, through the species indicator values, that land-use changes because of land abandonment (increase in forests and decrease in open habitats) under the USU and INT scenarios will have a higher impact than climate warming, at least until 2055. On the other hand, this is not the case for the EXT scenario, for which almost opposite trends were found compared to the two other land-use scenarios, indicating more of a synergetic interaction between land-use and climate change, rather than an antagonistic one. This is in agreement with the findings of Zellweger et al. [69], who showed that the reduction in forest cover may lead to the exacerbation of climate change's negative impacts on

species distribution. Perring et al. [63] and Saatkamp et al. [64] also found an antagonistic effect of the microclimate against the "thermophilization" and "xerophytization" of plant communities in vegetation stands with higher tree canopy, which was based on species indicator values.

Ecological strategies showed a corresponding pattern with that of indicator species values. Ecological strategies reflect the functional response of plant species and their communities to different intensities of stress and disturbance [19,20], and thus constitute an appropriate tool for assessing the impacts of environmental changes [70–72]. Here, the competitive dimension of plants' life strategy was found to increase for the USU and INT scenarios in the future, while ruderality decreased. This may be attributed, as in the case of ecological indicator values, to the increase in forest cover and the decrease in open habitats in these scenarios. Mastrogianni et al. [28] indeed found that the highest level of functional differentiation of vegetation communities in the study area was observed between forest and grassland communities, with forests hosting more competitive taxa, and grasslands more ruderal ones. For the EXT scenario, the opposite trends were found, and with a steeper slope of the trend. This indicates that the historical land-use changes already made until 2015 have already changed the landscape significantly, and the future (predicted) changes will almost complete these changes in terms of species ecological strategies by further minimizing non-competitive and ruderal species. Dalle Fratte et al. [71] in a regional scale study (northern Italy), also found the predominant impact of land-use change on plant traits, attributed to differential effects of land-use and climate change, with the former causing more abrupt differentiation of traits and the latter acting more gradually on the results of land-use changes. Their results, especially for the sub-mountainous part of their study gradient, agree with ours, indicating that future land-use circumstances will favor more competitive and/or shade-tolerant species. Furthermore, Chai et al. [73] found the predominance of ruderal species at the pioneer stage of vegetation succession, their replacement by a higher variance of intermediate plant ecological strategies in the intermediate stages of succession, and finally the dominance of competitive or competitive/stress-tolerant species in the last successional stages represented by forests. From a conservation management perspective, these findings underline the importance of retaining at least part of the historical disturbance regimes, such as low-intensity grazing or mowing, to preserve the full spectrum of ecological strategies across the landscape. Such interventions can maintain structurally diverse habitats and prevent the competitive exclusion of stress-tolerant or ruderal species, which often support unique ecological functions and contribute disproportionately to regional plant diversity.

The results concerning species distribution changes in relation to their preferential occurrence in plant communities align with the overall results. Land-use change was again found to have a higher effect on the observed patterns compared to climate change. These patterns were found to be common among the plant communities of each major vegetation type (open habitats or forests) but different between them, highlighting the decisive role of the distribution pattern of the two vegetation types. The comparatively small percentage increase in the species distribution of forest communities in relation to the at least double decrease in distribution of species of open habitats for the USU and INT scenarios probably is due to the land cover types trends described by Kiziridis et al. [31] for the study area, and indicates that the changes in the distribution of species and their communities because of land abandonment are reaching towards a saturation stage. Similarly, Chontos and Tsiripidis [21] found that land abandonment and the corresponding landscape changes in a region of southern Pindos (central Greece) have also reached their semi-final stage in the last decade.

Additionally, these observed patterns of distribution changes enable further inferences with important implications for conservation. This is particularly the case for one community of open habitats and one forest habitat, namely, the *Phlomis fruticosa* community and the riparian forests, respectively. As outlined below, our study highlights two examples of high conservation value communities, from which one will be critically endangered in the future due to land abandonment, while the second has been naturally restored and will continue to be restored in the future for the same reason.

On the one hand, riparian forests are expected to be positively affected by land abandonment. Specifically, the high suitability of the sites of these forests for the expansion of farmlands under the EXT scenario is possibly the reason for the very high decrease in their species distribution under this scenario. On the other hand, the *Phlomis fruticosa* community is expected to be negatively affected by land abandonment. It constitutes the most thermophytic and xeophytic community in the study area but occurs at higher altitudes compared to the other communities of open habitats according to the results of Mastrogianni et al. [28]. It is also the richest community in terms of taxonomic and functional diversity, albeit with a small difference compared to the other semi-natural grassland community of an advanced but stable successional stage, the *Chrysopogon gryllus* community. These two communities of semi-natural grasslands comprise typical examples of high conservation value vegetation types that have been formed by traditional human management practices (especially grazing) and are highly threatened by land abandonment [11,13]. The small distribution reduction in the species of the *Phlomis fruticosa* community, even for the EXT scenario, which favors significantly the cover of open habitats, as well as its very high decrease for the remaining land-use change scenarios, contradicts the trends found for the other open habitat communities. This peculiar trend of the distribution of the species of *Phlomis fruticosa* community may be attributed to the fact that this community has been formed mainly by grazing, which, however, shows decreasing trends with time in the study area [22] and is predicted to further reduce until 2055 [31]. Furthermore, its occurrence in higher altitudes and steeper slopes than other open habitat communities renders this community more prone to replacement by forests [31], as these conditions favor their establishment in the study area [31]. The same ecological characteristics of the *Phlomis fruticosa* community make its area less suitable for farmland re-establishment under the EXT scenario, which explains the fact that its differential species area does not increase under this scenario.

Therefore, the results of species distribution changes in relation to their preferential occurrence in plant communities highlighted special case habitats and species that may be more threatened in the future under certain scenarios of land-use policy and/or the expected environmental changes.

4.4. Concluding Remarks and Conservation Implications

Mainly, we found that (a) land-use changes exert a much higher impact on species distribution than climate change, and (b) both changes may drive a significant part of plant taxa (around 10 to 15%) to be threatened with very high (>80%) distribution reduction. These findings were interpreted on the basis of the spatial (local) and the temporal (year 2055) scale of the study, its temperate macro-climate, the altitudinal gradient of the study area, its long history of traditional land-use by humans and significant changes in land cover types during the past 77 years (1945–2015), and saturation of the landscape changes according the past trends in the next 40 years (2015–2055).

Such a pronounced impact of land-use change over climate change on plant species distributions echoes patterns reported also in other Mediterranean and European submountainous landscapes [16,74]. However, we acknowledge limitations in direct generalization. Local factors such as landscape configuration, microclimatic heterogeneity, and the

intensity and legacy of traditional land uses can substantially modulate species responses. Therefore, extrapolation of the herein identified trends should consider site-specific ecological and socioeconomic contexts. Future studies at regional and continental scales would be essential to confirm the consistency of these patterns across gradients of climate, land-use, and biodiversity.

Land abandonment may have already progressed significantly in many places of the world, as in our study area [22,31], and in such areas, a small time window remains to conserve species and habitats before they are represented by non-viable/persistent populations/patches at the landscape level. Retaining traditional anthropogenic disturbances, such as grazing or re-introducing naturally caused disturbances, is crucial for the conservation of biodiversity at the landscape level [75,76].

Land abandonment leads to an increase in the extent of high-canopy vegetation, which may buffer the climate change-induced temperature rise and precipitation reduction, through their influence on the microclimate [68], but such a positive impact mainly concerns species of forest habitats. Considering the high taxonomic diversity of the grasslands of the study area and their very high taxonomic turnover with forests [28], it is shown that a very high proportion of the total species diversity (γ) at the landscape level will not be favored by the aforementioned buffering effect of forests. Therefore, it is becoming prevalent that conservation plans at the landscape level, which are detailed and based on appropriate data, are needed to counteract the negative impacts of land abandonment. Such plans will also take advantage of the natural restoration of habitats they enhance, to minimize losses and maximize gains in terms of biodiversity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land14071438/s1, Table S1: Minimum number of indicator taxa per plant community within the general study area; Table S2: Percentage change of distribution extent per species, across the three climate (SSP126, SSP370 and SSP585) and three land-use scenarios compared to their current (2015) distribution; Table S3: Coefficients and statistical significance of the regression analyses between the percentage of change in the distribution extent of the modelled plant taxa and their indicator values, as well as ecological strategies.

Author Contributions: Conceptualization, S.T., D.A.K., and I.T.; methodology, S.T.; formal analysis, S.T., A.M., and D.A.K.; investigation, A.M., F.X., M.P., and I.T.; writing—original draft preparation, S.T. and I.T.; writing—review and editing, S.T., A.M., D.A.K., F.X., M.P., and I.T.; visualization, A.M.; funding acquisition, I.T. All authors have read and agreed to the published version of the manuscript.

Funding: The present study was supported by the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "1st Call for H.F.R.I. Research Projects to support Faculty Members & Researchers and the Procurement of High-cost Research Equipment Grant" [Project Number: 2333].

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

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

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Revealing the Spatiotemporal Changes in Land Use and Landscape Patterns and Their Effects on Ecosystem Services: A Case Study in the Western Sichuan Urban Agglomeration, China

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Abstract: Land use change significantly influences landscape pattern adjustments, thereby altering ecosystem functions and service flows, ultimately impacting ecosystem service value (ESV). However, previous studies have often examined the impacts of land use change and landscape patterns on ecosystem services from a one-dimensional perspective, overlooking the complex interactions among these factors. This study proposes a "process–structure–value" response framework and applies it to a case study of the western Sichuan urban agglomeration. Its aim is to identify the spatial and temporal characteristics of land use and landscape pattern evolution. Additionally, it quantitatively evaluates the synergistic effects of these changes on ESV evolution from 2000 to 2020 using a correlation analysis. The results show that, over the past 20 years, the study area experienced a significant expansion of construction land by 184,729.41 hm^2, leading to the dispersion and fragmentation of arable land, grassland, and waters, resulting in an overall trend of fragmentation and diversification in landscape patterns. The ESV increased by CNY 2.619 billion, primarily due to the increased ESV associated with forest land and waters. This study found that the synergistic effects of land use processes and landscape pattern structures significantly enhanced ESV. The transition from construction land and arable land to forest land and waters notably improved the ESV. Meanwhile, increased landscape diversity and patch connectivity further enhanced the ecosystem service function. Furthermore, the ecological environment of the study area remained vulnerable despite the increased ESV. Overall, the results highlight the significant correlation between changes in land use processes, landscape patterns, and ESV, emphasizing the necessity of integrating the "process–structure–value" framework in future research to comprehensively assess the responses of land use and landscape patterns to ESV, providing a more comprehensive reference for land use planning and policy development.

Keywords: ecosystem service values; landscape pattern; land use change; mountain urban agglomerations; process–structure–value

1. Introduction

Ecosystem services (ESs) encompass all of the benefits that humans derive from ecosystems and are commonly categorized into provisioning, regulating, supporting, and cultural

services. Provisioning services include the supply of food, water, and timber, whereas regulating services involve climate regulation, water purification, and pest control. Supporting services encompass essential ecological processes such as soil formation and nutrient cycling, while cultural services offer recreational opportunities, tourism benefits, and spiritual enrichment [1]. These ESs serve as fundamental environmental prerequisites for human survival and societal development [2]. ESs are significantly influenced by changes in land use. Driven by the rapid expansion of the global economy and population growth, urbanization and the proliferation of human settlements have intensified land overuse. This has adversely affected on climate regulation, biodiversity conservation, habitat protection, and soil and water conservation [3], ultimately culminating in environmental degradation [4]. Changes in the spatial configuration of land use can induce structural alterations in landscape composition, leading to fragmentation, reduced habitat connectivity, biodiversity loss, and increased risks of migration corridor disruption and habitat degradation, thereby undermining ESs. In recent years, there has been a growing research focus on mitigating the decline of ESs [5–7]. Studies have suggested that optimizing land use and landscape configuration can significantly enhance the sustainable provision of ESs [8,9]. Therefore, understanding the synergistic effects of land use dynamics and landscape patterns on ESs is crucial for optimizing landscape configurations and improving the provision of ecosystem service value (ESV).

Regional land use change has garnered considerable attention in international ecological and environmental research [10,11]. Land use change serves as a key indicator of the profound impact of human activities on the natural environment. Studies have indicated that land use change is a major driver of changes in terrestrial ESV [12,13]. By altering surface physical parameters, land use change affects ecological processes and ecosystem structures, leading to substantial shifts in ESs [14–16]. Monetizing ESs not only reveals the effects of land use change, but also facilitates the tracking of ES dynamics, thereby providing essential feedback for landscape planning. Consequently, assessing the impacts of land use change on ESs has become a focal point in global ecological and environmental research, drawing growing scholarly attention to its influence on ESV. Research indicates that land use change primarily affects ESV through multiple dimensions, including land use type, intensity, and landscape configuration [17–20]. For example, Han et al. [21] explored the effects of land use type changes on ESV, emphasizing the redistribution of ESV among various land categories. Zhong et al. [22], employing a spatiotemporal regression model, demonstrated a significant relationship between landscape pattern indices and ESV, highlighting the positive impacts of improved landscape connectivity and increased diversity. Zhang et al. [23] examined the impact of land use changes on ESV in Ezhou City, utilizing the Markov-FLUS model to simulate future land use and ESV trajectories under various scenarios. Existing research predominantly investigates the effects of land use types or landscape configurations on ESV in isolation. However, such one-dimensional approaches often overlook the interdependencies between land use types and landscape structures, thereby limiting the ability to comprehensively understand their complex and multifaceted impacts on ESV [24,25]. A systematic framework is thus required to thoroughly investigate their interrelationships and underlying impact mechanisms. To bridge this gap, this study proposes the "process–structure–value" theoretical framework, which integrates land use processes, landscape patterns, and ESV to analyze their spatiotemporal dynamics and interdependent responses. This framework offers a novel pathway to mitigating ESV degradation, refining urban landscape planning, enhancing ecological conservation, and promoting sustainable development.

The evaluation of ESV has emerged as a primary focus in sustainable development research. The assessment methods have been progressively improved and can be broadly

categorized into methods based on raw data and unitary values [20,26,27]. Raw data-based methods, including productivity methods, travel cost methods, carbon tax methods, and biophysical modeling efforts, provide valuable insights for decision-making and environmental management by calculating ESV directly from the analysis of raw data [28,29]. While these methods apply to small-scale regions or single ecosystems, their complex input parameters and assessment processes limit their applicability for large-scale and long-term dynamic valuation, thereby hindering the standardization of assessment methods [30,31]. Among these methods, the equivalent factor approach for value assessment is the most widely used [32,33]. This approach is suitable for large-scale evaluations, as it better reflects accurate ESV and more clearly identifies spatiotemporal trends in service value. Costanza et al. [1] established a classification framework and valuation system for ESs on a global scale, highlighting the importance of converting ESV into monetary units, which subsequently garnered international attention to ESV and ecological assets. In 1999, Ouyang et al. [34] conducted the first comprehensive evaluation of terrestrial ecosystem services in China. Subsequently, in 2008, Xie et al. [35] developed a unit area equivalent table for the value of TES in China by revising the research outcomes of Costanza et al. [1]. Drawing on the expertise and input of Chinese researchers and adapted to local conditions, this work assigns monetary values to the various ESs provided by China's ecosystems. However, the applicability of ecosystem service equivalent factors can be influenced by geographic, social, and cultural contexts. The value of the same ES differs under different regional background conditions, and the generalized equivalent factor is unable to fully capture this variation [36]. To address this challenge and enhance assessment accuracy, more studies have begun to examine the specific impacts of land use change on ESV. Scholars employ case studies and refined equivalent factor methods to explore the regional heterogeneity of these effects. Recent studies [7,21,37–40] have yielded significant findings at global, national, and regional scales. Xiao et al. [27] focused on quantifying the impact of land use changes on ESV in the ecologically vulnerable Aksu River Basin located in the arid region of northwest China. Ocloo et al. [41] examined the spatial dynamics of land use and landscape patterns in Ghana, West Africa, from 1995 to 2020 and their implications for ESs. Zhang et al. [42] used adjusted value coefficients to assess ESV and quantified the critical relationship between land use change and the dynamics of ESV. Although urban agglomerations are a key scale for studying urbanization and land use change, their impact on ESs, especially in mountainous regions where human–environment conflicts are more pronounced, has received limited attention.

The Western Sichuan Urban Agglomeration (WSUA), a typical mountainous urban cluster, plays a crucial role in ecological functions; its complex topography and resource endowments exacerbate environmental pressures. As economic development and urbanization have progressed rapidly, land use patterns have undergone significant changes, resulting in increased pressure on land resources, intensified landscape fragmentation, and ecological issues such as biodiversity loss and soil erosion. These changes have not only had a profound impact on ESV, but have also exacerbated regional ecological vulnerability, thereby restricting sustainable development. In addition, the WSUA, as the economic core of Sichuan Province and a typical region experiencing rapid urbanization, serves as an important development hub in Southwest China. The conflict between urban expansion and the ecological environment is particularly evident during rapid urbanization, making the WSUA a highly representative case [43]. Hence, this study adopts the "process–structure–value" interdisciplinary evaluation framework to systematically examine how land use changes drive the evolution of landscape patterns and influence ESV from a theoretical perspective. The specific research objectives are as follows: (1) to systematically quantify the mechanisms through which land use changes in the WSUA influence the dynamic evolution of landscape patterns; (2) to assess ESV changes in the WSUA; (3) to construct

a comprehensive model based on the "process–structure–value" theory and explore how land use processes and landscape patterns jointly drive the spatiotemporal dynamics of ESV; and (4) to identify key land use processes and landscape pattern characteristics that impact ESV and propose targeted strategies to enhance it. Identifying key land use and landscape pattern features that affect ESV in the WSUA will provide a theoretical basis for localized ecological restoration, construction, and management in mountainous urban agglomerations.

2. Materials and Methods

2.1. Study Area

The WSUA is located in the central and western regions of China (29°25′–33°02′ N, 102°49′–105°57′ E) and encompasses eight prefecture-level cities—Chengdu, Deyang, Meishan, Leshan, Ya'an, Ziyang, Mianyang, and Suining—covering an area of approximately 86,000 km^2 (Figure 1). The topography of the WSUA is characterized by high elevations in the southwest and northwest and lower elevations in the east, with diverse terrain including plains, hills, and mountains. This varied landscape contributes to the region's distinct geographic features and complex urban structures, while also resulting in a fragile and ecologically sensitive environment. Most of the region experiences a subtropical monsoon climate. Meanwhile, due to its higher elevation, the western region has a plateau mountainous climate. The region receives an average annual precipitation of over 1000 mm, with distinct seasons, rich water resources, and high plant biodiversity. This region serves as a crucial ecological barrier in the upper reaches of the Yangtze River and includes numerous nature reserves as well as the Giant Panda National Park. The WSUA had an average annual GDP growth rate of 13.15%, a permanent population of 41.9 million in 2020, an urbanization rate of 64.58%, and an annual urbanization growth rate of 1.52%. As a key area for ecological development and economic expansion, the WSUA is undergoing rapid economic growth and urbanization, thereby intensifying the impact of human activities on the ecosystem. This region's distinctive geographical setting and complex terrain contribute to its high ecological sensitivity, thereby amplifying the effects of land use changes and landscape structure evolution on ESV. Thus, a comprehensive evaluation of these effects is urgently needed to optimize land use planning and support regional sustainable development.

2.2. Theoretical Mechanisms

This study integrates the ecosystem service cascade paradigm proposed by Haines-Young et al. [44] with the "Pattern–Process–Service–Sustainability" framework developed by Fu et al. [45] to develop the "process–structure–value" theoretical model. This model examines how changes in land use and landscape patterns influence ESV, providing theoretical insights for addressing environmental change. The ecosystem service cascade paradigm emphasizes the hierarchical relationships between ecosystem structure, processes, functions, services, and human well-being, illustrating how natural systems provide services through ecological processes and functions, thus impacting human societies [44]. Meanwhile, the "Pattern–Process–Service–Sustainability" paradigm underscores the interdependence between landscape patterns and environmental processes, asserting that landscape patterns influence the intensity of ecological processes, which, in turn, determines ecosystem service provision. Additionally, it incorporates the sustainability of ES and socio-ecological feedback mechanisms [45,46]. Drawing on both paradigms, this model constructs a more holistic analytical framework. Firstly, this framework offers a novel perspective on human–environment interactions. Unlike traditional models, it emphasizes the temporal evolution of land systems and landscape patterns, aiming to quantify

land system value, clarify land use and conservation priorities, and identify high-value areas requiring prioritization for protection. Secondly, this model builds on the cascade paradigm's logic of transforming ecosystem functions into services and values, emphasizing the mediating role of landscape patterns in this transition. Finally, it incorporates the "Pattern–Process–Service–Sustainability" paradigm by treating land use change as a key driver of ecosystem service provision through spatiotemporal landscape pattern evolution, thereby informing land use decision-making. This model transcends the limitations of traditional unidirectional analyses by emphasizing the dynamic interconnections among these three components. It elucidates how land use change reshapes ecosystem service value through landscape pattern reconfiguration and proposes optimization strategies to enhance ecosystem sustainability.

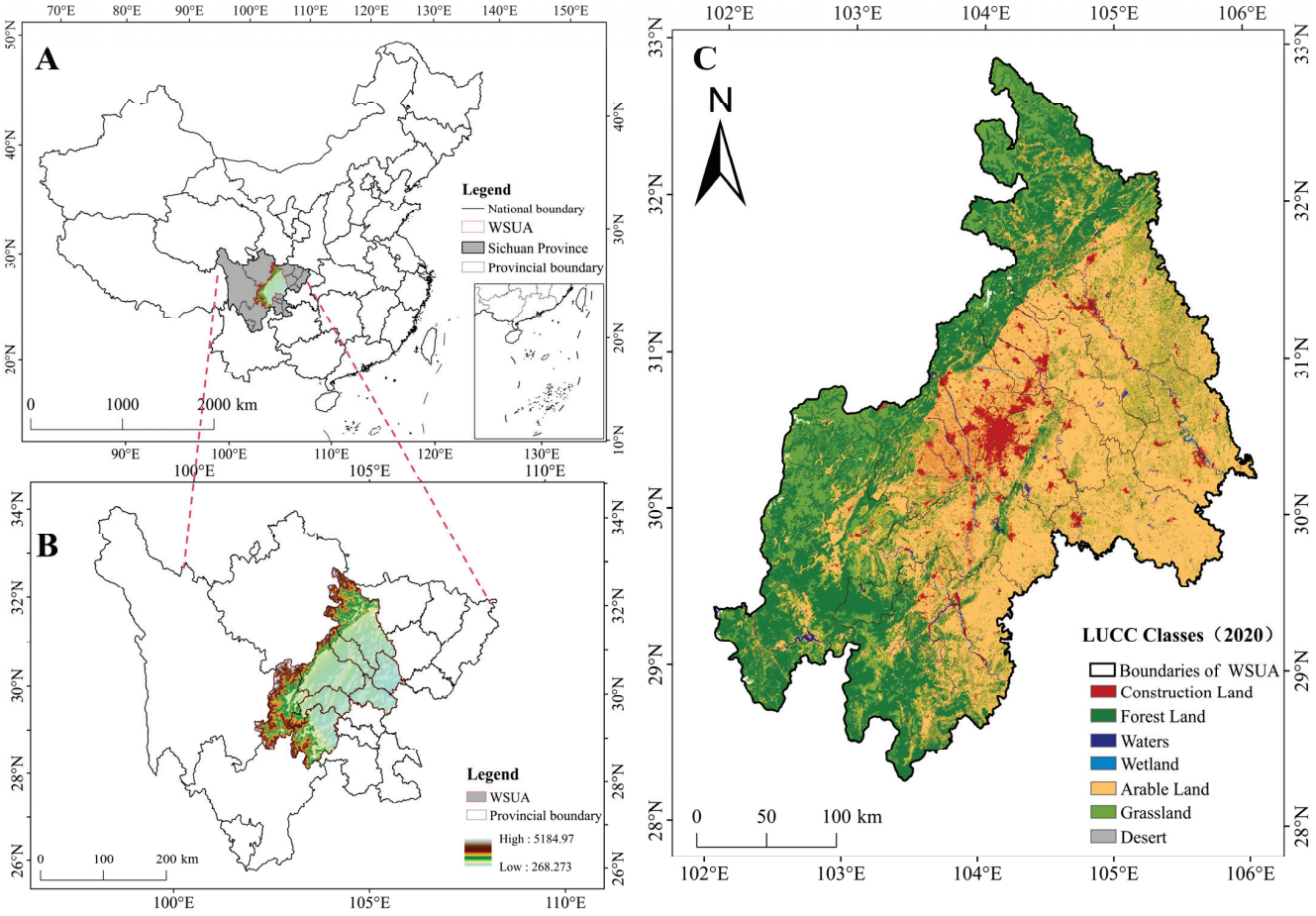


Figure 1. Location map of the WSUA. (**A**) Location of WSUA in China. (**B**) Location of WSUA in Sichuan Province. (**C**) WSUA 2020 land use types.

The "process" focuses on land use changes, encompassing the dual effects of natural factors and human activities on land function. Natural processes (e.g., climate change and terrain evolution) and human processes (e.g., urbanization and agricultural expansion) jointly influence land functions, reflecting the dynamic competition and trade-offs between different land use types, particularly in the context of urban expansion, agricultural development, and ecological protection [46]. Land use processes are the key driving force behind landscape pattern adjustments, revealing the complex interaction between human activities and the natural environment. "Structure" refers to the spatial configuration and heterogeneity of landscape patterns, including connectivity, diversity, and patch size and shape [47]. Landscape structure is the spatial expression of the impact of land use processes on natural systems, and it also influences the stability, connectivity,

and service capacity of ecosystems. By analyzing changes in landscape structure, we can understand the interactions between different land use types and the specific impacts of these changes on ecosystem service provision and ecological functions. "Value" refers to the measurement of ES, denoting the contribution of ecosystems to human well-being by providing goods and services and the benefits humans derive from ecosystems [48–50]. These benefits can be expressed in monetary units or other metrics, such as water source protection, air purification, and food provision [51]. By regulating the spatial configuration and heterogeneity of landscape patterns, land use changes significantly impact the supply and distribution of ESV. Changes in ESV, through feedback mechanisms, affect land use decisions and landscape pattern optimization, forming a dynamic coupling relationship between the "process–structure–value". Integrating land use processes, landscape patterns, and ESV helps uncover the driving mechanisms of ecological services and key regulatory factors. The "process–structure–value" model offers a comprehensive perspective for analyzing interaction mechanisms and promoting the sustainability of ecosystem service value, thereby providing scientific support for policy development (Figure 2).

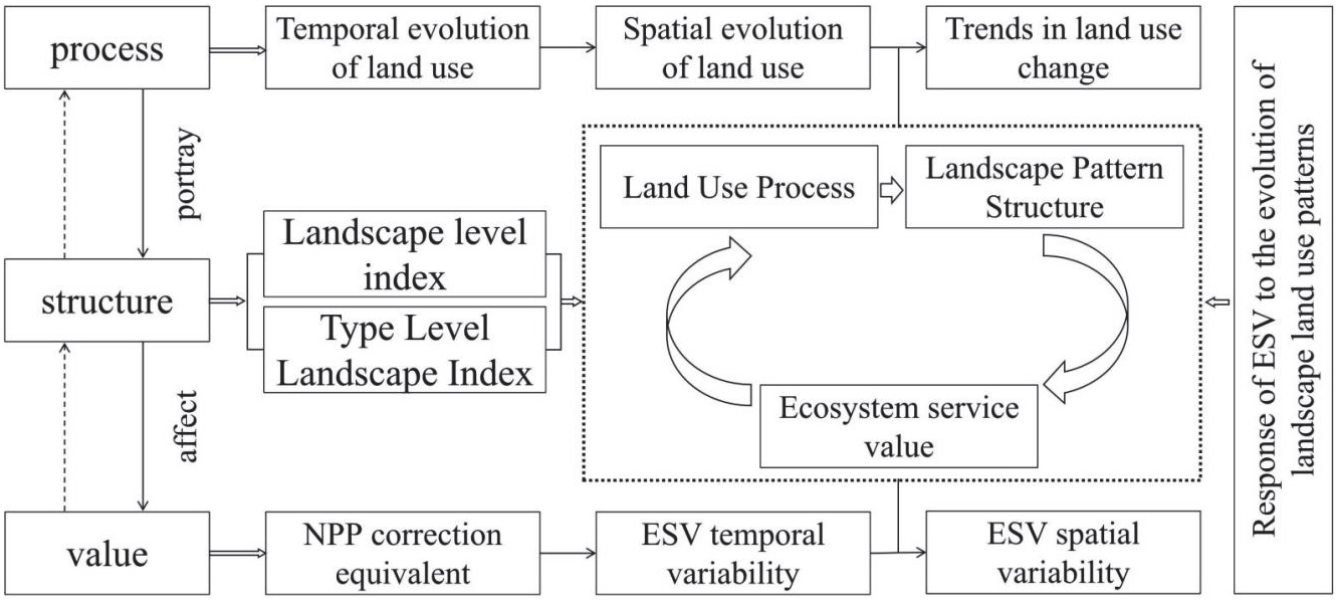


Figure 2. The theoretical model of "process–structure–value".

Based on the above considerations, we selected land use, landscape pattern, and ESV as representative indicators of process, structure, and value, respectively. The research framework of this study comprises three components. First, the "process" component utilizes remote sensing imagery from 2000 to 2020 and applies spatial statistical analysis and transition matrix methods in ArcGIS 10.2 to analyze land use change processes. The "structure" component is represented by landscape metrics calculated using Fragstats 4.2, including patch density (PD), mean patch size (MPS), edge density (ED), aggregation index (AI), landscape shape index (LSI), Shannon's diversity index (SHDI), division index (DIVISION), and contagion index (CONTAG). Second, the "value" component explores the spatiotemporal evolution of ESV based on land use data from 2000 to 2020, employing a modified equivalent factor method. Finally, to capture the dynamic coupling relationships among "process–structure–value", we developed a land use process–ESV response model (Figure 3).

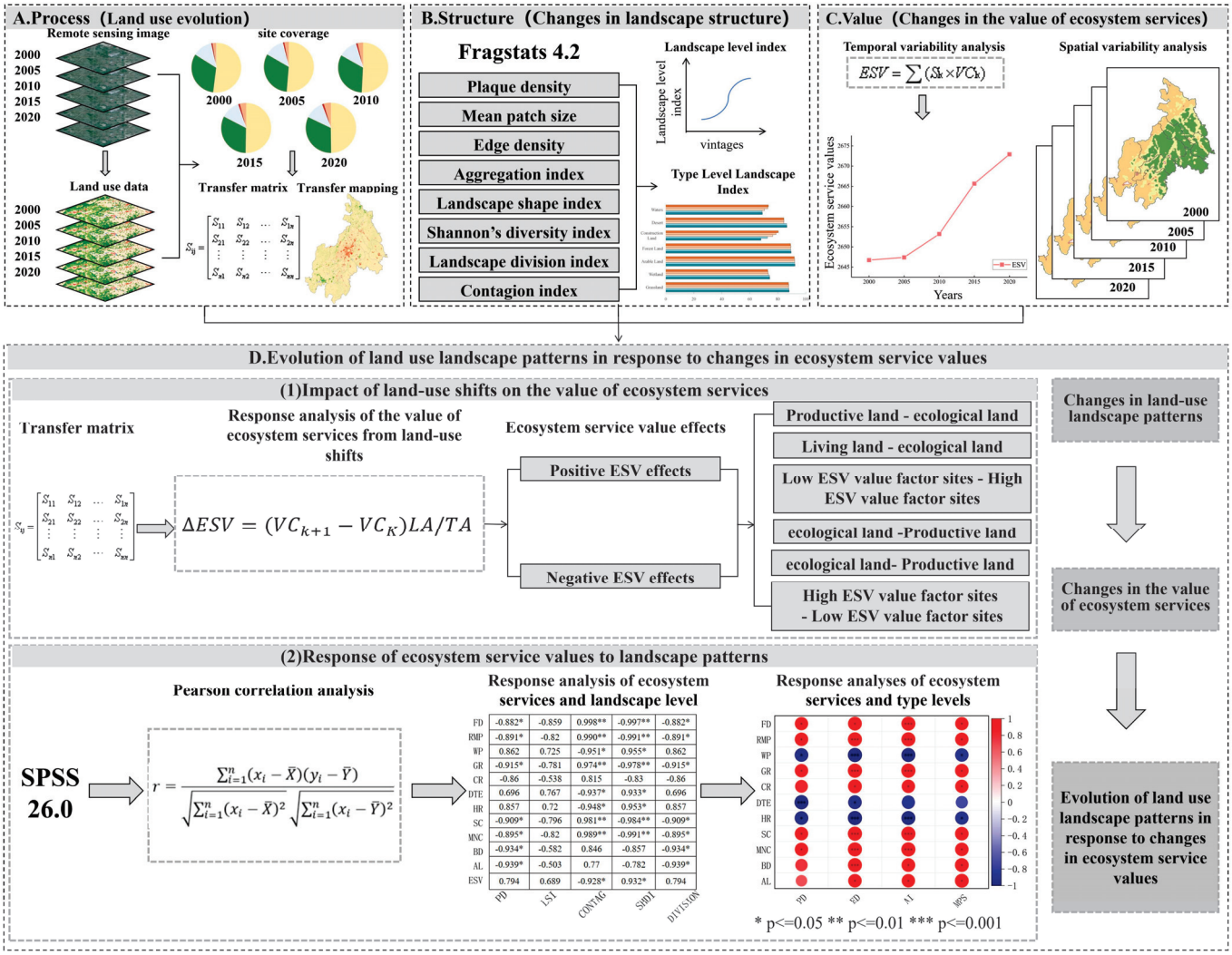


Figure 3. Technical route and research methodology. (**A**) Process (Land use evolution). (**B**) Structure (changes in landscape structure). (**C**) Value (changes in the ESV). (**D**) Evolution of land use landscape patterns in response to changes in ESV.

2.3. Data Sources

We acquired land use data spanning five periods at five-year intervals (2000–2020) from the Resource and Environment Science Data Center (https://www.resdc.cn, accessed on 21 October 2022). The data originated from the China National Land Use and Cover Change (CNLUCC) dataset, which underwent nationwide field surveys and random-sampling-based accuracy assessments [52]. Approximately 10% of county-level administrative units were randomly sampled for accuracy assessment, thereby ensuring high data quality and reliability [53]. This dataset has been widely utilized in numerous academic studies [21,54–57]. The data were generated using the human-assisted visual interpretation of Landsat TM/ETM imagery, featuring a spatial resolution of 30 m and an accuracy rate exceeding 85%. Based on the classification system defined in "Equivalent Functions of Unit Area Services of China's Terrestrial Ecosystems" [58], this study reclassified 25 secondary land use types into the following seven categories: arable land, forest land, grassland, waters, wetlands, construction land, and desert. Among these, given the relatively low ESV of construction land, assigning it a zero value was deemed appropriate. Meteorological data, including temperature and precipitation, were acquired from the National Meteorological Science Data Sharing Platform (http://data.cma.cn). Statistical data, including the sown area, grain yield, and grain prices, were primarily sourced from the Sichuan Statistical Year-

book, city-level statistical yearbooks, and the Compilation of National Agricultural Product Cost–Benefit Data.

2.4. Detecting Spatial and Temporal Changes in Land Use Processes and Landscape Pattern Structures

2.4.1. Detection of Spatiotemporal Changes in Land Use Processes

This study examines the spatiotemporal dynamics of land use processes in the WSUA from 2000 to 2020, using ArcGIS 10.2 as the analytical platform. We quantified the changes in both area and proportion of seven land use types over the five time points. A land use transfer matrix was used to analyze the transitions among various land use types [59]. Subsequently, we utilized the raster calculator to identify the spatial characteristics of land use transitions between successive periods.

2.4.2. Analysis of Landscape Pattern Structures

Landscape indices capture information about landscape patterns, providing a quantitative approach to describe both the structural composition and spatial configuration [60]. This study selected two landscape scales—landscape-level indices and type-level indices—based on their distinct functions and characteristics, in consideration of the unique context and research aims of the WSUA. Landscape-level indices are typically used to evaluate the overall landscape characteristics and spatial patterns across the entire area. In contrast, type-level indices focus more on the characteristics and patterns within and among specific land use or land cover types [61]. We selected five landscape-level indices (PD, LSI, SHDI, DIVISION, CONTAG) and four type-level indices (MPS, ED, AI, PD). This study employed Fragstats 4.2 to compute the selected landscape pattern indices, with land use/land cover classification maps (typically in raster format) as input. The ecological significance of each landscape pattern index is detailed in Table A2.

2.5. Ecosystem Services Valuation

This study adopts the global ecosystem service value estimation method proposed by [1], selecting 11 types of ES, including food production (FP), raw material production (RMP), water supply (WS), gas regulation (GR), climate regulation (CR), decontamination of the environment (DTE), hydrological regulation (HR), soil conservation (SC), maintaining nutrient cycling (MNC), biodiversity (BD), and esthetic landscape (AL). The ESV assessment was conducted using the equivalent factor method, which was well-suited for large-scale ecosystem service assessments and accurately represents ESV using a standardized quantitative framework [22]. The revised "Equivalent Factor Table of Ecosystem Service Values" proposed by Xie et al. [58] was used as the basis for the calculations. Adjustments to the regional ESV were made based on biomass variations, particularly considering the extensive areas of arable and forest lands in the WSUA. Net primary productivity (NPP) was used as a proxy for biomass, and the ESV equivalent factors were calibrated accordingly. The method for estimating NPP was based on the formulas provided in [62,63]. The improved methodology more accurately captures the unique ecological characteristics of the region, ensuring that the estimations better align with local conditions.

The revised model for ESV was as follows:

$$NPP = 3000 \times \left[1 - e^{-0.0009695(V-20)}\right] \tag{1}$$

$$V = \frac{1.05_{pre}}{\sqrt{1 + \left(1 + 1.05_{pre}/L\right)^2}} \tag{2}$$

$$L = 3000 + 25Tmp + 0.05Tmp^3 \tag{3}$$

$$\lambda = NPP_{site}/NPP_{reference} \tag{4}$$

$$E_k = \lambda \times E_{0k} \tag{5}$$

where Net Primary Productivity (*NPP*) is measured in tons per hectare (t/ha). Annual evapotranspiration is denoted as *V* for long-term averages, both expressed in millimeters (mm). Similarly, *Pre* indicates annual precipitation (mm), and *Tmp* represents the mean annual temperature (°C). λ is the regional correction coefficient for ecosystem service equivalence(ESE); $NPP_{reference}$ denotes the national average NPP, expressed in kilograms per square meter (kg/m^2) of carbon (C); NPP_{site} represents the average NPP in the WSUA, also in kg/m^2 (C); E_k is the regionally adjusted ESE for the *k*th ecosystem type; and E_{0k} is the national average of ESE of the kth ecosystem type, where k = 1, 2, . . ., 11.

According to the study, the economic value of one unit of the equivalent factor of ESV was equal to 1/7 of the average market value of grain produced nationwide that year [58]. To account for monetary inflation, this study used the average grain price in the WSUA for 2020 (2.81 CNY/kg) as the baseline for calculations, resulting in an economic value of 2030.01 CNY/hm^2 for a single equivalent factor of ESV within the WSUA. The information above was used to determine the ecosystem value coefficients associated with the different land use types in the WSUA (Table A3).

The ESV of the WSUA was computed using the following formula:

$$ESV = \sum(S_k \times VC_k) \tag{6}$$

where *ESV* denotes ecosystem service value (RMB); S_k is the area of k land use types (hm^2); and V_{Ck} is the ecosystem service value coefficient of the adjusted k land use types [CNY·hm^{-2}·a^{-1}].

A grid-based approach was employed to analyze the spatial variations in ESV across five time periods (2000, 2005, 2010, 2015, and 2020). Drawing on the extensive literature on grid-based land use studies [64–66] and considering the potential influence of the Modifiable Areal Unit Problem (MAUP), the study adopted established practices for selecting grid scales, while taking into account the region's complex geomorphology and significant ecological heterogeneity. Several commonly used grid resolutions were initially selected, including 500 m × 500 m, 1 km × 1 km, 3 km × 3 km, 5 km × 5 km, and 10 km × 10 km. To identify the most appropriate spatial analysis unit, land use change data for the WSUA were used to compare spatial characteristics and their temporal evolution across different grid resolutions. The results indicated that the spatial patterns of land use dynamics and ESV were largely consistent across different scales. However, the 5 km × 5 km grid resolution struck an optimal balance between spatial detail and regional representativeness, making it well-suited to the spatial structure of the region, which is characterized by small- to medium-scale mountainous settlements. Accordingly, a 5 km × 5 km grid was generated using ArcGIS 10.2, from which seven land use types were extracted. The ESV for each grid cell was calculated using the equivalent value coefficient method in combination with the raster calculator. The grids were converted into both raster and point formats, and Kriging interpolation was applied to visualize the spatial distribution of ESV.

To assess the reliability of the ESV coefficients in the WSUA, this study employed the sensitivity coefficient (CS) commonly used in economics [67]. A CS greater than 1 indicates that the ESV is elastic with respect to VC, implying the low accuracy of VC; conversely, if CS is less than 1, it suggests that the ESV is inelastic with respect to VC, and that VC is more accurate, making the ESV assessment more reliable. A higher CS value indicates greater sensitivity of ESV to changes in the VC of a given landscape type, suggesting a more substantial contribution to the overall ESV.

2.6. Construction of the Response of ESV to Land Use Processes and Landscape Pattern Structure

2.6.1. Calculations of the Response of ESV to Land Use Processes

The dynamic evolution of ESV during land use conversion can be classified into two forms: ESV improvement and ESV degradation. The corresponding calculation formula is given as follows:

$$\Delta ESV = (VC_{k+1} - VC_K)LA/TA \quad (7)$$

where ΔESV denotes the dynamic impact of ESV resulting from land use transfers. It refers to the flow of ecological values that occur as a result of land use transfers, where the transformation of one land use type to another leads to a rise or decline in ESV within a given area. VC_K and VC_{k+1} represent the ecological value coefficients of the land use types at the beginning and end of the transfer, respectively. *LA* refers to the area affected by the land use change, while *TA* represents the total area of the region.

2.6.2. Calculations of the Response of ESV to Landscape Pattern Structure

The Pearson correlation coefficient is a commonly used statistical measure for assessing the strength of the linear relationship between two independent continuous numerical variables. Before performing the analysis, a Shapiro–Wilk test should be conducted to assess whether the data follow a normal distribution, ensuring the validity of the Pearson correlation analysis [68]. A two-tailed *t*-test is then conducted to evaluate the statistical significance of the correlation between landscape pattern indices and ESV over time. If the correlation coefficient is statistically significant ($p < 0.05$), the correlation is deemed meaningful. A statistically significant negative correlation coefficient suggests a trade-off relationship, whereas a positive correlation implies a synergistic effect [69]. Data analysis was conducted using the Statistical Package for the Social Sciences (SPSS) 26.0 to quantify the impact of landscape pattern changes on ESV. Correlation heatmaps were generated using Origin 2021 to visually illustrate their dynamic relationship.

3. Results

3.1. Analysis of Land Use Processes and Landscape Pattern Structures Changes

3.1.1. Characteristics of Spatiotemporal Changes in Land Use Processes

Land use changes in the WSUA followed a trend characterized by "four increases and three decreases", with construction land experiencing the most substantial increase and arable land showing the most significant decrease from 2000 and 2020. The areas of construction land (184,729.41 hm^2), forest land (30,816.45 hm^2), waters (22,487.22 hm^2), and desert (10,261.89 hm^2) showed an increasing trend, whereas arable land (189,336.69 hm^2), grassland (52,986.96 hm^2), and wetland (6339.87 hm^2) exhibited a decreasing trend. Land use changes were most significant between 2000 and 2010, after which the rate of change slowed down. Specifically, construction land steadily increased over the past two decades, with the most substantial increase of 51,612.39 hm^2 occurring between 2005 and 2010, followed by a gradual decline in the growth rate after 2010. Conversely, the area of arable land decreased less since 2005. In addition, arable land was widespread in the WSUA, while forest land and grassland were distributed in the northwest and southwest. The study area revealed a distinct trend of construction land expansion, with expansion characteristics in Chengdu being particularly noteworthy. This expansion manifested as outward growth towards the urban fringe and adjacent counties, thereby forming a peripheral urban expansion zone (Figures 4 and A1).

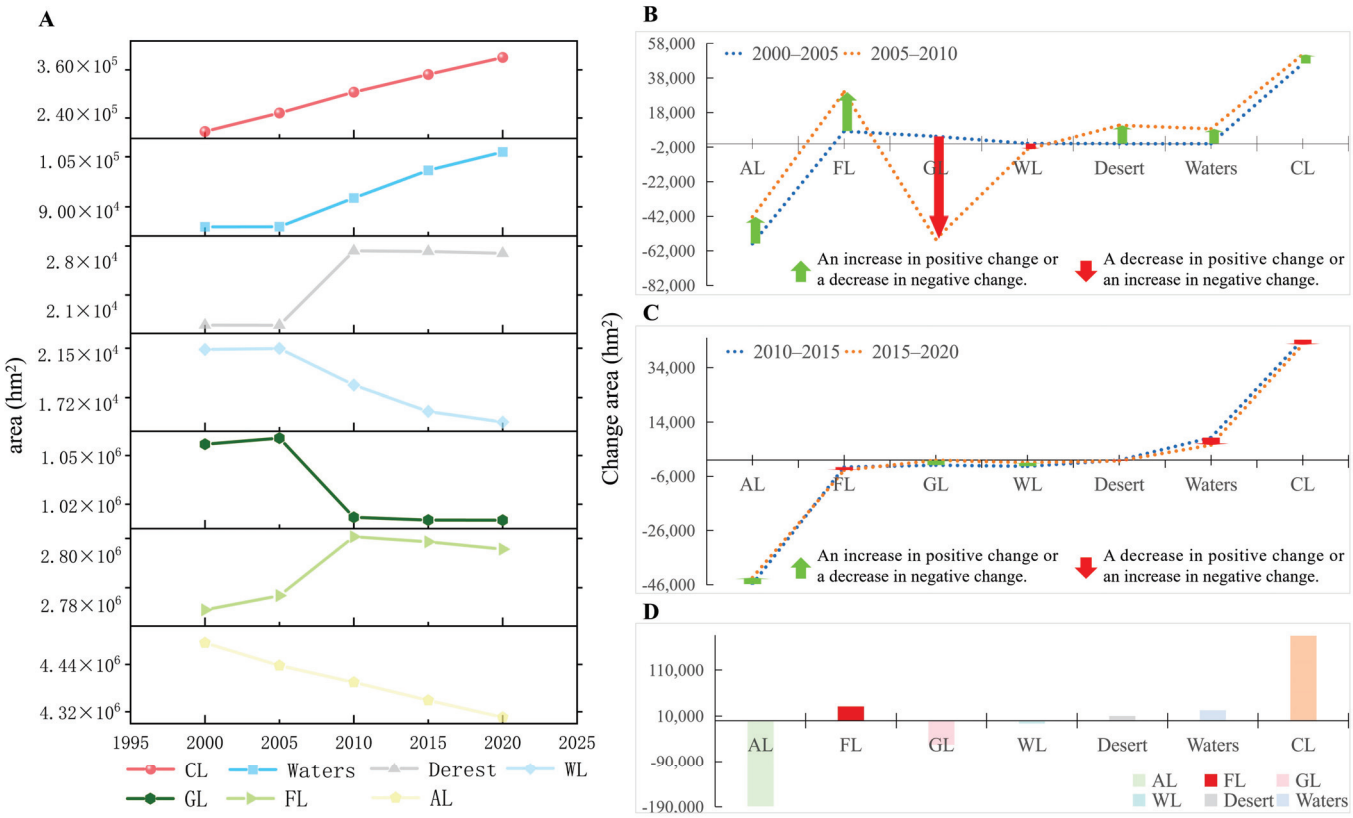


Figure 4. Changes in the area of land use types in WSUA from 2000 to 2020. (**A**) Land use change by category, 2000–2020. (**B**) Characteristics of changes in various types of land use, 2000–2010. (**C**) Characteristics of changes in various types of land use, 2010–2020. (**D**) Characteristics of overall changes in multiple types of land use, 2000–2020.

Throughout the research period, arable land in the WSUA exhibited the largest transfer area, showing significant reciprocal transfer trends between arable and forest land, with some arable land being converted into construction land. In terms of outflows, arable land accounted for the largest area transferred (522,002.88 hm^2), with the majority transitioning to forest land (225,857.97 hm^2) and construction land (217,843.02 hm^2), constituting 85% of the total outflow area. For inflows, the largest area transferred was forest land (362,600.55 hm^2), followed by arable land (332,793.36 hm^2) and construction land (217,843.02 hm^2). Forest and construction land inflows primarily originated from arable land, accounting for 62.29% and 93.20% of each inflow, respectively. Moreover, land use changes were most intense during the periods 2005–2010 and 2015–2020, characterized by a significant reciprocal transfer between arable land and forest land alongside a notable shift in arable land to construction land. Between 2005 and 2010, the largest outflow was from arable land (193,158.27 hm^2), primarily directed towards forest land (92,990.43 hm^2) and construction land (72,276.3 hm^2). The outflow of forest land was also significant, totaling 160,683.75 hm^2, primarily directed towards arable land (93,227.76 hm^2) and grassland (53,906.31 hm^2). From 2015 to 2020, substantial outflows from arable and forest land continued. Furthermore, the inflow of construction land primarily occurred in the peripheries and suburbs near city centers, while forest land inflows were concentrated in mountainous and hilly areas. In contrast, the inflow of arable land was more widespread, encompassing suburbs and adjacent counties, industrial parks, economic development zones, and emerging cities and new districts, such as Pengzhou, Qionglai, Mianyang, Meishan, Ya'an, and Deyang (Figure 5).

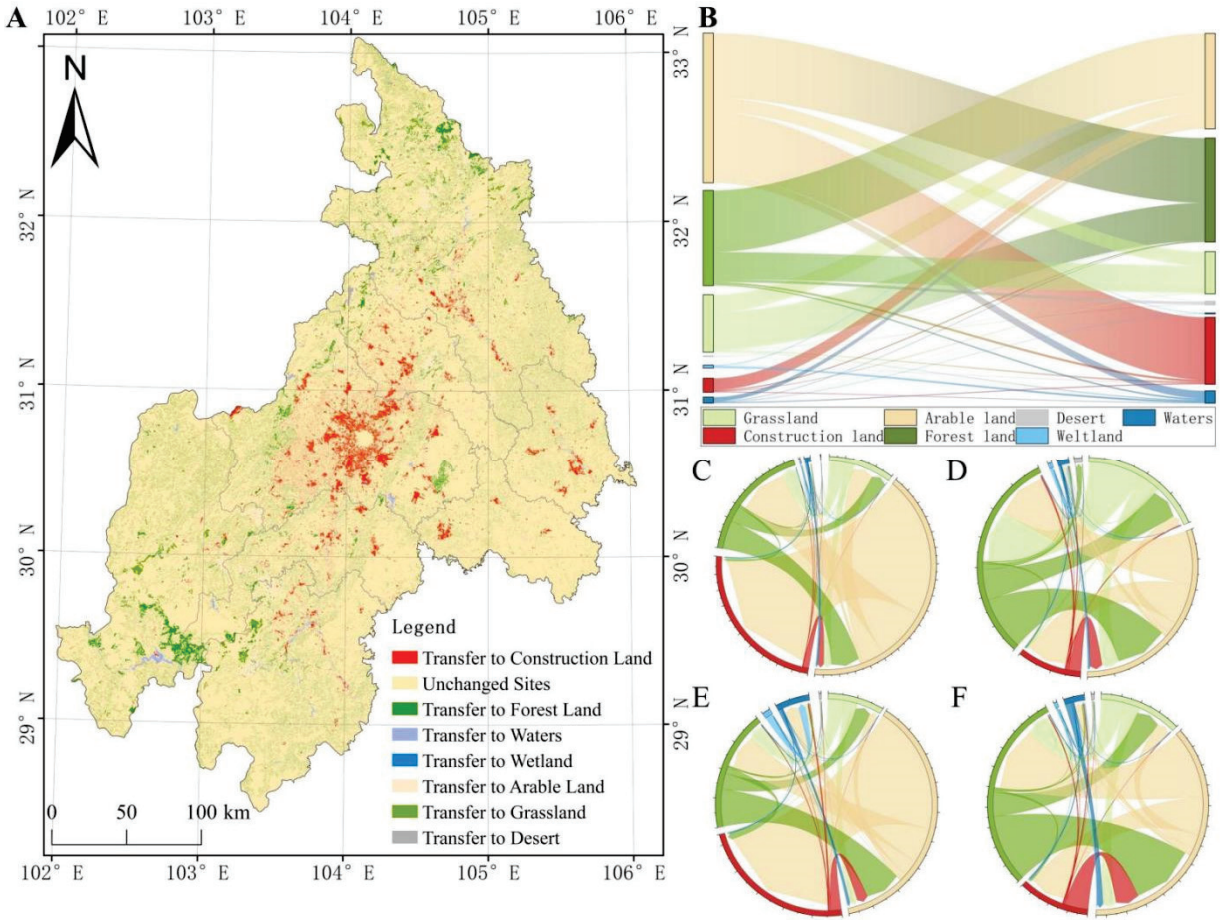


Figure 5. Mapping the land transfer area in WSUA, 2000–2020. (**A**) Spatial mapping of land use change, 2000–2020. (**B**): Total land use transfers 2000–2020. (**C**) Land use transfer characteristics, 2000–2005. (**D**) Land use transfer characteristics, 2005–2010. (**E**) Land use transfer characteristics, 2010–2015. (**F**) Land use transfer characteristics, 2015–2020.

3.1.2. Characteristics of Structural Changes in Landscape Patterns

Landscape-level indices revealed that, over the past 20 years, the overall landscape of the WSUA has undergone significant fragmentation, characterized by irregular landscape patches and high fragmentation levels. This led to the formation of numerous small patches, thereby diminishing landscape connectivity; however, the patches exhibited diverse characteristics. Throughout the study period, CONTAG consistently declined, while SHDI consistently increased. PD demonstrated an overall increasing trend, peaking in 2010 before it began to decline. DIVISION exhibited a steady increase, peaking in 2015, and subsequently began to decline. LSI exhibited a significant upward trend between 2000 and 2010, followed by a decline in 2015, and then peaking in 2020 (Figure 6).

At the type level, over the past 20 years, arable land, forest land, grassland, and desert have become increasingly fragmented and dispersed, illustrating a fragmentation trend. Meanwhile, the edges of construction land continuously extended, enhancing overall integrity and increasing aggregation. Water distribution became more complex and diverse, with abundant water bodies maintaining a high level of aggregation. Wetland patches have become more concentrated and contiguous, resulting in weakened edge effects and an increase in the overall scale. The highest ED, MPS, and AI values were observed in arable land, forest land, and grassland. This indicated that arable land, forest land, and grassland were the primary land use types in the study area, with these three landscape types being fragmented into several large patches. PD peaked in forest land and showed an increasing

trend, whereas the PD of construction land significantly decreased. Significant growth in MPS and AI was noted in construction land, indicating the rapid expansion and aggregation of this land type. Desert and grassland were the land types that experienced the most substantial reduction in MPS, indicating their high vulnerability to human encroachment, which exacerbated their fragmentation (Figure 7).

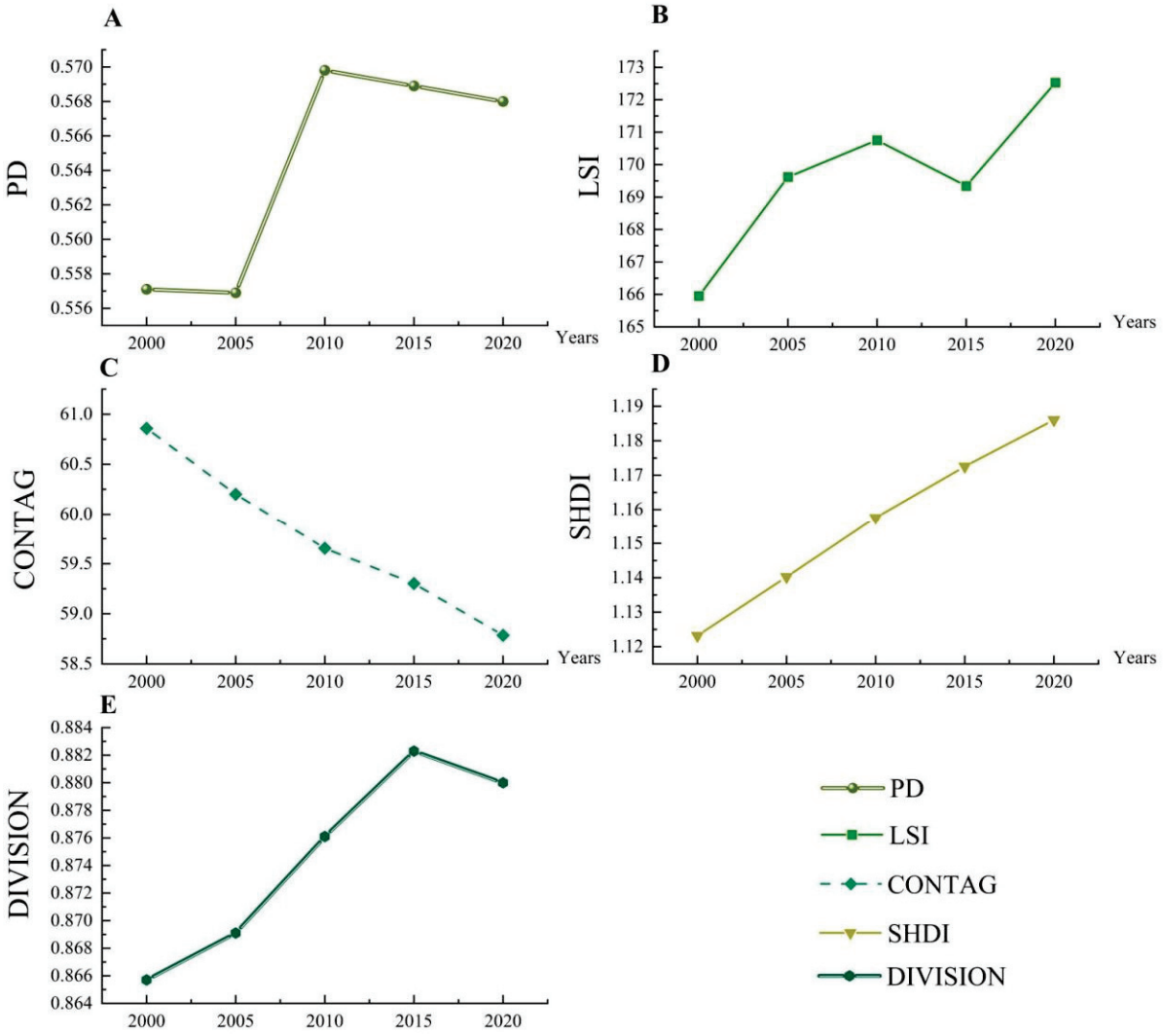


Figure 6. Changes in landscape level index of WSUA from 2000 to 2020. (**A**) Changes in patch density in WSUA, 2000–2020. (**B**) Changes in landscape shape index of WSUA, 2000–2020. (**C**) Changes in contagion index of WSUA, 2000–2020. (**D**) Changes in Shannon's diversity index of WSUA, 2000–2020. (**E**) Changes in landscape DIVISION of WSUA, 2000–2020.

3.2. Spatial and Temporal Changes in ESV

3.2.1. Temporal Variability Analysis

From 2000 to 2020, the ESV in the study area increased by CNY 2.619 billion, primarily due to significant contributions from forest land and waters (Figure 8). The contribution rates of ESV in the study area were ranked as follows: forest land > grassland > arable land > waters > wetland > desert. The primary components included forest land, grassland, arable land, and waters, collectively accounting for over 99% of the total. Notably, forest land exhibited the highest contribution rate to ESV, surpassing 56%. Over the study period, the ESV of forest lands and waters continued to rise, with a significant increase after 2005. In contrast, grasslands, arable lands, wetlands, and deserts exhibited declining trends, particularly with grasslands and wetlands experiencing sharp decreases in ESV after 2005.

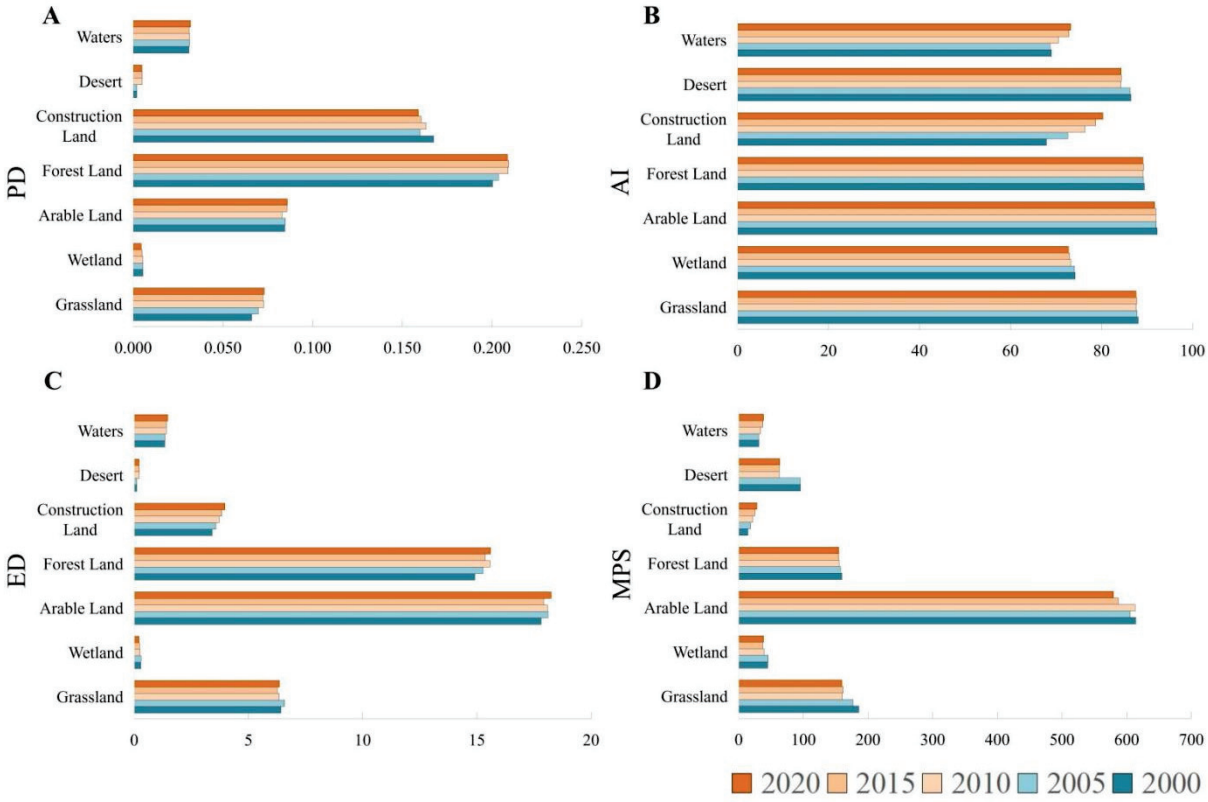


Figure 7. Changes in landscape pattern index of WSUA at type level, 2000–2020. (**A**) Changes in patch density by site type, 2000–2020. (**B**) Changes in aggregation index by site type, 2000–2020. (**C**) Changes in edge density by site type, 2000–2020. (**D**) Changes in mean patch size by site type, 2000–2020.

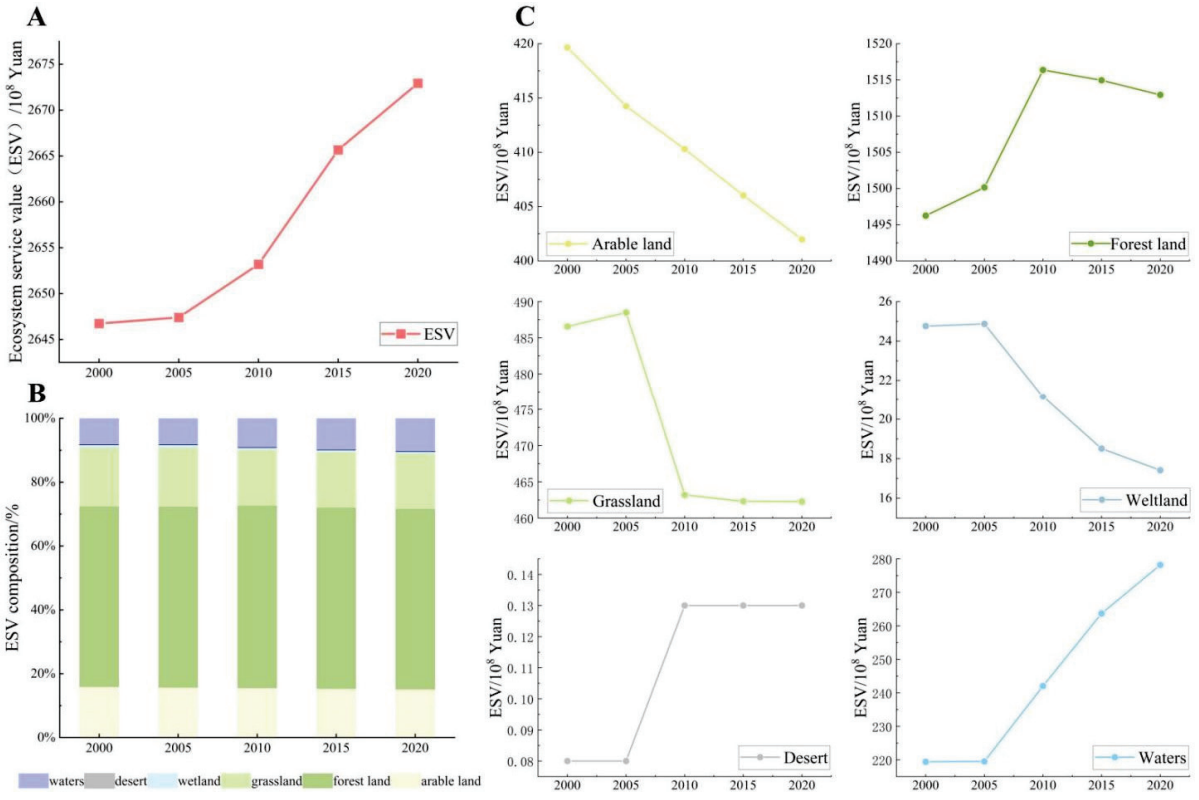


Figure 8. Changes in ESV for WSUA in general and for each land type. (**A**) Changes in the Total ESV, 2000–2020. (**B**) Percentage of ESV by land use type, 2000–2020. (**C**) Changes in the ESV by land use type, 2000–2020.

Over the study period, the ESV in the study area was ranked as follows: Regulatory Services (RS) > Support Services (SS_support) > Supply Service (SS_supply) > Cultural Service (CS) (Table A4). Specifically, CR, HR, SC, GR, BD, and DTE made significant contributions, accounting for 25%, 18%, 11%, 10%, 9%, and over 7%, respectively, and together represented more than 83% of the total ESV. During this period, the ESV for HR and WS increased significantly by 8.31% and 7.35%, respectively. However, the ESV of FP decreased by CNY 388 million, mainly due to the continued reduction in arable land area.

3.2.2. Spatial Variability Analysis

In terms of spatial distribution, the ESV in the WSUA from 2000 to 2020 showed significant variation, with higher values generally observed in the northern, western, and southern edges, gradually decreasing toward the east (Figure 9). Areas with high ESVs were mainly distributed in the northern and southwestern mountainous regions, as well as along river corridors encompassing Ya'an, Leshan, northwestern Chengdu, and northwestern Mianyang, corresponding to the presence of forests and rivers. Areas with moderate ESVs were located in the eastern part of the WSUA and along riverbanks, which correlated with the distribution of grasslands. Low ESVs were observed in the eastern and central parts of the study region, as well as in the central areas of each city, which coincided with urban development zones.

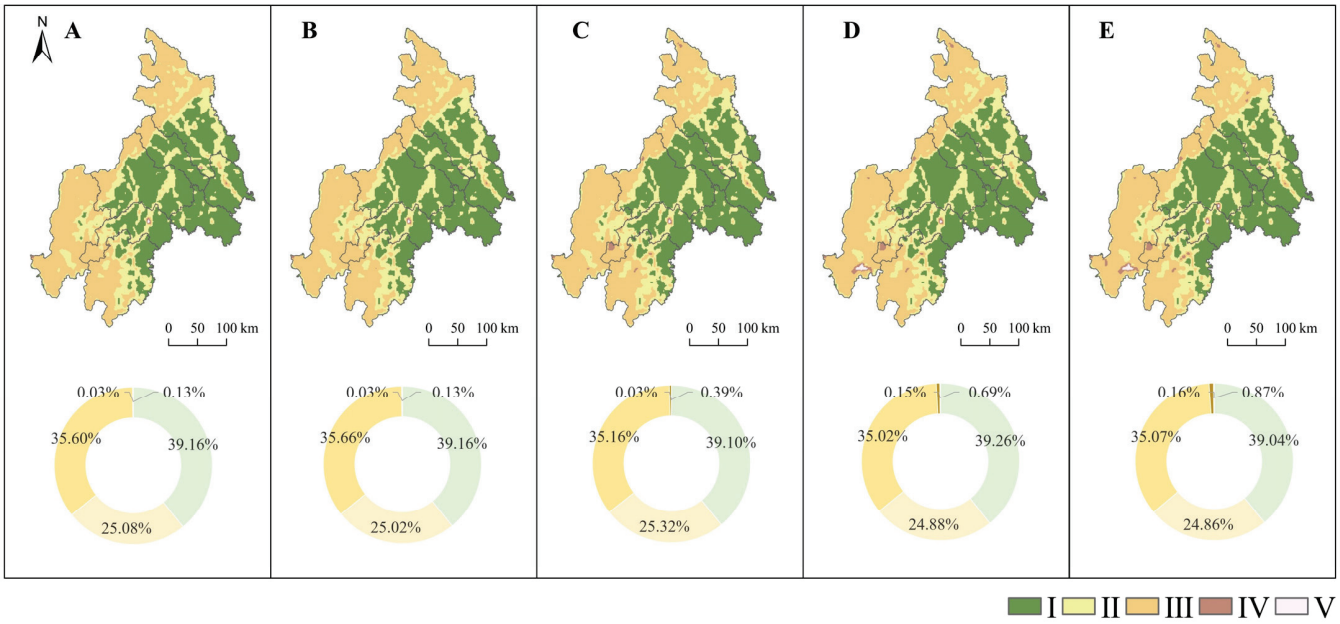


Figure 9. Spatial distribution of ESV in WSUA, 2000–2020. (**A**) Spatial characteristics of ESV, 2000. (**B**) Spatial characteristics of ESV, 2005. (**C**) Spatial characteristics of ESV, 2010. (**D**) Spatial characteristics of ESV, 2015. (**E**) Spatial characteristics of ESV, 2020.

From 2000 to 2020, the spatial dynamics of ESV across the WSUA remained largely stable, with areas of improvement and degradation accounting for only 3.45% and 2.28%, respectively (Figure 10). Over the past two decades, ESV improvements were detected across all cities, particularly in Mianyang, Chengdu, Ya'an, and Leshan, with improvements mainly concentrated in river and lake regions such as the Dadu River, Minjiang River, Fujiang River, Sancha Lake, Wawu Mountain, and Longcanggou National Park, as well as in agricultural and ecological conservation zones along these waters. These regions overlapped with areas where arable land was converted to forest, grassland, and waters, likely driven by ecological protection policies and natural recovery processes. Initiatives such as reforestation and wetland restoration have improved vegetation cover and

enhanced water retention capacity. Between 2000 and 2020, ESV degradation primarily occurred in peri-urban areas and expanding rural settlements, particularly in the hilly to plain transition zones of Ya'an and Mianyang. These regions coincided with areas that experienced both the conversion of arable land to construction land and the transformation of forest and grassland into arable land. This trend was likely driven by urbanization and agricultural expansion, as the encroachment of arable land on forests and grasslands weakened ecosystem service capacity. In contrast, the expansion of construction land further accelerated the decline in ESV. Specifically, over the five periods from 2000 to 2020, both areas of ESV improvement and degradation showed an upward trend; however, the proportion of improvement consistently exceeded that of degradation. Notably, the most significant changes in ESV occurred between 2005 and 2010.

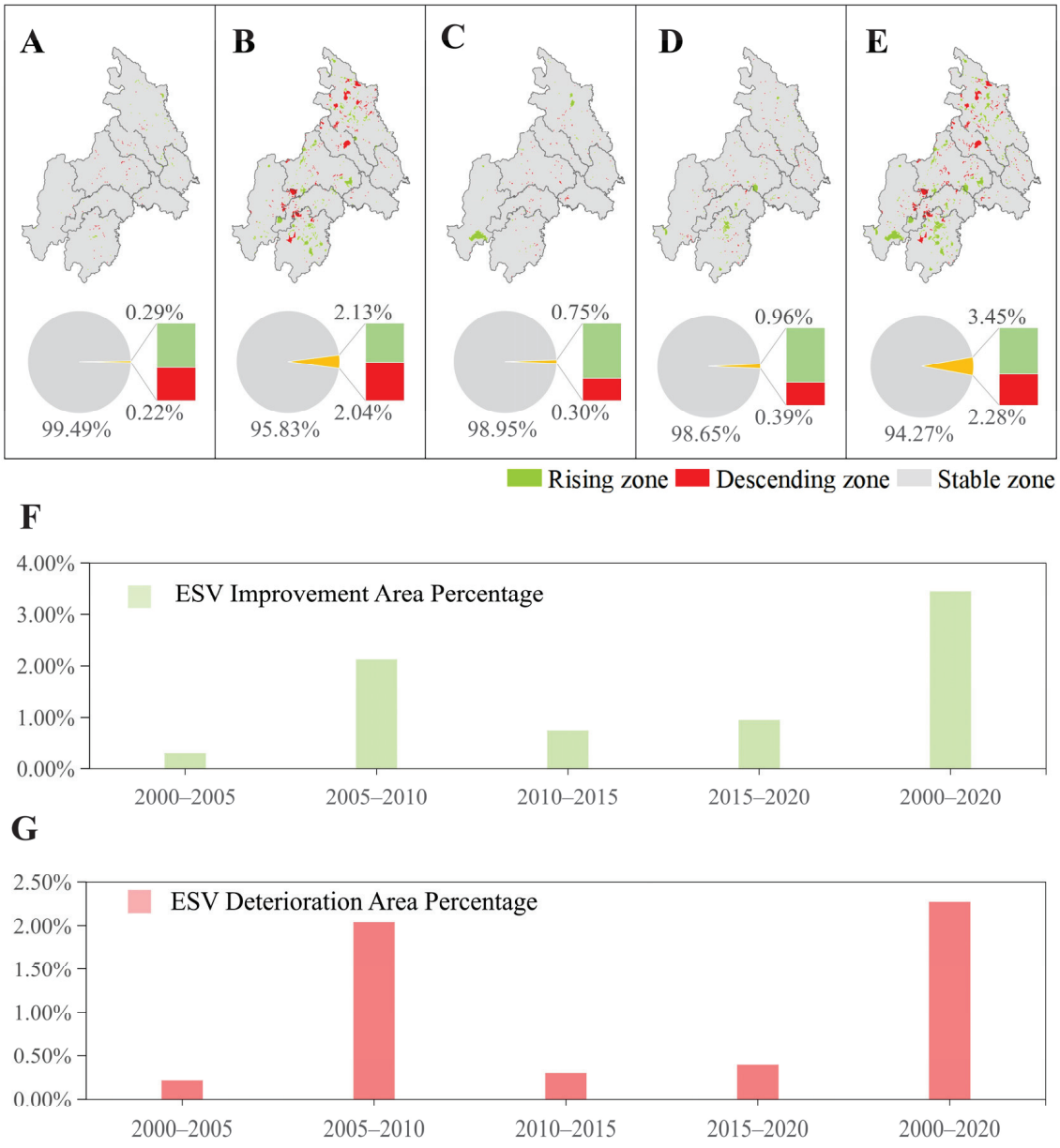


Figure 10. Spatial ESV Changes in WSUA, 2000–2020. (**A**) Trend of ESV Evolution in WSUA, 2000–2005. (**B**) Trend of ESV Evolution in WSUA, 2005–2010. (**C**) Trend of ESV Evolution in WSUA, 2010–2015. (**D**) Trend of ESV Evolution in WSUA, 2015–2020. (**E**) Trend of ESV Evolution in WSUA, 2000–2020. (**F**) Percentage area of ESV improvement by period, 2000–2020. (**G**) Percentage of deteriorated ESV area by period, 2000–2020.

3.2.3. Sensitivity Analysis of ESV

From 2000 to 2020, the sensitivity indices of ESV for all landscape types in the WSUA remained consistently below 1. The sensitivity ranking was as follows: forest land > grass land > arable land > waters > wetland > desert. Forest land exhibited the highest sensitivity, maintaining a value consistently above 0.56. The sensitivity of grassland, arable land, and waters was also relatively high, each exceeding 0.08. Over the 20 year period, the sensitivity of forest land and waters increased, rising from 0.56532 to 0.56602 and from 0.08291 to 0.10408, respectively. In contrast, the sensitivity of arable land and grassland showed a downward trend, decreasing by 0.00816 and 0.01088, respectively (Table 1).

Table 1. Ecological Sensitivity Index of WSUA, 2000–2020.

Land Space	2000	2005	2010	2015	2020
Arable land VC ± 50%	0.15855	0.15647	0.15464	0.15232	0.15039
Forest land VC ± 50%	0.56532	0.56665	0.57153	0.56832	0.56602
Grassland VC ± 50%	0.18383	0.18452	0.17457	0.17343	0.17295
Weltland VC ± 50%	0.00936	0.00939	0.00798	0.00694	0.00652
Desert VC ± 50%	0.00003	0.00003	0.00005	0.00005	0.00005
Waters VC ± 50%	0.08291	0.08293	0.09123	0.09893	0.10408
Construction land VC ± 50%	—	—	—	—	—

3.3. The Response of ESV to Changes in Land Use Processes and Landscape Pattern Structures

3.3.1. Impact of Land Use Processes on the ESV

(1) Impact of land use area on the ESV

The correlation analysis between various ESV components and different land use types revealed that land use composition and changes in the study area had a significant influence on ESV. The arable land area showed significant positive correlations with FD, RMP, GR, SC, and MNC, as well as significant negative correlations with WS, DTE, and HR. The grassland area exhibited significant positive correlations with RMP, GR, CR, SC, MNC, BD, and AL. The wetland area was significantly positively associated with most ESV components, except for a significant negative correlation with WS and HR. The desert area exhibited significant negative correlations with RMP, GR, SC, MNC, BD, and AL. The water body area was significantly negatively correlated with FD, RMP, GsR, CR, SC, MNC, and BD, and was significantly positively correlated with WS, DTE, and HR (Table A5).

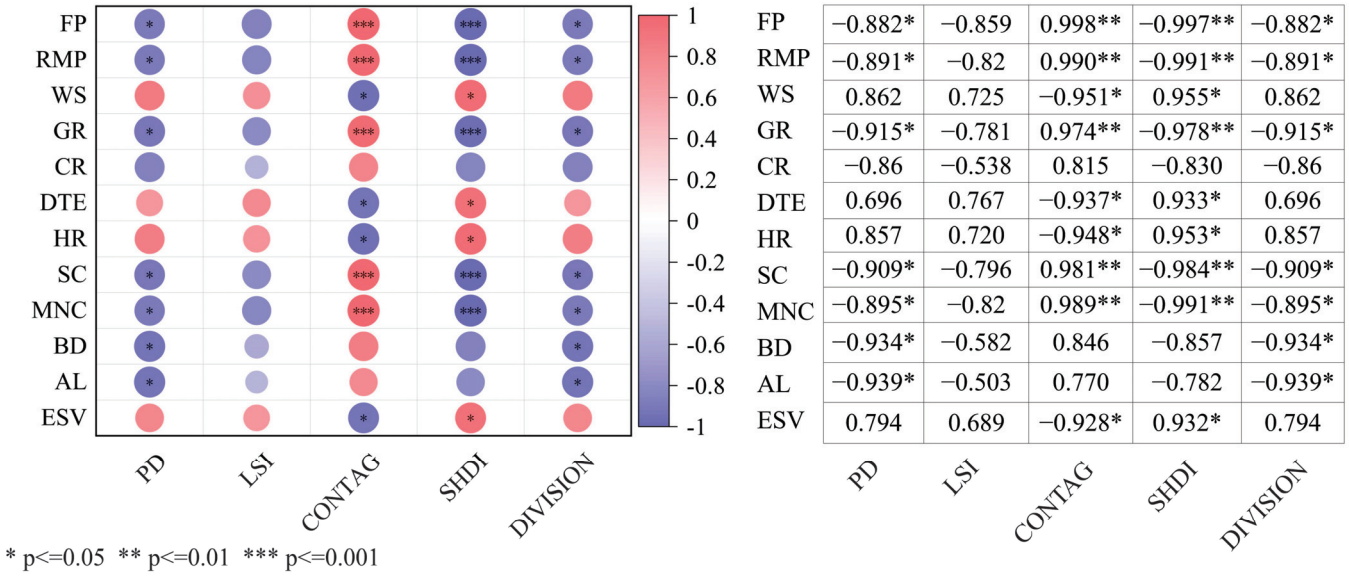
(2) The effects of land use transitions on the ESV

The conversion of ecological land during urbanization had a significant impact on ESV. Over the past two decades, transitions that led to an increase in ESV primarily fell into two categories. The first category involved conversion from residential and productive land to ecological land, with dominant transformations from arable and construction land to forests, grasslands, and water bodies accounting for more than 80.09%. The second category included transitions between different types of ecological land, particularly from land types with lower ecosystem service coefficients to those with higher ones, such as grasslands transitioning to water bodies and wetlands, which accounted for over 15.17%. The main types of transitions resulting in a decline in ESV can also be classified into two categories. The first involved the conversion of ecological land to residential and productive land, particularly grasslands and water bodies being converted into arable land, as well as arable and ecological lands being transformed into construction land, accounting for 81.45%. The second category involved transitions from ecological lands with high ESV coefficients to those with lower ones, representing 5.25% (Table A6).

3.3.2. Response of ESV to Landscape Pattern Structures

(1) Landscape level indices impacts on ESV

A more fragmented landscape pattern was associated with higher total ESV. Total ESV showed a strong positive correlation with SHDI and a strong negative correlation with CONTAG. Specifically, strong correlations were observed among landscape metrics (PD, DIVISION, SHDI, CONTAG) and various ecosystem service functions. PD and DIVISION exhibited significant negative correlations with FP, RMP, GR, MNC, BD, and AL. Conversely, CONTAG was significantly positively correlated with FP, RMP, GR, and SC, but negatively correlated with WS, DTE, and HR. Similarly, SHDI was positively correlated with WS, HR, and DTE, but negatively correlated with FP, RMP, GR, SC, and also DTE (Figure 11).



	PD	LSI	CONTAG	SHDI	DIVISION
FP	−0.882*	−0.859	0.998**	−0.997**	−0.882*
RMP	−0.891*	−0.82	0.990**	−0.991**	−0.891*
WS	0.862	0.725	−0.951*	0.955*	0.862
GR	−0.915*	−0.781	0.974**	−0.978**	−0.915*
CR	−0.86	−0.538	0.815	−0.830	−0.86
DTE	0.696	0.767	−0.937*	0.933*	0.696
HR	0.857	0.720	−0.948*	0.953*	0.857
SC	−0.909*	−0.796	0.981**	−0.984**	−0.909*
MNC	−0.895*	−0.82	0.989**	−0.991**	−0.895*
BD	−0.934*	−0.582	0.846	−0.857	−0.934*
AL	−0.939*	−0.503	0.770	−0.782	−0.939*
ESV	0.794	0.689	−0.928*	0.932*	0.794

Figure 11. Correlation analysis between ESs and landscape level indices.

(2) Impact of landscape type level indices on ESV

The findings indicate that the increased connectivity of similar landscape patches is crucial for enhancing ESs, especially in ecological lands. The MPS of forests and grasslands was strongly positively correlated with various ecosystem service functions, including FP, RMP, GR, SC, and MNC. The AI of arable land was significantly positively correlated with FP, RMP, GR, SC, and MNC, but significantly negatively correlated with DTE. The PD and ED of deserts were significantly negatively correlated with RMP, GR, SC, MNC, BD, and AL. The ED and AI of waters were significantly positively correlated with HR, WS, and DTE. The PD, ED, AI, and MPS of wetlands were significantly positively correlated with FP, RMP, GR, SC, and MNC (Figure 12).

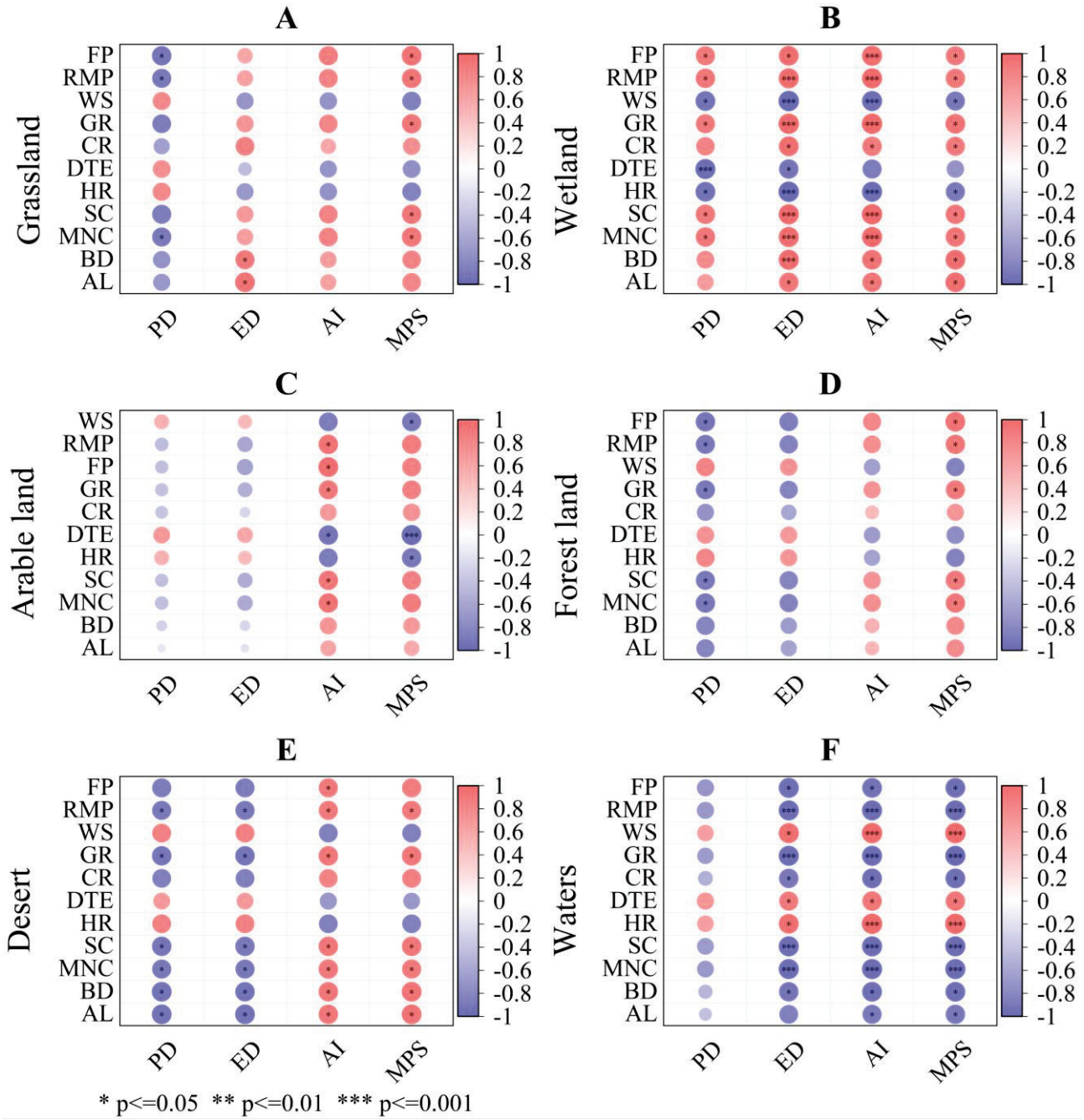


Figure 12. Correlation analysis of ESs and landscape-type indices. (**A**) Correlation analysis of ESV with the desert. (**B**) Correlation analysis of ESV with waters. (**C**) Correlation analysis of ESV with grassland. (**D**) Correlation analysis of ESV with wetland. (**E**) Correlation analysis of ESV with arable land. (**F**) Correlation analysis of ESV with forest land.

4. Discussion

4.1. Land Use Processes Lead to Structural Changes in Landscape Patterns

Land use change research aims to identify the trends, underlying drivers, and consequences of land use over defined time periods [41]. In the context of rapid urbanization and policy incentives, land use in the WSUA has undergone frequent and complex transformations over the past two decades. A "four increases and three decreases" pattern emerged, characterized by the most significant expansion of construction land and the largest loss of arable land. A notable trend of conversion between arable land and forest land was also observed. On one hand, policies such as the Implementation Opinions on

Several Policy Measures for Western Development accelerated urban expansion, leading to the encroachment of construction land on arable land. On the other hand, ecological policies—including the Regulations on Returning Farmland to Forests, Sichuan's Water Pollution Control Action Plan, and farmland protection measures—facilitated the conversion of arable land into forests and water bodies, with some forest land being reverting to agricultural use. This interplay illustrates the growing tension between agricultural production and ecological conservation. Notably, after 2005, the decline in arable and grassland areas slowed, likely due to the implementation of a series of land protection and ecological restoration policies, such as the National Grain Production Development Plan (2006–2020) and the 11th Five-Year Plan for Livestock Development (Table A1). After 2010, the expansion of construction land slowed due to stricter national land use planning, improved land management, and Sichuan's initiatives to coordinate industrialization and urbanization. These measures included optimizing spatial layout, restricting land quotas, and reinforcing approval procedures. Additionally, under the combined influence of ecological protection policies, new urbanization strategies, and macroeconomic regulation, the overall expansion of construction land has been effectively controlled, while still ensuring land allocation for key infrastructure projects [43].

Amidst rapid urbanization, land use changes profoundly impacted landscape patterns [70]. The accelerated urbanization of the WSUA propelled the expansion of construction land, making it a primary driver of landscape fragmentation. Urbanization directly increased landscape diversity while simultaneously exacerbating habitat fragmentation, progressively raising the isolation level among different regions within the urban agglomeration. Notably, the outward expansion of construction land in the central urban areas encroached upon large arable land areas, leading to fragmentation and scattering, further impacting the integrity of ecological lands such as forests, grasslands, and waters. This expansion trend was especially pronounced in 2005, particularly in the central region of the study area, where construction land density markedly increased, likely linked to rapid urbanization and large-scale infrastructure projects. The chaotic growth in the initial phase of this expansion diminished the overall integrity and connectivity of the natural landscape, worsening the extent of landscape fragmentation. Notably, with the involvement of planning management and ecological restoration, the trend of landscape fragmentation showed signs of alleviation by 2010. The execution of more scientifically informed land use planning and ecological restoration initiatives, along with a deceleration in urbanization, resulted in a more orderly distribution of landscape patches, balancing human impacts on landscape patterns and decreasing fragmentation. This suggests that effective land use planning and management are crucial for maintaining landscape stability and conserving the ecological environment. The primary influence of land use changes in the WSUA on landscape patterns is reflected in the fragmentation and division caused by rapid urbanization and construction land expansion. Nevertheless, effective land use planning and management can mitigate landscape fragmentation trends, thereby preserving the integrity and stability of ecosystems.

4.2. ESV Responds to Changes in Land Use Processes and the Structure of Landscape Patterns

Human activities are one of the primary drivers of land use change [70–72]. These activities are shaped and regulated by policies, which, in turn, can be influenced and modified by human actions [73,74]. An analysis of the impact of land use changes on ESV shows that the region has experienced rapid urbanization, with a significant expansion of construction lands. However, the total ESV increased by CNY 2.619 billion, with a notable rise, particularly between 2010 and 2020. This finding contrasts with existing studies suggesting that the rapid expansion of construction lands leads to a decline in ESV [75,76].

This indicates that the impact of land use changes on ESV varies across regions due to differences in land use planning and management, land use changes, and ecosystem service types influenced by economic and policy factors.

The Chinese government has made significant efforts to implement ecological protection initiatives [77–79]. However, due to the complexity of land systems and regional disparities in natural resource availability and economic development, governments at all levels face multiple challenges and varying demands when formulating and implementing land policies [80,81]. Policies that emphasize ecological restoration and management in land use planning play a vital role in maintaining and enhancing ecosystem service value (ESV). For instance, Guo et al. [82] found that the Environmental Protection Red Line policy safeguarded ecological land from land use changes, thereby enhancing ESs. Similarly, Yu et al. [83] found that environmental compensation effectively promoted the growth of ESV in the Xin'an River Basin. This study further confirms that the impact of policies on ESV varies significantly across different regions. The conversion of arable land and construction land to ecological land types—such as forests, grasslands, and water bodies—within the study area resulted in a CNY 2.218 billion increase in ESV. These ESV gains were predominantly located in areas where cropland was converted into forests, grasslands, and water bodies, with a spatial overlap of 40.9% between zones of ESV increase and these types of land conversions. These findings suggest that state-led ecological protection policies—such as the Grain-to-Green Program, ecological redline regulations, and compensation mechanisms—have played a critical role in enhancing ESV. Therefore, amid rapid urbanization, it is essential to comprehensively consider ecological, economic, and social factors in land use planning, implement ecologically prioritized land use policies, and strengthen the protection of ecological lands—including forests, grasslands, wetlands, and water bodies—to promote ESV growth. By contrast, under land use policies that prioritize economic development, ESV in many regions tends to decline, especially when ecological land is reduced. For example, Cao et al. [84] found that land-driven urbanization in China led to substantial losses in the ESV of wetlands. Similarly, Liu et al. and Duan et al. [19,85] reported that the reduction in ecological land areas—such as forests, grasslands, and wetlands—caused a notable decline in ESV. This study revealed that ESV declines were predominantly concentrated in the peripheral zones of urban and rural settlements, with a high spatial overlap (75.33%) between ESV reduction areas and the conversion of forests and grasslands into arable land, as well as arable land into construction land. This phenomenon is closely associated with rapid urbanization, especially during periods when government policies prioritized economic development, with the expansion of construction land as the main driver. The peripheral zones of urban and rural settlements typically serve as transitional areas between arable land and ecological land. As urban expansion continues, large areas of arable land are converted into construction land. Meanwhile, the arable land occupation compensation policy has caused forests and grasslands to be converted into cropland to compensate for farmland loss, significantly weakening ecosystem service functions. These findings indicate that policy regulations are a key driver of land use changes, particularly by influencing the extent of ecological land, thereby altering the supply of ES. Well-designed ecological protection policies and effective land management strategies can enhance ESV, whereas insufficient policy support may accelerate ecosystem degradation (Figure A3).

Landscape patterns refer to the spatial arrangement and organization of different land use types within a geographic area. Changes in these patterns are key indicators of land use transformation and significantly influence ecosystem structure and processes, thereby directly affecting ESs [86–88]. In the WSUA, the expansion of construction land has encroached upon arable and forest lands, leading to greater fragmentation, increased

landscape diversity, and reduced connectivity—yet, paradoxically, ESV has significantly increased. However, previous studies have shown that higher fragmentation levels are often linked to lower ESV. For example, Biswas et al. [89] reported that fragmentation in Jangipur significantly reduced regional ESV, while Hou et al. [90] observed similar negative effects in Xi'an. These disparities suggest that the impacts of landscape fragmentation on ES is spatially context-dependent and multifaceted, potentially mediated by land use type, fragmentation scale, and local ecological characteristics. Therefore, more in-depth studies that account for regional heterogeneity are urgently needed. Interestingly, some studies have identified positive ecological outcomes under certain fragmentation conditions. For instance, Zhu et al. [65] found that, in the farmland-dominated region of Nanchang, higher fragmentation increased landscape diversity, which in turn promoted ecosystem functions and enhanced overall ESV. Our findings in WSUA corroborate these observations, suggesting that landscape fragmentation can, under certain conditions, enhance ESV. This may be attributed to the fragmentation of large arable land patches caused by land expansion, creating a heterogeneous mosaic of forests, water bodies, grasslands, arable lands, and construction lands. Such complexity enhances ecological diversity and creates diverse land use interfaces, which can increase provision, regulation, and support for ESs. Additionally, the region's pronounced topographic variation and geomorphic complexity may interact with fragmentation to increase spatial heterogeneity, supporting a wide range of ecosystems—such as forests, grasslands, and wetlands—at different elevations and across various terrain types. This ecological diversity fosters functional complementarity and strengthens ecosystem processes such as water conservation and soil retention, ultimately contributing to the optimization of ESV in the WSUA.

Research on the correlation between ES and type-level relationships can demonstrate the effect of landscape aggregation and fragmentation on ESV [65]. Studies have shown that human activities increase the fragmentation and dispersion of arable land, forests, grasslands, and deserts while construction land aggregation rises. As a dominant landscape type, arable land shows more significant benefits with higher aggregation, supporting large-scale agricultural management, improving food production efficiency, and enhancing the service value of food and raw material production. Furthermore, the greater the aggregation of ecological lands, such as forests, grasslands, waters, and wetlands, the greater the resulting ESV. In summary, the aggregation and fragmentation of different landscapes have far-reaching effects on ESV. As human activities continually transform land use patterns, proper planning and management of various land types, mainly arable and ecological lands, are crucial for ensuring and enhancing ESV. Therefore, the WSUA should adopt a well-designed land use strategy, promoting the aggregation of ecological lands and focusing on protecting forests, grasslands, waters, and wetlands. This approach will enhance functionality in water resource management, food production, and nature conservation, achieving a harmonious balance between ecological protection and socio-economic development.

This study found that the ESV of the WSUA increased by CNY 26.19 billion, directly supporting the development of the regional green economy by enhancing the capacity for ecological product provision (e.g., water source conservation and carbon sinks) while also creating pathways for value transformation in emerging industries, such as environmental compensation and ecotourism. This increase supports the development of green industries in the WSUA, including the growth of ecological tourism and carbon trading markets, driving the transformation of the local economy and promoting green growth. The improved environmental environment has enhanced residents' quality of life while generating new opportunities for ecological compensation and green employment, fostering sustainable development within the regional society. Notably, this increase in value arises from the

unique "process–structure–value" coupling mechanism: in the context of land use changes driven by human activities and ecological policies (process), the conversion of farmland into forests, grasslands, and water bodies reshapes the landscape's heterogeneity (structure). Enhancing patch diversity and connectivity within the landscape pattern promotes the synergistic effects of various ecosystem elements, ultimately driving the improvement of ESV (value). Unlike traditional research that focuses solely on the direct impact of land use changes or landscape pattern evolution on ESV, the framework proposed in this study systematically reveals the cascading transmission mechanism between land use process changes, landscape pattern evolution, and ESV changes [44,45]. It explores how land use changes, by influencing landscape structure changes, further drive the increase in ESV, which feeds back into land use decisions. The case of WSUA demonstrates that, although the expansion of built-up land exacerbates landscape fragmentation, positive ESV growth can still be achieved by scientifically guiding the spatial aggregation of ecological land (e.g., improving forest patch connectivity). In subsequent sections, this provides a theoretical foundation for developing "process–structure synergy optimization" land policies.

4.3. Suggestions for Optimizing ESV in the WSUA

Drawing from the above analysis, the ESV of the study area exhibits specific vulnerabilities. Therefore, several recommendations are proposed to optimize policies, offering guidance for tailoring urban agglomerations' land use and landscape structure to local conditions (Figure A2).

(1) To ensure the long-term ecological sustainability of the WSUA, it is crucial to accurately designate ecological priority protection zones, optimize green space planning, promote the multifunctional ecological use of farmland, and implement a region-specific ecological compensation mechanism. In regions where ESV is steadily improving, priority ecological protection zones should be designated by the Technical Guidelines for Ecological Red Line Delineation. Core areas where ESV has shown a sustained and substantial increase, such as the Ya'an section of the Dadu River, should be established as permanent conservation zones with stringent development limitations. Meanwhile, areas with steady ESV growth potential, such as the upper Minjiang River reforestation belt, can facilitate the growth of environmentally friendly industries. Furthermore, a coordinated "core ecological protection zone–urban ecological buffer belt" system should be implemented, establishing a 100–300 m-wide buffer around ESV-enhancing areas while strictly regulating development intensity. For arable land bordering protected areas, "ecological conservation-oriented farming" should be adopted. Regions such as Ya'an and Meishan could implement the "wetland farm + ecological picking garden" model to establish a mutually beneficial balance between conservation and development. A "performance-driven" ecological compensation system should be established to support these initiatives. Provincial financial resources should be allocated for ESV improvement, with a tiered compensation structure applied to regions within protected zones that exhibit sustained ESV growth. Compensation standards should align with the Sichuan Provincial Watershed Horizontal Ecological Protection Compensation Incentive Policy Implementation Plan and be adjusted dynamically based on the annual ESV variation rate.

(2) Based on the sensitivity and spatial distribution of ESV, ecological restoration zones should be strategically delineated along urban fringes to create a well-connected ecological network that integrates mountains, rivers, forests, farmlands, lakes, and grasslands. Sensitivity analysis revealed that forestland exhibited the most pronounced response to ESV variations, underscoring its essential regulatory and conservation functions. Therefore, restoring forest ecosystems should be prioritized to preserve

both their integrity and connectivity. It is recommended that ecological restoration zones be established in areas experiencing significant ecosystem degradation—such as regions with declining ESV and fragmented forests—particularly along urban fringe areas impacted by expansion. These zones should enhance the stability and connectivity of ecological networks by integrating habitat patches and restoring ecological corridors. Priority should be given to water source protection and wetland restoration projects to rehabilitate aquatic ecosystems and enhance water quality regulation. The development of the Minjiang–Dadu River ecological corridor with wetland restoration and ecological shoreline transformation will promote connectivity within the upper Yangtze River aquatic ecosystems and help regulate regional hydrological processes. A green corridor linking Longquan Mountain and the Tuojiang River should be established based on a mountain–river ecological coupling framework. This initiative will restore natural riparian zones along the Tuojiang River, reconnect fragmented mixed forests in Longquan Mountain, and establish ecological buffer zones in peri-urban areas, forming a continuous landscape-scale ecological network. Furthermore, "forest–grassland" ecological corridors should be created on the urban periphery. For instance, a biodiversity corridor connecting the Longmen and Qionglai Mountains should be delineated with habitat identification, ecological corridor restoration, and disturbance regulation. This would help sustain the genetic exchange of endangered species, such as the giant panda, preserve upstream water sources of the Yangtze River, and mitigate ecological fragmentation caused by urban expansion in the WSUA.

(3) To optimize ecological networks and multifunctional landscape management, it is essential to integrate current land use patterns, economic development levels, and policy directives by implementing a regionally differentiated and category-specific strategy. In the biodiversity core zone of Longmenshan-Qionglai Mountain, natural restoration should be prioritized, with strict development controls. In the core area of the WSUA, existing land resources should be revitalized with urban renewal and the redevelopment of inefficient land use (e.g., old factories and urban villages). The transit-oriented development model should be promoted, prioritizing high-density development around high-speed rail and metro hubs. Adopting the "ecological function zone and permeable green infrastructure" approach in city centers is advisable. For instance, Chengdu's central district should maintain a green coverage rate of over 20%, with main road green belts measuring no less than 30 m in width. Furthermore, implementing "green roofs and rain gardens" should be encouraged to strengthen ecological connectivity. In the low-mountain ecological forestry zone of Longquanshan, an east–west ecological buffer zone should be established to expand mixed forests, promote suburban recreational green corridors, and limit high-density development, thereby curbing urban sprawl, enhancing ES, and mitigating soil erosion. In the eastern hilly farmland protection area, a "field–forest–pond" integrated ecological network should be developed, the rice-fish farming model should be promoted, and spatial flexibility for urban expansion should be preserved to achieve farmland protection, non-point source pollution mitigation, and urban-rural coordinated development. The "government–market–community" model should be adopted, integrating financial subsidies, ecological compensation, and public–private partnership mechanisms to secure financial sustainability. Public engagement, environmental education, and community co-construction should be promoted to foster public acceptance and advance sustainable development.

Furthermore, the potential impacts of current land use processes and landscape pattern evolution on future ESV should be examined. This study reveals that landscape

fragmentation generally increased from 2000 to 2020; however, the diversity and heterogeneity of landscape types significantly improved, contributing to the overall increase in ESV. ESV notably increased in areas where forests and water bodies expanded, indicating that moderate fragmentation, diversified configurations, and the expansion of ecological land have somewhat optimized the structure of ES. However, if urban expansion and the occupation of arable land continue in the future, they may further reduce the connectivity of core ecological patches, intensify the fragmentation of ecological land patterns, and undermine the stability, supply, and regulatory functions of ecological networks. The risk of functional degradation due to "disordered fragmentation" should be carefully monitored. In contrast, ecological restoration, the expansion of blue-green spaces, and the enhancement of patch integration and boundary optimization are expected to improve the spatiotemporal stability of ESV. It is recommended to incorporate land use simulation and scenario prediction models into spatial planning, integrate remote sensing monitoring with ecosystem simulation, develop dynamic ESV evolution models, and enhance the foresight and adaptability of land management. This approach would support the development of a "simulation–response–optimization" framework, continuously improving ecosystem service functions.

4.4. Limitations

This study builds upon theories from landscape ecology, geography, and urban planning and adopts the "process–structure–value" framework to examine the interrelationships among land use processes, landscape patterns, and ESV in the WSUA. However, several limitations should be considered. A Pearson correlation analysis was employed to quantify the relationships between land use change, landscape structure, and ESV. While the results suggest that ESV is primarily influenced by dominant ecological landscape types, with distinct regional disparities, these relationships are not strictly causal. Instead, they reflect complex interactions among multiple factors, underscoring the need for a deeper investigation into their underlying mechanisms. Additionally, measurement errors, scale effects, and sampling biases may influence the robustness of the findings. Future research should interpret correlation results cautiously, incorporate multi-source data and diverse methodological approaches to validate the outcomes, and consider developing a complex network model linking the three dimensions. Such efforts could strengthen the theoretical foundation of the "process–structure–value" framework and enhance its practical relevance. Furthermore, the influence of landscape metrics on ESV may differ across spatial scales. This study did not perform a multi-scale landscape analysis, which limits insights into scale-dependent effects. Future studies should integrate multi-scale metrics to better understand the sensitivity and spatial responses of ESV to changes in landscape patterns. Finally, this research did not include land use simulation models to assess future changes. Integrating landscape-driven models—such as the Land Patch, Cellular Automata (LP–CA) approach—could help simulate ESV dynamics under alternative land use scenarios, providing stronger support for spatial planning and ecological conservation. Although the CNLUCC dataset used in this study offers relatively high classification accuracy, the region's complex terrain may introduce uncertainties. Combining high-resolution remote sensing data with field observations in future research would help improve the accuracy of fine-scale analyses. Despite these limitations, this study presents a valuable case that can inform land use planning and ecosystem management in mountainous urban agglomerations.

5. Conclusions

This study evaluates changes in land use and landscape patterns in the WSUA and investigates the relationship among land use processes, landscape pattern structure, and

ESV. The results demonstrate that, in the context of rapid urbanization, policy regulations and human activities in the WSUA have significantly driven the dynamic evolution of land use processes, resulting in profound changes in landscape patterns. Over the past two decades, influenced by policies such as "Grain for Green" and farmland protection, as well as human activities, construction land has significantly expanded, and a dramatic trend in land transfer between arable land and forest land has emerged, leading to significant fragmentation of forests, grasslands, arable lands, and waters. Nevertheless, landscape heterogeneity has improved, and the overall structure has become increasingly complex. Furthermore, the ESV of the WSUA has increased by CNY 2.619 billion, with forests and grasslands being the primary contributors to ESV, while waters play a significant role in the dynamic changes in ESV. Simultaneously, HR and WS account for a substantial proportion of the service value, approximately 40%. The ESV is higher in the study area's northern, western, and southern regions, decreasing towards the east, with areas of increased ESV concentrated primarily in ecological restoration zones, such as those involved in "Grain for Green" and "lake restoration". Further analysis shows that the synergistic effects of land use processes and landscape structure are critical factors in enhancing the ESV of the WSUA. The transition from human-dominated construction land and arable land to nature-dominated forests and waters has significantly increased the ESV. Simultaneously, the increase in landscape diversity has a significant positive effect on overall ESV, and the enhancement of connectivity between similar landscape patches plays a crucial role in the functioning of ESs. However, despite the improvement in ESV, the ecological environment of the WSUA remains vulnerable. To balance economic development and ecological protection, based on the "process–structure–value" model, this study suggests measures for the WSUA, such as establishing environmental protection zones, promoting rational urban expansion, and developing ecological restoration areas. This aims to encourage policymakers to prioritize the protection of environmental functions when planning mountainous urban agglomerations and to guide the spatial arrangement of construction land and arable land development, providing decision-making support for regional sustainable development.

This study constructs a "process–structure–value" response framework to systematically reveal the synergistic impacts of land use and landscape pattern changes on ESV, providing new theoretical support for integrated assessments. Building on this foundation, future research should prioritize the development of new tools and frameworks to optimize ESV evaluation, strengthen ecological management and planning systems, and offer scientific guidance for land use strategies. These tools should enable the monitoring of long-term dynamics in land use and landscape patterns, along with their impacts on ESV, by leveraging data-driven approaches to improve the accuracy of land management. In the short term, integrating remote sensing with big data analytics can enhance the evaluation of land use processes, landscape evolution, and ecosystem service interactions, while supporting the formulation of policies focused on optimizing ecological functions and ensuring the sustainable provision of ESV. In the long term, efforts should focus on institutionalizing this framework and establishing a governance model rooted in legal and planning systems, engaging government agencies, research institutions, and social organizations to ensure the effective implementation of environmentally sustainable land management.

Author Contributions: J.W. (Jing Wang): Conceptualization, Methodology, Software, Visualization, Writing—original draft; P.P.: Conceptualization, Supervision, Writing—review and editing, Funding acquisition; T.L.: Supervision, Writing—review and editing, Conceptualization; J.W. (Juan Wang): Writing—review and editing; S.Z.: Writing—review and editing; P.N.: Writing—review and editing, Funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Special Project of Orchid Survey of National Forestry and Grassland Administration (contract No. 2019073015); Henan Province 2023 Science and Technology Development Plan Science and Technology Research Project (Project No: 23210232027); Spatial and temporal characteristics and influencing factors of the distribution of giant panda's staple bamboo based on the ecological and geological environmental information system (2024NSFSC0355).

Data Availability Statement: The raw data in this paper are available from 10.6084/m9.figshare.27321711.

Acknowledgments: We thank the anonymous reviewers and the editor for their valuable comments and suggestions, which contributed to improving this work.

Conflicts of Interest: The authors declare no competing interests.

Appendix A. Appendix Tables

Table A1. Time series of Chinese policies related to the research findings.

Time	Policy	Measures	Mainly Affects the Type Used	Related Research Results
1998–2020	Decision of the People's Government of Sichuan Province on Implementing the Natural Forest Resources Protection Project	Take resolute measures to stop the logging of natural forests, strengthen forest resource management, and promote the construction of ecological public welfare forests.	Forest land	Increase in forest land from 2000 to 2020.
2001	Implementation Opinions on Several Policy Measures for Western Development	Improve the approval efficiency of construction land, reduce approval procedures, and promptly provide and ensure land for economic development, infrastructure, and industrial parks as the demand for land increases.	Construction land	Explosive increase in construction land.
2002	Regulations on Returning Farmland to Forests	Farmland with a slope greater than 25 degrees should be converted back to forests or grasslands, with corresponding subsidies provided.	Arable land, forest land, grass land	From 2005 to 2010, the most converted land was arable land, with the majority being transferred to forest land (92,990.43 hm^2).
2006—2020	National Grain Production Development Plan (2006–2020)	Implement the strictest farmland protection system, adopt practical and feasible measures, encourage farmers to plant grain and local governments to focus on grain production, and stabilize the grain sowing area at a reasonable level.	Arable land	After 2005, the rate of decline in arable land slowed down.
2006	11th Five-Year Plan for Livestock Development	Strengthen grassland construction and environmental protection and promote the harmonious development of animal husbandry and grassland ecology.	Grass land	After 2005, the rate of decline in grassland slowed down.
2006	Notice on Strengthening Land Regulation Issues	Clarify the responsibilities for land management and arable land protection and prohibit the unauthorized conversion of agricultural land into construction land.	Arable land	After 2005, the rate of decline in arable land slowed down.

Table A1. *Cont.*

Time	Policy	Measures	Mainly Affects the Type Used	Related Research Results
2008	Special Plan for Ecological Restoration in the Post-Wenchuan Earthquake Recovery and Reconstruction	Protecting natural forests, converting farmland to forests, converting grazing land to grassland, closing mountains for forest restoration, afforestation, and comprehensive watershed management, with ecological restoration projects implemented in the upper reaches of the Min River, Jialing River, Fu River, and Bailong River basins.	Forest land	The restoration of forest land in Mianyang and the northwest of Chengdu aligns with the distribution of high-value and increasing ESV areas.
2009–2020	Development Plan for the Chengdu Plain Urban Agglomeration	Increase forest coverage and strictly control development in the western mountainous areas.	Forest land, construction land	From 2000 to 2020, the forest area increased, and the high-value ESV areas were primarily distributed in the northern and southwestern mountainous regions.
2011	Opinions on Accelerating the Interactive Development of New-Type Industrialization and New-Type Urbanization	Coordinate the spatial layout of urban and rural development, make reasonable use of natural resources such as land and water, and protect the natural ecological environment.	Construction land	After 2010, the expansion of construction land slowed down.
2016	Sichuan's Water Pollution Control Action Plan	Strictly manage the urban planning blue line and ensure that a certain proportion of water area is retained within the urban planning area. New projects must not unlawfully occupy urban wetlands, rivers, lakes, or other water bodies.	Waters, wetland	From 2000 to 2020, the area of water bodies increased.
2017–2020	Sichuan Province "13th Five-Year" Ecological Protection and Construction Plan	Focus on protecting forests, grasslands, farmland, wetlands, and river ecosystems.	Forest land, grass land, waters, arable land	From 2015 to 2020, ESV significantly increased.
2018	Sichuan Province Ecological Protection Red Line Plan	The distribution pattern of ecological protection red lines in Sichuan Province is 'Four Axes and Nine Cores'. The 'Four Axes' refer to the Daba Mountains, the lower reaches of the Jinsha River's arid river valley, the southeastern Sichuan mountains, and the hilly areas within the basin, which are distributed in a belt-like shape. The 'Nine Cores' refer to the Ruoergai Wetland (Yellow River Source), the Yalong River Source, the Dadu River Source, as well as the Daxue Mountain, Shaluo Mountain, Min Mountain, Qionglai Mountain, Liangshan-Xiangling, and Jinping Mountain, which are concentrated and distributed in large areas, with water systems and mountain ranges serving as their framework.	Forest land, grass land, waters, desert	ESV improvement areas are distributed across various cities, mainly in Mianyang, Chengdu, Ya'an, and Leshan. These areas are primarily located in river and lake regions such as the Dadu River, Min River, Fu River, and Sancha Lake, as well as in some agricultural areas along the rivers. They overlap with areas where cropland has been converted into forest, grassland, and water bodies.

Table A2. Selected landscape pattern indexes.

Landscape Pattern Index	Landscape Level	Formula	Ecological Meaning
PD	Category/Landscape	$PD = \frac{N}{A}$ A is the overall landscape area and N represents the quantity of landscape plates.	The overall patch count in the landscape indicates its heterogeneity and fragmentation. A larger value corresponds to a higher degree of fragmentation.
MPS	Category	$MPS = \frac{A}{N} \times 10^{-6}$ A is the overall landscape area and N is the number of landscape plates.	The mean area of a specific patch type indicates landscape heterogeneity.
ED	Category	$ED = \frac{E}{A} \times 10^{-6}$ E denotes the cumulative length of all patch boundaries within the landscape and A is the overall landscape area.	Reflects the degree of landscape fragmentation: the larger the value, the greater the landscape fragmentation.
AI	Category	$AI = \frac{g_{ii}}{\max \to g_{ii}}$ g_{ii} represents the count of neighboring patches of the same landscape type.	Reflects the degree of aggregation of plaques: the larger the value, the more concentrated the plaques.
LSI	Landscape	$LSI = \frac{0.25E}{\sqrt{A}}$ E denotes the cumulative length of all patch boundaries within the landscape and A is the overall landscape area.	Reflects the shape characteristics of patches within the landscape, with larger values indicating more complex types and shapes and more separated patches.
SHDI	Landscape	$SHDI = -\sum_{i=1}^{N} [p_i \ln(p_i)]$ P_i is the area proportion of a landscape patch type i.	Reflecting the diversity and richness of landscape types, a decrease implies that particular landscape types are beginning to dominate or increase their coverage in the landscape.
DIVISION	Landscape	$DIVISION = 1 - \sum_{j=1}^{N} \left(\frac{a_j}{TA} \right)^2$ TA is the total area of the region; a_j is the area of the jth patch of a given landscape type.	It indicates the extent of landscape fragmentation: the closer to 1, the more fragmented the landscape is.
CONTAG	Landscape	$CONTAG = \left[1 + \sum_{i=1}^{m} \sum_{j=1}^{n} \frac{P_{ij} \ln(P_{ij})}{2\ln(m)} \right]$ P_{ij} signifies the likelihood that two randomly chosen neighboring patches are of types i and j. Here, m denotes the total number of patch types.	It reflects the extent of aggregation among patch types, with larger values indicating that the landscape consists of a few clustered large patches with better connectivity.

Table A3. Ecosystem value coefficients for land use types in the WSUA.

Category I	Category II	Arable Land	Forest Land	Grassland	Weltland	Desert	Waters	Construction Land
Supply service (SS_supply)	FP	2103.22	767.06	940.27	1261.93	0.00	1979.51	0
	RMP	989.75	1756.81	1385.65	1237.19	0.00	569.11	0
	WS	40.60	751.10	629.30	5257.73	0.00	16,828.81	0
Regulatory services (RS)	GR	1657.84	5814.80	4874.53	4701.33	49.49	1905.27	0
	CR	890.78	17,394.90	12,891.53	8907.77	0.00	5666.33	0
	DTE	247.44	4924.02	4255.94	8907.77	247.44	13,732.82	0
	HR	548.10	7125.35	7754.65	49,187.22	60.90	207,548.57	0
Support Services (SS_support)	SC	2090.91	5805.84	4872.03	4689.33	40.60	1887.91	0
	MNC	296.93	544.36	445.39	445.39	0.00	173.21	0
	BD	321.67	6433.39	5394.15	19,473.38	49.49	6309.67	0
Cultural service (CS)	AL	148.46	2820.80	2375.41	11,703.83	24.74	4676.58	0

Table A4. Changes in the value of individual ESVs in the WSUA, 2000–2020 (10^8 RMB).

Ecosystem Services		ESV/(10^8 RMB)					2000–2020 ESV (10^8 RMB)	Rate of Change/%
Category I	Category II	2000	2005	2010	2015	2020		
SS_supply	FP	127.66	126.54	125.49	124.62	123.78	−3.88	−3.04%
	RMP	108.50	108.12	107.47	106.96	106.48	−2.02	−1.86%
	WS	44.52	44.59	45.74	46.96	47.80	3.27	7.35%
RS	GR	289.61	289.28	287.64	286.69	285.81	−3.79	−1.31%
	CR	664.36	665.65	663.56	662.72	661.91	−2.45	−0.37%
	DTE	205.89	206.29	206.23	206.85	207.23	1.34	0.65%
	HR	488.76	489.41	503.34	518.84	529.36	40.61	8.31%
SS_support	SC	308.78	308.20	306.38	305.23	304.16	−4.62	−1.50%
	MNC	33.36	33.25	33.04	32.89	32.74	−0.62	−1.86%
CS	BD	259.02	259.54	258.28	257.94	257.72	−1.30	−0.50%
	AL	116.29	116.52	116.02	115.96	115.94	−0.36	−0.31%

Table A5. Correlation analysis of ESV and land use types. * $p <= 0.05$; ** $p <= 0.01$.

Land Space	FP	RMP	WS	GR	CR	DTE	HR	SC	MNC	BD	AL
Arable land	0.999 **	0.993 **	−0.962 **	0.977 **	0.825	−0.955 *	−0.960 **	0.984 **	0.992 **	0.849	0.767
Forest land	−0.851	−0.841	0.782	−0.856	−0.743	0.636	0.775	−0.854	−0.846	−0.846	−0.858
Grassland	0.877	0.891 *	−0.872	0.920 *	0.883 *	−0.698	−0.867	0.912 *	0.896 *	0.951 *	0.957 *
Weltland	0.959 **	0.980 **	−0.990 **	0.993 **	0.948 *	−0.899 *	−0.989 **	0.989 **	0.981 **	0.964 **	0.913 *
Desert	−0.873	−0.880 *	0.851	−0.906 *	−0.851	0.681	0.845	−0.900 *	−0.886 *	−0.929 *	−0.937 *
Waters	−0.961 **	−0.984 **	1.000 **	−0.991 **	−0.945 *	0.934 *	0.999 **	−0.989 **	−0.984 **	−0.943 *	−0.875

Table A6. Changes in and contribution of major land use types to the improvement and deterioration of regional ESV, 2000–2020 (10^8 RMB).

Period	Positive ESV Effects			Negative ESV Effects		
	Land Use Transfers	ESV Contribution	Percentage	Land Use Transfers	ESV Contribution	Percentage
2000–2020	Grassland–Forest land	125.87	4.54%	Grassland–Arable land	253.47	10.28%
	Grassland–Weltland	0.92	0.03%	Grassland–Desert	10.36	0.42%
	Grassland–Waters	63.04	2.28%	Grassland–Construction land	23.38	0.95%
	Arable land–Grassland	205.75	7.43%	Arable land–Desert	0.97	0.04%
	Arable land–Forest land	1169.99	42.24%	Arable land–Construction land	235.14	9.54%
	Arable land–Weltland	24.40	0.88%	Desert–Construction land	0.00	0.00%
	Arable land–Waters	774.71	27.97%	Forest land–Grassland	91.25	3.70%
	Desert–Grassland	5.36	0.19%	Forest land–Arable land	1110.94	45.06%
	Desert–Arable land	0.17	0.01%	Forest land–Desert	60.78	2.47%
	Desert–Forest land	5.58	0.20%	Forest land–Construction land	45.22	1.83%
	Desert–Weltland	0.43	0.02%	Weltland–Grassland	0.35	0.01%
	Desert–Waters	14.53	0.52%	Weltland–Arable land	33.60	1.36%
	Construction land–Grassland	10.87	0.39%	Weltland–Desert	0.12	0.00%
	Construction land–Arable land	44.59	1.61%	Weltland–Construction land	11.44	0.46%
	Construction land–Desert	0.00	0.00%	Weltland–Forest land	1.14	0.05%
	Construction land–Forest land	20.23	0.73%	Waters–Grassland	11.44	0.46%
	Construction land–Weltland	2.20	0.08%	Waters–Arable land	408.81	16.58%
	Construction land–Waters	67.71	2.44%	Waters–Desert	6.74	0.27%
	Forest land–Weltland	1.95	0.07%	Waters–Construction land	101.65	4.12%
	Forest land–Waters	124.89	4.51%	Waters–Forest land	38.31	1.55%
	Weltland–Waters	106.50	3.85%	Waters–Weltland	20.54	0.83%
	Total value	2769.70	100.00%	total value	2465.66	100.00%

Appendix B. Appendix Figures

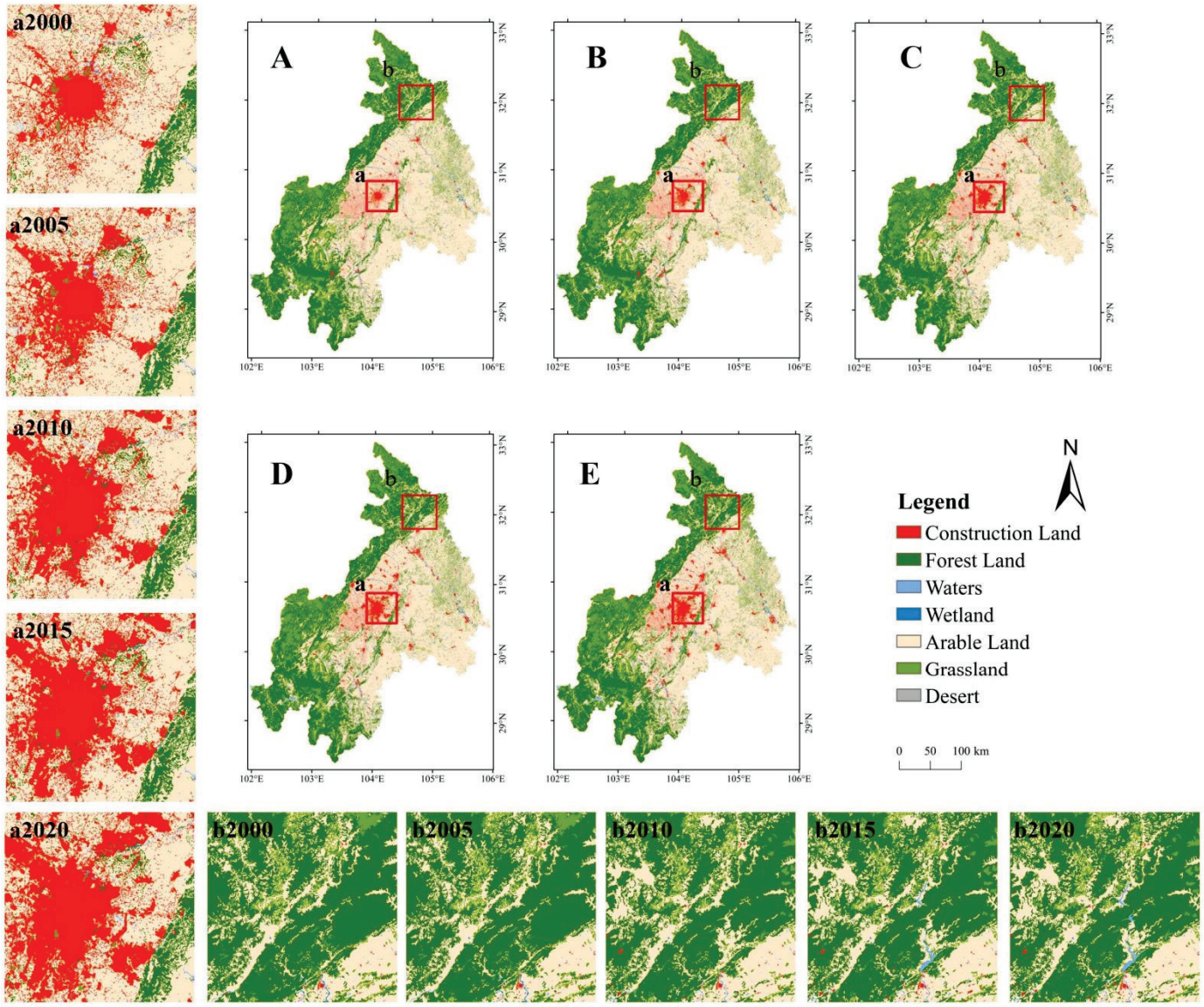


Figure A1. Changes in the spatial pattern of current land use in WSUA from 2000–2020. (**A**) Land use distribution of WSUA in 2000. (**B**) Land use distribution of WSUA in 2005. (**C**) Land use distribution of WSUA in 2010. (**D**) Land use distribution of WSUA in 2015. (**E**) Land use distribution of WSUA in 2020. (a) Typical area of construction land expansion. (b) Typical area of ecological land change.

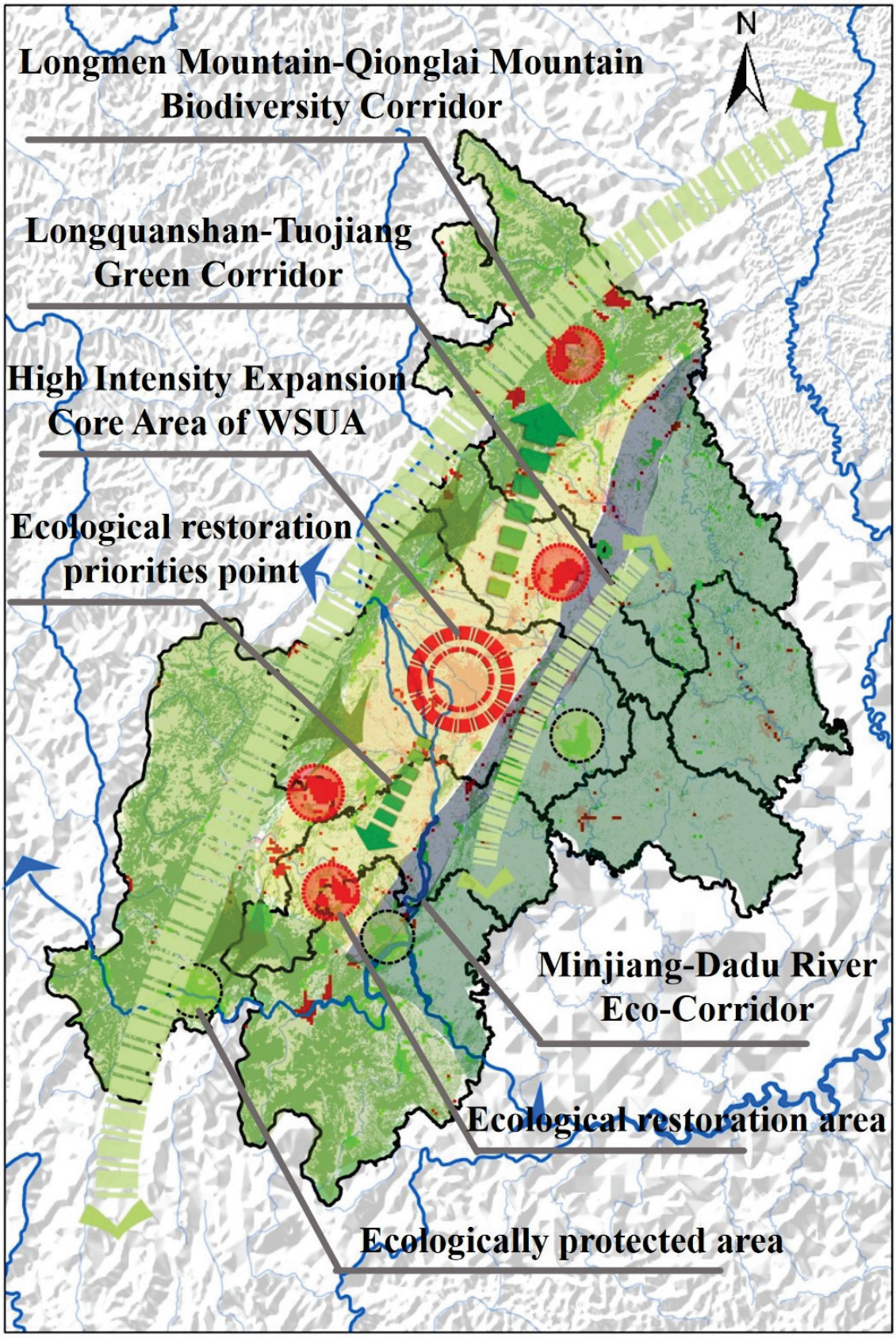


Figure A2. Ecological Planning Strategy for WSUA.

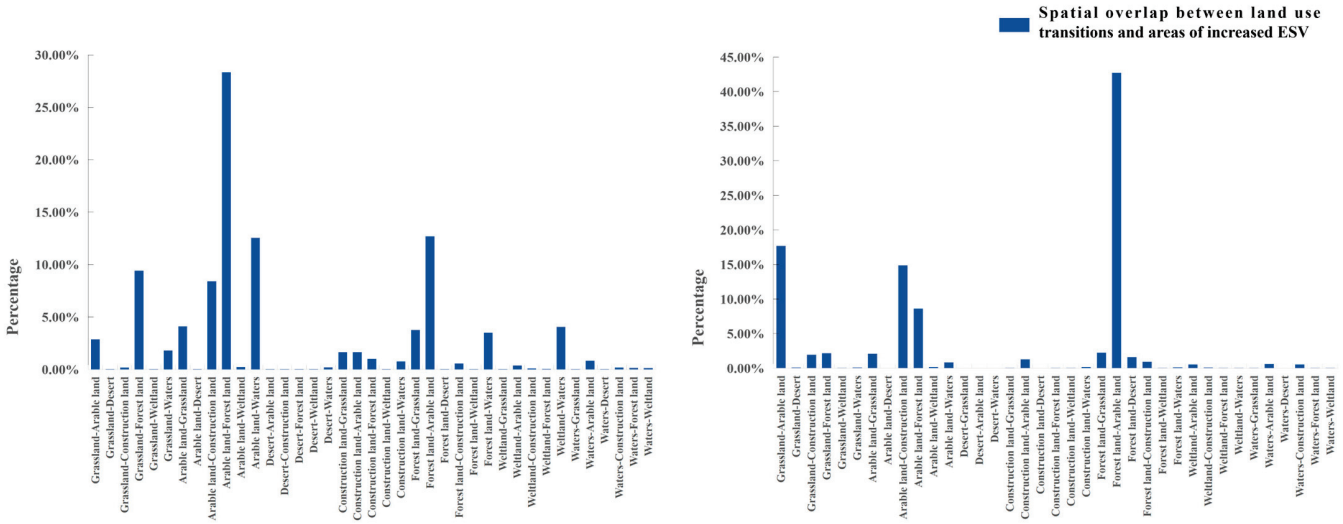


Figure A3. Overlay and proportion analysis of land use transfer map and ESV spatial change map.

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Article

Ecological Transition in Spain: Political Polarization Through Institutions and Media

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Abstract: While most Spanish citizens recognize the urgency of climate change, opinions differ on the specific measures to mitigate it, which are grouped under the concept of ecological transition. The ecological transition policies put forward by states, parties, and political leaders have become a factor of political polarization, with the media—through their role as shapers of public discourse—playing a significant part. In this article, we examine the ecological transition from two perspectives. First, we explore the level of political polarization among Spanish society regarding how ecological transition is framed and how ecological transition measures are perceived. Second, we investigate how the media cover these measures and views to identify potential connections between their portrayal of the issue and the public's perceptions. A two-pronged methodological approach is applied: a survey to assess citizens' perceptions and a content analysis of four Spanish newspapers with diverse editorial leanings to evaluate the media treatment of the topic. Results show that left-wing respondents agree more with the idea that ecological transition is the solution to climate change, whereas right-wing respondents more frequently view it as a threat to current lifestyles and as a process imposed by governments. These results are also reflected in the press coverage of ecological transition. We conclude that the press emerges as an actor that reinforces the existing political polarization in society around ecological transition.

Keywords: ecological transition; climate change; polarization; news media; public perception; public opinion; survey; content analysis; Spain

1. Introduction

Climate change is an issue that has been gaining importance in the public arena since the beginning of the 1990s, when the UN created the Intergovernmental Panel on Climate Change (IPCC). Its relevance increased during the 2010s, with the UN Sustainable Development Goals (SDGs) [1], the Paris Agreements [2], and the European Green Pact [3], whose goal is for each country to establish a series of measures to fight climate change from both an environmental and a social perspective. The actions set out in these agreements are called ecological transition actions and are considered a key concept, as they place us in front of a profound change [4] that, according to García [5], affects multiple areas (institutional, social, productive, consumption, way of life, and values) and must take place in a short time and on a worldwide level [6].

Ecological transition is a concept that is increasingly used in different forums, and according to Jarillo [7], this makes its delimitation and interpretation difficult. Garcia [5]

adds that it is a vague and imprecise concept due to its political origins. Vagueness and imprecision are reflected in the different definitions and interpretations of the phenomenon. Thus, in the face of the emergency framed in the context of the quadruple crisis—ecological, energy, climate, and economic–financial [4]—a transition towards a more environmentally friendly development model is necessary. According to the IPCC, this transition integrates adaptation and mitigation measures, with greater international cooperation, sufficient financial resources, inclusive governance, and better coordinated policies [8].

This set of measures is referred to as the ecological transition and is proposed as the path that will allow for a transformation of the current society into a climate-neutral society. However, as García [5] (p. 94) states, there is not a single way of transition or a single social transformation; there are "different post-carbon societies and different ways to get there". That is, the ecological transition may involve social and political changes of different intensities that can give rise to different models of society. These can range from those that partially modify the productive model to continue growing, in line with sustainable development and ecological modernization [9,10], to those that seek a profound transformation of the model with proposals for economic degrowth [11,12].

These transformations, whether partial or radical, imply a transformation of the socio-economic model and, therefore, generate social conflict. According to Fischer & Giuliani [13] (p. 1), "how eco-social risks should be addressed and in which way social and ecological policies can and should be combined is highly conflictual".

Without avoiding the fundamental debate on the depth of the social transformations that the various possible ecological transitions may generate, and the conflicts that can arise from them, in this article, we take as a reference the policies currently being implemented by the European institutions under the name of ecological transition. García [5] (p. 92) defines it as "actually existing" and frames it as a variant of the doctrines of ecological modernization. According to Dimitrova et al. [14], Jarillo [7], and García [5], for the institutions, the ecological transition involves proposing and implementing policies for the transition to a more ecological productive and social model, i.e., maintaining growth that improves social conditions while considering environmental aspects.

Likewise, in Spain, the term "ecological transition" was adopted by the socialist government of Pedro Sánchez to lump together all the policies designed to address climate change, with the creation of the Ministry for Ecological Transition and the Demographic Challenge, which is tasked with "proposing and implementing the Government's policy in the fight against climate change for the transition to a more ecological productive and social model" [15]. The term "ecological transition", therefore, includes a series of political measures that the government conveys to public opinion, through the media.

In today's society, there is much consensus concerning the importance of climate change. In the case of Spain, 83% of citizens believe that it should be a priority, while a quarter place it as one of the three most pressing problems [16] (p. 2). In the same vein, Suso et al. [17] identify only 6% of the population as being climate change denialists. The work of Leon et al. [16] and of Suso et al. [17] also shows the high consensus in Spanish society (around 65%) regarding the need to apply measures to mitigate it. However, there is no such consensus in relation to the measures that should be applied. Regarding knowledge, Suso et al. [17] highlight that the ecological transition is a concept that more than half of the population (51%) is unaware of or has a very vague idea about. Regarding consensus, León et al. [16] point out that different ecological transition measures generate different levels of agreement and that society is divided around these measures.

Thus, these data reveal that while climate change can be considered a cross-cutting issue [18] on which there is some degree of consensus in society, ecological transition (the measures to mitigate it) can be considered a positional issue [18]. The latter author defines

positional issues as those in which different social actors adopt different positions that usually confront each other from different ideological positions that lead to polarization. This logic is also noted by van Eck et al. [19] when they state that polarization dynamics around climate change are shifting from debates about the reality and severity of climate change to debates about climate solutions. In this context of polarization, of ideological dispute regarding the direction that the ecological transition should take [4], several actors interact in the public sphere to establish their positions in relation to this issue [20]. These include the media, which play a key role [21,22] in setting the agenda [23], in creating interpretive frames [24], in disseminating scientific knowledge [21], and in raising the awareness of the citizens [25] in regard to this phenomenon.

Hence, in this paper, we propose to analyse the ecological transition from a dual perspective. On the one hand, we study the level of polarization generated among Spanish society by the different ecological transition measures, and on the other, we analyse how the media treat these measures to identify possible alignments between their treatment of this issue and the citizens' perceptions.

2. Theoretical Framework

2.1. Ecological Transition and Polarization

While the fight against climate change is perceived as an important issue for citizens, the ecological transition policies put forward by states, parties, and political leaders to address it have become a factor of political polarization, especially in Anglo-Saxon and Western European democracies [26–30]. Political polarization can be understood as the division of society into two opposing ideological groups that contain the majority of individuals [31,32]. The degree of polarization would be determined, among other things, by the distance between the groups and the uniformity of each group [33]. Such a division is related to people's attitudes, but often, it also has an emotional component in so-called affective polarization, which focuses on the negative sentiments aroused by the social group at the other ideological extreme, beyond the actual political issues in question [34].

As has become evident, political polarization has been widely studied, especially in the context of the United States, where bipartisanship and a largely ideologically aligned media system have contributed to shaping a highly polarized society. These studies conclude that Democrat and Republican followers take different positions on the phenomenon [35–40]. While Democrats are more likely to believe in the anthropogenic origin of climate change and accept measures to mitigate it, Republicans are more resistant to these ideas. However, political polarization has also been detected in other countries with multiparty systems and very different political cultures from that of the US. Hornsey et al. [41] observed this ideological correlation also existed in 56 countries of Europe, Asia, and South America, although with less intensity than in the US. Particularly in Europe, polarization between the positions of progressives and conservatives does also exist [42]. The former consistently showed greater conviction regarding the existence of climate change and greater support for mitigation measures compared to conservative citizens. Garmendia Madariaga et al. [43] explain that Spain is a country with high levels of affective, territorial, and left-right polarization, especially since the emergence of new parties on the political landscape such as Podemos (far left), Ciudadanos (unionist liberal centre), and Vox (far right). In their work conducted in Germany, Coffé et al. [44] observe that polarization between left- and right-wing ideological groups has increased over time. The authors conclude this is due to those on the far-right of the ideological spectrum progressively showing less support for regulations against climate change, confirming a trend observed in other studies [45] regarding the rejection of climate change and mitigation measures by citizens aligned with far-right ideologies. Specifically, this includes measures affecting workers in polluting

industries who, as identified by Heddesheimer et al. [46], may be more likely to support far-right parties that oppose ecological transition measures.

Thus, the cited studies in this regard confirm that citizens' positioning with respect to ecological transition measures is greatly conditioned by their political ideology and by partisan identification; in other words, it is an issue that incites polarization.

Tschötschel [47], however, explains that this polarization is often created artificially and is a response to biased perceptions about the different proposals and positions on the subject rather than to a real difference in attitudes and beliefs. In the same vein, Schwaller et al. [48] note that in the US, political ideology is not a relevant factor in the opinion about policies to combat climate change when referring to concrete and first-hand experiences. ElHaffar et al. [49] and Berkebile-Weinberg et al. [50] use the concept of the "green gap" to refer to the mismatch between people's climate beliefs and their behaviours. These authors state that the green gap affects both pro-climate liberals and climate-sceptic conservatives. The green gap affects the former more intensely, as they do not exhibit sustainable behaviours in energy consumption, food choices, or transportation despite their pro-climate beliefs. In the case of conservatives, the authors found that, even considering their climate scepticism, they can adopt pro-environmental practices.

Regarding the factors that moderate the effect of political affiliation on perceptions concerning climate change and ecological transition measures, the academic literature has highlighted, on the one hand, levels of education and income. It has thus been observed that people with a higher level of knowledge and greater income tend to be more polarized, either in favour (progressive) or against (conservative) climate change mitigation policies, compared to people with lower levels of education and income, who are not so polarized [51,52]. On the other hand, it has been reported, especially in the United States, that factors such as gender, age, or religiosity also condition perceptions of climate change, with the young, female, and less religious population being most in favour of adopting policies to address it [27]. Other research points out at the quality of a country's governance as a factor that influences the support for or rejection of these measures [53].

In Spain, Simón and Claveria [30] have analyzed how social class and place of residence (rural or urban) influence support for environmental policies. These authors find that socio-cultural workers (an electoral stronghold of the left) support these policies more than manual workers (who are increasingly supporting the far-right). Therefore, they link the factor of social class to ideology to explain the polarization towards these measures. Nevertheless, they do not find significant differences in support for these policies by territory (although other, more applied studies, such as the one led by Suso et al. [54], do detect a territorial polarization gap related to policies that directly affect rural areas, such as the implementation of renewable energy installations in the territory).

In conclusion, we can affirm that, although there are different structural factors that can nuance support for climate change mitigation measures, ideology is a determining factor when it comes to generating divisions on the environment and climate.

2.2. Ecological Transition and the Media

In the context of the public debate, the media can play a fundamental role in polarization processes on environmental issues [19,35,53,55] and not just due to their association with certain parties or political positions in relation to climate change [47]. On the one hand, the degree of media coverage of the subject, specifically the volume, frequency, and prominence with which it appears [56,57], affects the population's level of knowledge on the issue [58] and helps shape a public agenda that conditions the citizens' attitudes [59]. On the other hand, the way the media frames climate change can contribute both to exacerbating and moderating polarization around the issue. Thus, according to Cole et al. [34],

in the United States, framing climate change as a threat to national security, linking it to innovation and new, green jobs, or appealing to national identity all increase support among conservatives for measures to mitigate it and, consequently, reduce polarization. In addition, it should be borne in mind that, while the media can cause polarization, they can also be beneficiaries, since their messages have been seen to generate a greater impact on the population in contexts of high polarization [59].

As for Spain, political polarization is also reflected in media consumption, where selective exposure due to ideological reasons is frequent [60,61], especially among those most interested in being informed [62]. In fact, according to Rodríguez [63], historically, the media system has been decisive in the growth of polarization in Spain. Added to this are social networks, which are also highly polarized areas [64,65], where clear signs of territorial polarization can also be observed [66].

Based on the finding that the role of the media, and especially the printed press, in the symbolic construction of reality and in the shaping of public opinion is more relevant in complex risks that are hard to perceive directly and have long-term effects—as is the case of the ecological transition [67]—academic studies highlight that the media are key in many ways.

First, several investigations conclude that the media are decisive in making this matter visible and in establishing the interpretative frames of the issue. In relation to media coverage, in their study on the coverage of the SDG and the 2030 Agenda in the Spanish digital press, López-Carrión and Martí-Sánchez [68] conclude that the appearance of these issues has increased over the years, especially coinciding with international summits, although this coverage is unequal, since the media with the highest audiences and greatest influence do not follow this trend. In respect to interpretive frames, it is concluded that the media generate frames from which the ecological transition is narrated, interpreted, and debated in the public sphere [21]. In their study on the coverage of the ecological transition on Spanish state television networks, Espinar et al. [20] identify four narratives that show that the issue is in constant construction and deconstruction. These ways of approaching the subject include economistic techno-optimism, green capitalism, the green new deal, and de-growth and operate as interpretative frames that mark the understanding of the subject; these frames are used according to the ideology of the media [20,22]. Along these lines, the study by Gozzer and Domínguez [69] shows how ecological transition measures that can transform our economic system can lead to media coverage that reflects their rejection in times of economic crisis.

Secondly, another group of studies focuses on the role of the media as intermediaries between science and citizens in processes of awareness-raising and mobilization [70]. These authors demonstrate that the media are an essential source of information and awareness-raising in Spain regarding the ecological transition and highlight, above all, their influence via social networks. In this vein, Fernández-Castrillo & Magallón-Rosa [71] assert that the relationship between the political agenda, public opinion, and the media is decisive in order to understand the evolution in levels of awareness based on the measures that have been adopted in the public sphere. Finally, and in line with the observations made in the previous section, García-Escribano et al. [72] show how the media can bring about affective polarization by creating homogeneous echo chambers that arouse emotional responses in positional issues.

In this article, on the one hand, we propose to observe what are the public's perceptions of the policies, practices, and dilemmas posed by ecological transition in Spain and to determine the extent to which this issue is a cause of political polarization. On the other hand, since we understand that the media are fundamental for shaping opinions and are a relevant actor in polarization processes, we will also look at the presence of the issue in the

agenda of the media and analyze whether citizens' information consumption can be related to their perceptions of the issue. We therefore propose to establish relationships between public perceptions of ecological transition and the media treatment of the issue which, to our knowledge, has been scarcely explored in the literature. One exception is the work by Wædegaard et al. [73] on the relationships between the frames used by the Danish press to deal with the issue of carbon sequestration and storage and public attitudes towards this policy, which focuses on a specific policy and not on ecological transition as a generic concept. In this regard, our research aims to better identify the concept of the "actually existing" ecological transition in Spain and contribute to expanding knowledge on this issue by addressing two research questions:

(RQ1) What are the perceptions of Spanish citizens on issues related to ecological transition, the degree of political polarization in this regard, and the associated media consumption?

(RQ2) Which treatment does the Spanish press give to ecological transition and the policies to implement it, according to editorial policy?

To do so, a two-pronged methodological approach is applied.

3. Method

3.1. Analysis of Citizens' Perceptions

3.1.1. Data Collection Process and Questions

The analysis of citizens' perceptions was carried out based on a survey, which is a particularly useful instrument for collecting information due to its versatility, generalizability, and cost-effectiveness [74]. Some of the questions that were included in a more general survey on the social dimension of ecological transition were used; these questions were part of a research project that focuses on the socio-economic analysis of ecological transition in the regions of Spain. The survey was administered to a representative sample of the Spanish population of legal age (N = 7029) during the months of June and July 2023, via computer-assisted telephone interviewing by the Spanish research institute GESOP. The sample of telephone numbers was stratified by autonomous community and municipality size. Sex and age quotas following the actual distribution of the population under study were used for the final selection of the person to be interviewed. Under a p = q = 0.5 assumption, the margin of error of the results is 1.2%, with a 95% confidence interval. A total of 48.7% of participants were men, and 51.3% were women, which is quite similar to sex distribution in the Spanish population over 18 years old (47.94% vs. 52.06% on April 2023, according to Instituto Nacional de Estadística [INE]). As for their age, 15% of those surveyed were 18–29 years old (compared to 14.7% of the whole Spanish adult population who is in this age gap, according to INE), 24.6% were 30–44 years old (23% in the whole population), 28.5% were 45–59 years old (27.5% in the whole population), and 31.9% were older than 59 (34.8% in the whole population).

The survey addressed issues such as Spaniards' environmental habits and behaviours and their opinions and knowledge of these matters. Specifically, for this article, an initial set of questions that poses several statements about ecological transition, to which respondents must rate their degree of agreement or disagreement on a Likert scale of 1–5, proves useful. These statements are based on ideological positions present in the public debate on ecological transition in Spain and were detected in a previous exploratory analysis of press articles regarding the ecological transition. Two of the statements denote a rather negative perception of ecological transition ("Ecological transition is a process forced by governments" and "Ecological transition endangers our current way of life"), while a third denotes a positive view ("Ecological transition is the only remedy for the current situation").

Moreover, questions are also analyzed on the respondents' degree of agreement (Likert scale of 1–5) with possible actions to be taken in order to carry out the ecological transition: ban fossil fuels, produce renewable energy, close nuclear power plants, and pay more for energy. All of these actions had a notable presence in the previous exploratory analysis of press articles. Together, the agreement with these actions enables one to determine the respondents' global attitude towards ecological transition policies.

Finally, a question was asked about the use of the media and other sources to obtain information regarding issues related to the environment. Respondents were able to choose up to a maximum of three options. Given their importance in the Spanish context, in the cases of the press (printed and digital), radio, and television, a distinction is made between local/regional, state-wide, and international media. Respondents who mentioned social networks were also asked which ones they use most to find out about environmental issues.

As sociodemographic variables of the study that may present significant associations with perceptions concerning the ecological transition, the survey included questions about sex, age, ideology (left/right on a scale of 1–5), the size of the municipality of residence (up to 10,000 inhabitants, 10,000–100,000 inhabitants, 100,000–500,000 inhabitants, and >500,000 inhabitants), level of studies (none, compulsory, post-compulsory, vocational, and university training), and respondents' prior knowledge of the ecological transition.

To some extent, some of the questions—such as those referring to ideological self-identification, media consumption habits, or knowledge of climate policies—may induce response bias. Although all questions were created following established standards, this is a limitation of surveys that will need to be considered when interpreting the results.

3.1.2. Data Analysis

Nearly all the variables included in the analysis are ordinal variables created through 1–5 Likert scales. However, following Norman (2010) [75], they are treated as interval variables, since many studies have shown that parametric statistics are robust when the data are from these kinds of scales.

First, Pearson correlations are carried out to assess the relationship between several dependent variables regarding ecological transition perceptions and political ideology (independent variable), which will allow to determine the degree of polarization on these issues. Moreover, political ideology is introduced in a regression model, together with other independent sociodemographic variables, to assess the specific importance of ideology in shaping opinions on ecological transition.

Two new variables were created, adding existing questions in the survey. First, "Global attitude towards ecological transition policies", which includes the mean responses in the four questions asking for perceptions about banning fossil fuels, producing renewable energy, closing nuclear power plants, and paying more for energy (1–5 scale). This variable is used as a dependent variable to assess how the general attitude of the public towards ecological transition measures correlates with political ideology.

The second variable was "Level of knowledge about ecological transition", which is used as an independent variable to assess how it impacts ecological transition attitudes and perceptions. This variable was created on the basis of the mean responses to five questions about respondents' knowledge (scarce to considerable, on a scale of 1–5) in relation to the possibility of using hydrogen for energy purposes, the Paris climate agreements, the European Commission's "climate action" project, the Spanish Climate Change act, and the climate and environmental regulation of their autonomous community of residence. All of them were questions included in the general survey due to their presence in the previous exploratory analyses of press articles; thus, they allow one to determine to what extent respondents are aware of ecological transition issues.

3.2. Content Analysis of the Spanish Press

Secondly, and based on the premise that the printed press is the second-most used medium by Spaniards to gain information concerning environmental issues (according to the survey carried out), all the news related to the ecological transition published in the press during the same period in which the fieldwork for the survey was carried out are extracted to observe the media narrative within that same time frame. Despite recognizing that media can influence the public's perception of social and political issues, our intention was not that of establishing a cause-and-effect relationship between the results of the survey and the media coverage. However, by examining both sources simultaneously, we can identify possible alignments between how the press handles the issue and citizens' perceptions.

The sample consisted of a total of four newspapers, two exclusively digital and two that also have a printed edition. It was decided to choose two publications with a conservative editorial policy and two publications with a progressive editorial line in order to observe whether the press is politically polarized regarding this issue. Within these criteria, those that, according to the Spanish audit body Information and Control of Publications (INTROL), have the most monthly readers were chosen. The four selected newspapers were El País (printed and digital, progressive editorial line), El Mundo (printed and digital, conservative line), OK Diario (exclusively digital, conservative), and Eldiario.es (digital only, progressive editorial line). All the news items containing the term "transición ecológica" were selected in the four newspapers for the period 25 May–25 July 2023, totalling 433 news items.

For each piece of information, a qualitative content analysis was carried out [76] based on the same variables that constitute the survey. Thus, it was determined whether the news story aligned generally with any of the three statements on ecological transition posed to the respondents ("Ecological transition is a process forced by governments", "Ecological transition endangers our current way of life", and/or "Ecological transition is the only remedy for the current situation"). For example, when a news item explains the push by governments and administrations for ecological transition measures, this aligns it with the claim that ecological transition is a process forced by governments. In another sense, when information focuses on the negative consequences that the implementation of ecological transition measures has for certain social and/or economic sectors, this aligns it with the affirmation that the ecological transition endangers our current way of life. Finally, when a news story stresses the need for and urgency of implementing ecological transition measures, this aligns it with the statement that ecological transition is the only remedy for the current situation. Naturally, one news story can be aligned with more than one of these statements.

In addition, it was also observed whether the news item refers to any of the measures for implementing the ecological transition considered in the survey (banning fossil fuels, producing renewable energy, closing nuclear power plants, and/or paying more for energy). If this is so, it is determined whether the news item denotes a position towards these policies that is either favourable, unfavourable, or neither favourable nor unfavourable.

Two coders analyzed the 433 news items that contained the term "ecological transition". To ensure reliable coding, the two coders met regularly to compare their findings. To achieve consensus, any uncertainties or disagreements were subsequently discussed and assessed in team meetings.

4. Results

4.1. Ecological Transition and Political Polarization

When asked about the degree of agreement with the different statements about ecological transition, most respondents strongly agree with the idea that it is the only remedy for the current situation. At the same time, however, many also consider ecological transition to be a process forced by governments. On the other hand, there is less agreement regarding the consideration that ecological transition endangers our current way of life. Now, when these statements are contrasted with the respondents' ideological standpoint, it is seen that those who consider themselves to be left of centre tend to agree more with the idea that ecological transition is the only remedy for the current situation, while those who consider themselves to be right of centre tend to agree more with the other two, more negative statements: that ecological transition is a forced process and that it endangers our current way of living (Table 1).

Table 1. Degree of respondents' agreement with different statements about ecological transition (scale 1 [strongly disagree]–5 [strongly agree]).

	Mean Agreement (Standard Deviation)	Correlation with Left/Right Ideological Self-Perception
ET is a process forced by governments	3.01 (1.45)	0.336 ($p < 0.001$) *
ET endangers our current way of life	2.52 (1.41)	0.141 ($p < 0.001$) *
ET is the only remedy for the current situation	3.66 (1.32)	−0.310 ($p < 0.001$) *

* Correlation is significant.

The strength of the association of positive and negative perceptions about ecological transition with left- or right-wing ideological positioning, respectively, is evident when this variable is introduced in a multiple linear regression model together with other factors that may be relevant in the perceptions of the respondents, such as age, the size of their municipality of residence, their level of education, or their previous knowledge about ecological transition. As can be seen in Table 2, the ideological scale is the only factor that is statistically significantly associated with the three statements, and it is always associated to a higher degree than other variables such as age or level of education. Variance analysis according to the gender of the respondents, on the other hand, yields an association with this variable, especially in the case of the statement "The ecological transition is the only remedy for the current situation", for which women are far more in agreement than men (3.84 vs. 3.48), which is not the case for the other two statements. In any case, the existence of an ideological polarization of the respondents with respect to their (positive or negative) perceptions about ecological transition is confirmed, which is more explanatory than the other factors considered.

Furthermore, the attitude towards different measures related to ecological transition, although generally positive, is also conditioned by the ideological positioning of the respondents (Table 3). Thus, left-leaning people are more in favour of banning fossil fuels, the production of renewable energy (although in this case with a very weak association), the closure of nuclear power plants, and paying more for energy. The issue of nuclear power plants is the one that generates the most polarization.

Table 2. Multiple linear regression of the agreement with different statements about ecological transition according to the respondents' ideology, age, size of the municipality of residence, level of education, and prior knowledge of ecological transition.

	ET Is a Process Forced by Governments **	ET Endangers Our Current Way of Life ***	ET Is the Only Remedy for the Current Situation ****
Ideological scale	β = 0.241 ($p < 0.001$) *	β = 0.144 ($p < 0.001$) *	β = −0.313 ($p < 0.001$) *
Age	β = 0.069 ($p < 0.001$) *	β = 0.027 ($p = 0.058$)	β = 0.048 ($p < 0.001$) *
Size of municipality	β = −0.008 ($p = 0.548$)	β = 0.015 ($p = 0.268$)	β = 0.030 ($p = 0.027$)
Level of education	β = −0.053 ($p < 0.001$) *	β = −0.059 ($p < 0.001$) *	β = −0.020 ($p = 0.159$)
Knowledge of ET	β = −0.013 ($p = 0.342$)	β = 0.015 ($p = 0.295$)	β = −0.019 ($p = 0.149$)

* Correlation is significant; ** R^2: 0.068/F: 73.302 ($p < 0.001$); *** R^2: 0.026/F: 27.448 ($p < 0.001$); **** R^2: 0.102/F: 116.217 ($p < 0.001$).

Table 3. Degree of respondents' agreement with different measures related to ecological transition (scale 1 [strongly disagree]–5 [strongly agree]).

Measure	Mean Agreement (Standard Deviation)	Correlation with Left-Right Ideological Self-Perception
Ban fossil fuels	3.38 (1.41)	−0.274 ($p < 0.001$) *
Renewable energy production	4.45 (0.85)	−0.097 ($p < 0.001$) *
Closure of nuclear power stations	3.31 (1.48)	−0.348 ($p < 0.001$) *
Pay more for energy	3.03 (1.43)	−0.186 ($p < 0.001$) *

* Correlation is significant.

If we create an index that groups all the above measures, we can see the general attitude of the respondents towards ecological transition policies, which stands at 3.55 on a scale of 1 to 5 (in which 1 equals a very negative and 5 a very positive attitude towards ecological transition policies), with a standard deviation of 0.85. This global attitude has a higher negative association with the respondents' ideological positioning than the specific correlations of each of the measures in Table 3: −0.369 ($p < 0.001$). Thus, it is observed that the general attitude towards ecological transition policies is clearly conditioned by this factor. Again, multiple linear regression (Table 4) shows that ideology is a more relevant factor than the respondents' age, size of the municipality of residence, level of education, or prior knowledge. Respondents' gender is also less affected (men have a mean attitude of 3.41 and women a mean attitude of 3.69).

Table 4. Multiple linear regression of the respondents' global attitude towards ecological transition policies according to their ideology, age, size of the municipality of residence, level of education, and prior knowledge of ecological transition.

Factor	β	Sig.
Ideological scale	−0.367	<0.001 *
Age	0.037	0.007
Level of education	0.049	<0.001 *
Size of municipality	0.042	0.002 *
Knowledge of ET	0.007	0.580

* Correlation is significant; R^2: 0.142/F: 160.600 ($p < 0.001$).

4.2. Political Polarization According to the Level of Instruction and Level of Knowledge on Ecological Transition Issues

Given that previous studies in other national contexts reveal greater ideological polarization with respect to the perception of climate change among people with a higher education qualification, this analysis is conducted to observe whether this phenomenon also occurs in Spain (Table 5). The data, in this case, do not clearly support a conclusion that this greater polarization exists among people with a higher level of education. The variations observed in correlating perceptions and attitudes towards ecological transition and the ideological scale in the sample as a whole and in the subpopulation with university studies are, in most cases, minor, and even on some points (such as agreement with the statement that the ecological transition is a process forced by the governments or agreement with the production of renewable energy), less polarization is observed in the population with university studies. Only in relation to the degree of agreement with the banning of fossil fuels is greater polarization observed among the university-qualified population than in the population as a whole.

Table 5. Comparison of the correlation of different opinions and attitudes on ecological transition and political ideology among the general population, the population with a higher education qualification, and the population with a medium and high level of knowledge on ecological transition issues.

Opinions And Attitudes On Ecological Transition	Correlation with Ideological Scale—General Population	Correlation with Ideological Scale—Population with a Higher Education Qualification (N = 3047)	Correlation with Ideological Scale—Population with a Medium and High Level of Knowledge About ET (N = 1143)
Agreement with the statement "ET is a process forced by governments"	0.336 ($p < 0.001$) *	0.289 ($p < 0.001$) *	0.298 ($p < 0.001$) *
Agreement with the statement "ET endangers our current way of life"	0.141 ($p < 0.001$) *	0.166 ($p < 0.001$) *	0.234 ($p < 0.001$) *
Agreement with the statement "ET is the only remedy for the current situation"	−0.310 ($p < 0.001$) *	−0.355 ($p < 0.001$) *	−0.386 ($p < 0.001$) *
Agree with banning fossil fuels	−0.274 ($p < 0.001$) *	−0.324 ($p < 0.001$) *	−0.357 ($p < 0.001$) *
Agree with producing renewable energy	−0.097 ($p < 0.001$) *	−0.073 ($p < 0.001$) *	−0.123 ($p < 0.001$) *
Agree with shutting down nuclear power plants	−0.348 ($p < 0.001$) *	−0.380 ($p < 0.001$) *	−0.364 ($p < 0.001$) *
Agree with paying more for energy	−0.186 ($p < 0.001$) *	−0.223 ($p < 0.001$) *	−0.243 ($p < 0.001$) *
Global attitude towards ecological transition policies	−0.369 ($p < 0.001$) *	−0.405 ($p < 0.001$) *	−0.416 ($p < 0.001$) *

* Correlation is significant.

Concerning prior knowledge about ecological transition issues, it seems logical to think that they may be related to greater ideological polarization about ecological transition, considering that being more informed about these issues could allow respondents to position themselves more forcibly. The analysis shows that prior knowledge is indeed a factor that generally increases ideological polarization around ecological transition in relation to most of the issues considered. For example, the degree of agreement with the

statement "Ecological transition endangers our current way of life" presents significantly greater ideological polarization among people with knowledge on the subject than among the population as a whole, as well as the degree of agreement with the banning of fossil fuels or the degree of agreement with the statement "Ecological transition is the only remedy for the current situation". In contrast, the degree of agreement with the statement "Ecological transition is a process forced by governments" has a lower correlation with the ideological scale among people with knowledge of the subject.

4.3. Media Consumption and Ecological Transition

When asked about the media they use to keep informed about environmental issues, most respondents select national television and, secondly, the national digital press (see Figure 1). However, regional and local television and digital press are also important sources of information on these issues, and television (either national, regional or local) is the medium selected by 48% of respondents. Social networks come in third place, with Instagram, X, and Facebook most mentioned (Figure 2). Of all respondents, 3.9% answer that they do not get informed about environmental issues. It can be said, therefore, that the media, and especially television, are by far the main source of information for respondents regarding ecological transition, and that there is a preference for national media to the detriment of regional/local and international media.

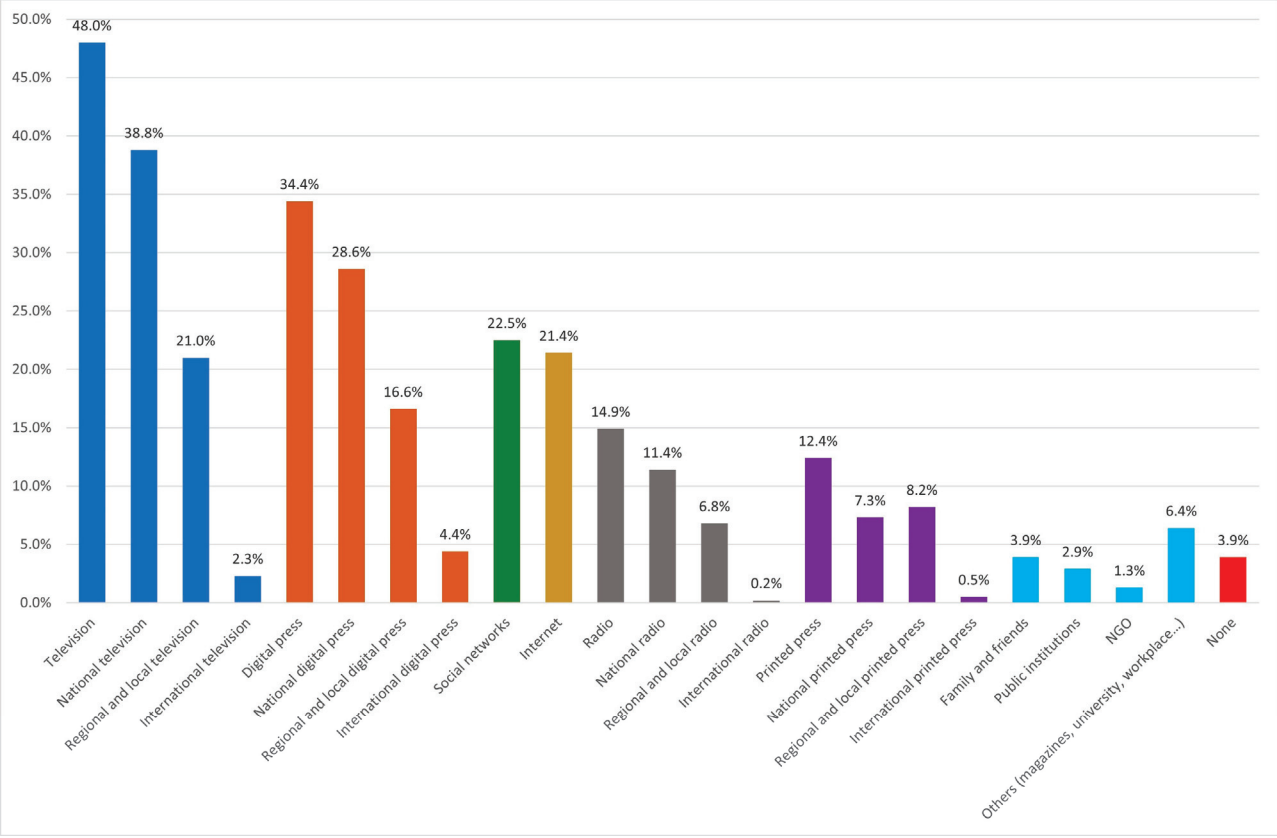


Figure 1. Medium used to keep abreast of environmental issues. Note: respondents could select up to a maximum of three media.

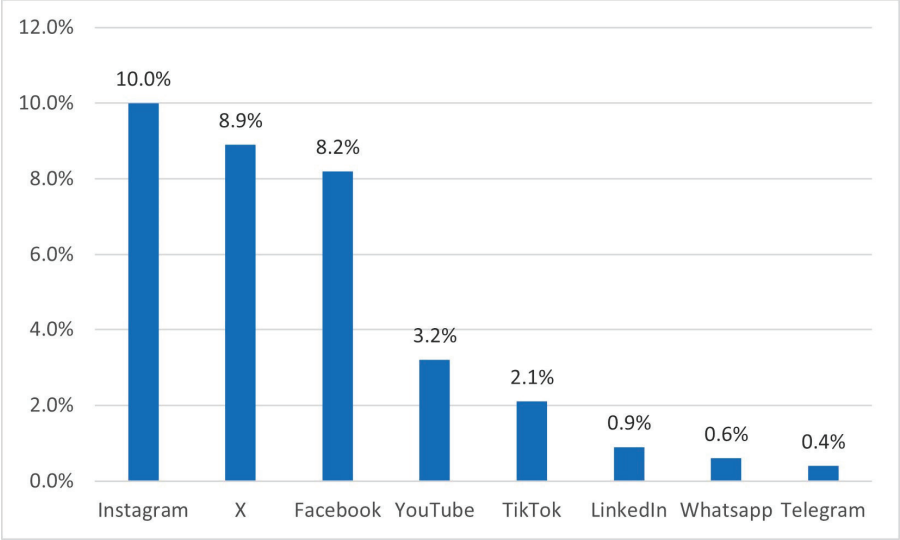


Figure 2. Social networks used to keep abreast of environmental issues.

The use of the different media to keep abreast of environmental issues does not imply significant variations in the perception of ecological transition or in the respondents' attitude towards ecological transition policies (Tables 6–9). Thus, both those who resort to television, as well as those who rely on the printed or digital press, radio, or social networks to keep informed about the environment have positions that are strongly aligned with the average of all respondents. On the other hand, more extreme values are observed among respondents who state that they obtain their information on environmental issues through NGOs, and these respondents have a far more positive perception and attitude than average towards ecological transition. The opposite can be said of respondents who report that they do not inform themselves about environmental issues: their attitude towards and perception of ecological transition is the most negative of the entire sample. To a lesser extent, people who obtain their information through public institutions also tend to have a more negative than average view of the issue.

Table 6. Degree of respondents' agreement with the statement "Ecological transition is a process forced by governments" according to the sources they use to find out about environmental issues (scale 1 [strongly disagree]–5 [strongly agree]).

Mean	Mean Agreement	Number of Persons Surveyed (N)
TV	3.06	3013
Radio	3.06	948
Printed press	2.95	790
Digital press	2.89	2296
Social networks	2.96	1516
Family, friends, and others	2.91	246
Public institutions	3.15	194
NGOs	2.80	87
Internet	2.97	1442
Others	2.70	429
Do not seek information on environmental issues	3.26	227
GLOBAL MEAN	3.01	6405

Note: respondents could select up to a maximum of three media.

Table 7. Degree of respondents' agreement with the statement "Ecological transition endangers our current way of life" according to the sources they use to find out about environmental issues (scale 1 [strongly disagree]–5 [strongly agree]).

Mean	Mean Agreement	Number of Persons Surveyed (N)
TV	2.53	3124
Radio	2.55	983
Printed press	2.58	820
Digital press	2.45	2355
Social networks	2.50	1543
Family, friends, and others	2.46	264
Public institutions	2.59	198
NGOs	2.38	89
Internet	2.48	1456
Others	2.44	432
Do not seek information on environmental issues	2.72	236
GLOBAL MEAN	2.52	6592

Note: respondents could select up to a maximum of three media.

Table 8. Degree of respondents' agreement with the statement "Ecological transition is the only remedy for the current situation" according to the sources they use to find out about environmental issues (scale 1 [strongly disagree]–5 [strongly agree]).

Mean	Mean Agreement	Number of Persons Surveyed (N)
TV	3.75	3129
Radio	3.72	979
Printed press	3.70	812
Digital press	3.66	2344
Social networks	3.67	1538
Family, friends, and others	3.62	260
Public institutions	3.52	201
NGOs	4.15	91
Internet	3.64	1468
Others	3.58	437
Do not seek information on environmental issues	3.26	234
GLOBAL MEAN	3.66	6583

Note: respondents could select up to a maximum of three media.

Table 9. Respondents' global attitude towards ecological transition according to the sources they use to find out about environmental issues (scale 1 [highly negative]–5 [highly positive]).

Mean	Mean Attitude	Number of Persons Surveyed (N)
TV	3.57	2867
Radio	3.58	902
Printed press	3.61	727

Table 9. *Cont.*

Mean	Mean Attitude	Number of Persons Surveyed (N)
Digital press	3.60	2205
Social networks	3.58	1447
Family, friends, and others	3.62	232
Public institutions	3.38	186
NGOs	3.83	85
Internet	3.54	1366
Others	3.60	409
Do not seek information on environmental issues	3.33	200
GLOBAL MEAN	3.55	6067

Note: respondents could select up to a maximum of three media.

4.4. Presence and Treatment of Ecological Transition in the Press

Eldiario, an exclusively digital medium with a left-wing editorial line, was the only one of the four newspapers analyzed to treat issues related to ecological transition intensively, as it published 244 news stories on the subject during the study period. Meanwhile, in El País, El Mundo, and OK Diario, the topic was covered far less (76, 57, and 56 news items, respectively). Also, in these three latter media outlets, most of the information tended to align with the idea that ecological transition is a process forced by governments (Figure 3), which can be explained by the fact that their news items refer to policies and actions that governments undertake or propose in relation to ecological transition. Thus, for example, El País headlined "The EU will force the inclusion of removable batteries in mobile phones as of 2027" in a news item published on 11 July 2023 [77], which highlighted the contribution of this measure to ecological transition; El Mundo reported on the government's plan to expand carbon sinks in order to comply with EU commitments ("There are not enough sinks for so much CO_2", 5 July 2023 [78]); and OK Diario criticized the proliferation of state institutions dedicated to promoting ecological transition ("Pedro Sánchez creates a Climate Observatory when he already has an office, a council and two commissions", 28 June 2023 [79]).

In contrast, in Eldiario, most information refers to the idea that ecological transition is the only remedy for the current situation (although news presenting ecological transition as a process forced by governments is also greatly present). For example, an opinion article published on 31 May 2023 titled "The conservative drift of society" [80] criticizes the rise of climate denialism among some of the Spanish electorate, or the article "High temperatures set alarms ringing on the Balearic Islands", published on 22 July 2023 [81], stresses the negative consequences of climate change and the need to ban fossil fuels to remedy it.

It should also be noted that OK Diario, with a right-wing editorial line, is the only medium with a significant presence of news that refers to ecological transition as a danger to our current way of life. Thus, several reports in this newspaper criticize the Spanish government for not wanting to regularize the illegal irrigation of the Doñana natural park for ecological reasons, which endangers the livelihood of strawberry producers in the area, who face a boycott ("Pedro Sánchez and Teresa Ribera spread the boycott by a German association against the Huelva strawberry" [31 May 2023] [82]; "The Junta de Andalucía demands that Sánchez should 'rectify' after 'supporting' the Huelva strawberry boycott" [1 June 2023] [83]; "Huelva risks losing 167 million in exports due to the German strawberry boycott backed by the government" [1 June 2023] [84]). In addition, the newspaper criticizes the Spanish government's possible support for the Euro7 standard, which would have a

negative effect on car manufacturers in Spain ("Ribera presses for Sánchez not to oppose the European green standard that France and Italy already reject", 1 June 2023 [85]), and it highlights that 20% of Spaniards believe that the ecological transition will be negative ("Half of Spaniards do not know what the ecological transition is and 20% think it will be negative", 28 June 2023 [86]).

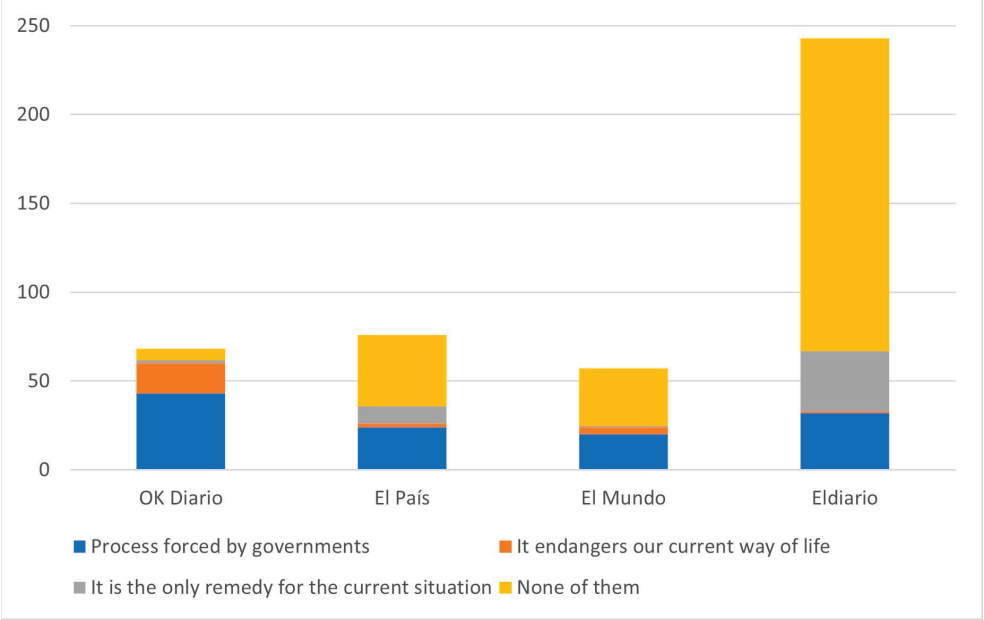


Figure 3. Alignment of ecological transition news with different statements about ecological transition in the newspapers analyzed. Note: A news story can be aligned with different statements.

If we compare these results with citizens' perceptions as recorded in the survey, it is observed that this treatment by OK Diario is consistent with the tendency of people who consider themselves to be right of centre to believe that ecological transition endangers our way of life, unlike those who consider themselves left of centre; and that Eldiario's treatment is consistent with the tendency of people who consider themselves to be left of centre to believe that ecological transition is the only remedy for the current situation, in contrast to those who consider themselves to be right of centre.

Finally, regarding the measures for implementing ecological transition, most media outlets make extensive reference to both the production of renewable energy (45 news stories) and the banning of fossil fuels (42 news stories) (Figure 4). The closure of nuclear power plants is covered in 17 news stories, while charging more for energy appears in only eight news items (all published by *OKDiario*). The issue of closing nuclear power plants, which generated considerable ideological polarization among the respondents, is also dealt with in different ways by the four newspapers of the sample. Thus, the only newspapers that publish news against the closure are the two with a right-wing editorial line (OKDiario and El Mundo). In addition, this is the only measure about which more negative (against) news items are published than positive (for) ones. On the other hand, the production of renewable energy is treated very positively, and in fact, no negative (against) news is published in this regard by any of the four newspapers.

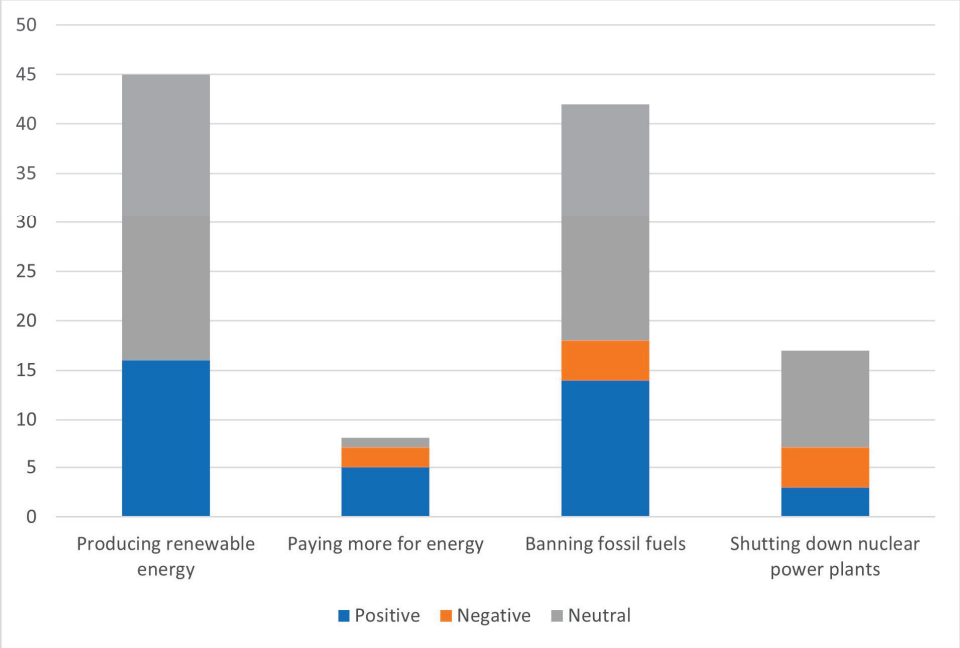


Figure 4. Number of news stories about ecological transition that mention different measures and the vision that emerges from them in the newspapers analyzed. Note: the same story can mention several measures.

5. Discussion and Conclusions

The results of the survey carried out on a representative sample of the Spanish population show a certain political polarization around ecological transition which goes beyond differences in age, sex, level of education, size of the municipality of residence, and previous knowledge of the issue. The further left-wing that respondents consider themselves, the more convinced they are that ecological transition is the only remedy for the current situation; conversely, the more right-wing that respondents consider themselves, the more that they agree with the idea that ecological transition endangers our current way of life and that it is a process forced by governments. In this respect, the results of the survey are similar to the contributions of Ballew et al. [51] and Tranter et al. [52], who already pointed to the ideological axis as a relevant element in the positioning on social and environmental issues.

If we look at the concrete measures related to ecological transition, the polarization around the closure of nuclear power plants stands out (people right of centre are far more opposed to it than those left of centre). However, the production of renewable energy is the measure that generates the lowest political polarization among respondents (a measure with which, generally speaking, the public is very much in agreement). It could be said, in line with the research of van Eck et al. [19], that polarization now lies in climate solutions and not so much in the fact that climate change is something that requires addressing. Galindo and Collado [87] also affirm that Spanish society grants (great) importance to the problem of climate change, but it is subject to specific divisions around policies to mitigate it, fuelled by ideologies. In this sense, the general attitude towards ecological transition measures, in any case, is clearly conditioned by the respondents' political leaning, with those who consider themselves to be left of centre being far more positive than those who consider themselves right of centre, in line with the general views they express on ecological transition.

These results are also reflected in the press treatment of ecological transition. Thus, it has been observed that dailies with a conservative editorial line tend to publish more news

presenting ecological transition and the measures to implement it in a negative way, while the opposite occurs in their counterparts with a progressive editorial line.

Without being able to determine a direct relationship between the press treatment of ecological transition according to their editorial line and the perceptions and attitudes of the public according to their ideology, it seems evident that there is a clear alignment regarding this issue. Indeed, in the case of specific measures such as the closure of nuclear power plants or the production of renewable energy, the treatment by the press very clearly emulates the perceptions of citizens. Thus, while the closure of nuclear power plants was the most polarizing measure among respondents, it is also one of the factors that most differentiates newspapers according to their editorial line, since only newspapers with a conservative editorial line publish news against their closure. Conversely, the low degree of political polarization generated by the promotion of renewable energy production is also reflected in the press, which, in general terms, treats it highly positively, regardless of the editorial line.

The press, therefore, emerges as an actor that reinforces the existing political polarization in society around ecological transition, which, in turn, confirms its role as a social builder of reality. The Mediterranean model of the media—polarized pluralist [88]—is characterized, among other factors, by a high degree of political parallelism in both public and private media. The results of this research enable one to corroborate that the critical positioning towards ecological transition in the conservative media is often related to questioning the policies and behaviour of the current, progressive Spanish government, emphasizing the negative consequences that these policies can have for the citizens and for the economy, thus aligning with the positioning of the conservative opposition.

However, the results of the survey also confirm that the consumption of media according to type (television, press, radio, social networks) to gain information about environmental issues does not significantly influence citizens' perceptions of ecological transition and its measures. There would be a need to see what happens if a distinction is made between different newspapers, TV channels, etc., with marked and differentiated editorial lines.

On the other hand, different perceptions of ecological transition are displayed by respondents who report that they do not keep abreast of environmental issues, who tend to have a more negative view; those who are informed through NGOs, who tend to have a more positive view; and those who are informed through public institutions, who also tend to have a more negative view. This latter result is interesting and can pave the way for future lines of analysis to establish how institutions communicate on these issues and how communication can be improved to have a positive impact on citizens' perceptions. Despite the "level of knowledge variable" not being statistically significant, it should also be noted that, unlike the findings of previous research, political polarization regarding ecological transition in Spain does not appear to be greater among the most highly educated people. In contrast, it is among those who have a deeper knowledge of the subject, which is to be expected if we base ourselves on the premise that greater knowledge denotes greater interest and, therefore, a stronger positioning with respect to the subject matter.

5.1. Limitations and Future Research

The research presented in this article has some limitations. For example, the analysis of citizens' perceptions via the survey can be considered a valid methodology to ascertain in a representative way the opinion of Spanish citizens about ecological transition. However, it provides us with quantitative data that do not enable us to fully understand the reasoning behind the responses of the people surveyed, and some of the questions inevitably may have induced response biases. Similarly, the media analysis focuses only on the press as a representative element of traditional media but does not look at how information about

ecological transition circulates on social networks, which according to Newman et al. [89], occupy an increasingly privileged place in the consumption of information. Lastly, the article presents Spain as a case study, but a comparative perspective with other countries where political polarization around ecological transition policies is evident would enhance the external validity of the conclusions. Future research could, therefore, use qualitative methodologies such as focus groups to investigate the narratives developed by Spanish citizens in relation to ecological transition and study how the contents on this subject are disseminated on digital platforms; in addition, future research could include other countries in the analysis. Furthermore, the analysis presented herein, which identifies the positions of citizens and the media on ecological transition, could be complemented by a study of how political actors define this issue.

5.2. Practical Recommendations

While polarization around the ecological transition needs to be addressed through measures that go beyond how the concept is communicated (e.g., by developing policies that support workers from traditional industries affected by ecological transformation; providing affordable, environmentally friendly public transport options, etc.), effective communication strategies implemented by institutions and the media can positively impact the achievement of a more consensual ecological transition. For example, ideological divides can be mitigated by encouraging dialogue between political actors with opposing views and involving stakeholders in the development of mitigation measures. There is an urgent need to move the discussion of the ecological transition beyond polarization. Communication can either increase or decrease polarization, and the media can play a crucial role in this process by framing the debate around the ecological transition with non-polarizing language and promoting a sense of shared responsibility among all members of society.

Author Contributions: Conceptualization, R.B., A.C. and C.M.M.-F.; methodology, R.B. and A.C.; validation, R.B. and A.C.; formal analysis, R.B. and A.C.; investigation, R.B. and A.C.; writing—original draft preparation, R.B., A.C. and C.M.M.-F.; writing—review and editing, R.B., A.C. and C.M.M.-F.; visualization: R.B. and C.M.M.-F.; funding acquisition, A.C. and C.M.M.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This work is part of the Social Perception and ECological TRansition Under a Multidimensional socio-economic analysis of the Spanish region (SPECTRUM) project [Grant TED2021-130835B-I00] funded by MICIU/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR.

Data Availability Statement: The original contributions presented in this study are included in the article, The details of the survey will be available at http://www.spectrumurv.com/en/ (accessed on 14 April 2025). Further enquiries can be addressed to the corresponding author.

Conflicts of Interest: The authors declare no potential conflicts of interest with respect to the research, authorship, or publication of this article.

Abbreviations

The following abbreviations are used in this manuscript:

IPCC	Intergovernmental Panel on Climate Change
SDGs	Sustainable Development Goals
INE	Instituto Nacional de Estadística
INTROL	Information and Control of Publications

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Article

From Soil to Servers: Persistent Neglect of Land Resources and Its Looming Repetition for Users in the Digital Age

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Abstract: For well over a century, unresolved ambiguities in defining land as a finite, non-renewable resource have often facilitated rent-seeking and shaped inequitable distributions of wealth derived from nature and collective contributions. In the absence of clear conceptual and legal distinctions between land's intrinsic worth and the incremental value conferred by human-made improvements, communities and ecosystems were frequently denied their rightful share, thereby influencing inequitable economic, social, and environmental trajectories. Though not universal, these historical patterns now reemerge in "digital land" platforms, where data, user engagement, and communal knowledge are likewise subject to private appropriation. By bridging these classical land debates with emerging forms of digital exploitation, this article offers a novel theoretical framework that reveals how unresolved land-valuation ambiguities reappear in user-generated data ecosystems. Without robust conceptual frameworks and effective regulatory oversight, such digital spheres risk replicating the exploitative logic once attached to physical land. By clarifying these parallels, this article underscores the urgent need for well-informed governance inspired by past land policy debates—particularly those focused on equity, transparency, and sustainability. Ensuring that resource management, whether rooted in soil or servers, consistently adheres to principles of fairness and shared prosperity is essential to avert new forms of unregulated extraction and to advance more inclusive, sustainable development.

Keywords: land definition; land value; valuation; land rent; digital land; digital rent; digital rent; land neglect; land exploitation

1. Introduction

For centuries, the pursuit of wealth, authority, and social influence has been closely associated with the control and intensive usage of land. From agrarian societies to industrialized nations, land has served not only as the physical substrate for human activity but also as a strategic resource capable of yielding unearned income—what classical economists defined as rent [1–3]. Rooted in the land's inherent scarcity, permanence, and immobility, rent initially arose as a surplus, captured by those holding exclusive claims to fertile soils, prime locations, or rich natural endowments [4]. Over time, as societies transformed and urbanized, the conceptions of land's role evolved. Yet, the persistent ambiguity in defining land as a finite, non-renewable resource, and in distinguishing its intrinsic worth from the improvements placed upon it, allowed a privileged minority to retain control [5]. This concentration of influence shaped the governance structures, steered economic trajectories, and sustained inequalities that disadvantaged both the communities and ecosystems fundamentally contributing to the land's value [6].

Early theoretical foundations, notably Ricardo [2], revealed how landlords secured differential rent from the most fertile or well-located plots—often seen as an unearned income stream. Similar ethical questions about resource exploitation and its impact on justice are addressed in broader environmental value debates [7]. Building on these insights, Marx [8] framed land ownership as a site of surplus extraction under capitalism, and George [9] insisted that unearned increments accruing to land should be reclaimed for the public good. Across diverse perspectives—including classical, Marxian, and Georgist—an emerging consensus recognized land as more than a mere commodity. Instead, it was understood as a co-created resource, shaped by nature, public investments, cultural significance, and collective efforts, implying that the gains derived from it deserved broader redistribution [10].

As the nineteenth and twentieth centuries advanced, scholars further documented how these processes played out. Sombart [11] detailed how commodification transformed the once-communal lands into private assets, restructuring socio-ecological relationships. Later studies, such as Cord and Andelson [12], demonstrated how taxation policies and valuation models often favored landowners, entrenching power imbalances. Environmental economists and ecologists, including Daly [13], warned of the environmental harm arising from neglecting the land's non-renewable limits, while Shiva [14] showed that commodification disproportionately impacted Indigenous peoples and marginalized communities. Ostrom's [15] work on common-pool resources challenged fatalistic assumptions like those associated with Hardin's [16] "tragedy of the commons", illustrating that well-defined, community-driven governance structures can sustainably manage shared resources. These insights collectively underscored that the land's value emerges from communal inputs—natural endowments, public infrastructure, and cultural vitality—and that failing to disentangle and equitably distribute this value fortified longstanding inequities [17].

Despite the intellectual clarity gained over time, transformative policy interventions proved elusive. Conceptual confusion, especially over how to separate the land's intrinsic value from that of capital improvements, persisted. Traditional urban planning models, legal frameworks, valuation methodologies, and taxation systems habitually treated land and improvements as an indivisible whole, concealing the unearned surplus attributable to land itself [18]. Even reformers like George [9], who advocated land value taxation, encountered vested interests, political complexities, and methodological challenges that limited their impact. As buildings depreciated and infrastructure aged, land values, paradoxically, soared—buoyed by communal investments, shifting demand, and finite supply [19]. Communities bore increasing fiscal burdens, without receiving any commensurate returns [20,21], and the environmental conditions deteriorated, as urban expansion proceeded with inadequate ecological compensation [22]. Thus, the debate over distinguishing the land's intrinsic value from human-made additions extended beyond mere conceptual and technical appraisal concerns, emerging as a profound inquiry into principles of fairness, justice, and sustainable management [23,24].

As we enter the digital age, the logic of resource capture adapts and transcends its original mediums. No longer limited to fertile fields or strategic urban and real estate developments, rent-seeking strategies now thrive in intangible domains—"digital land"—an ecosystem where user data, engagement, and collective knowledge serve as valuable resources subject to monopolistic control [25,26]. Just as historical land rents emerged from fertile soils or prime locations, digital rents arise from user interactions, personal information, and shared intellectual contributions [27,28]. The new "Mindowners" refine past methods, leveraging algorithmic opacity, data asymmetries, and global platform dominance to appropriate cognitive and informational commons [29], in many cases

capitalizing on limited oversight, data asymmetries, and outdated regulatory frameworks, that fail to capture the essence of these intangible assets.

This modern twist on exploitation reflects earlier patterns. Where landlords once exploited legal ambiguities and weak institutional oversight to secure disproportionate gains, platform owners now capitalize on the transition from physical land to abstract "digital land", leveraging conceptual and definitional gaps along with valuation uncertainties [30]. Without effective governance, digital platforms risk replicating the historical imbalances of physical land exploitation. In the past, unearned increments deprived communities of their rightful share of land's value; today, digital monopolies deny users fair access to the wealth generated by their collective data and intelligence. As the digital sphere increasingly shapes thought, interaction, and cultural exchange, the absence of principled, transparent, and equitable regulatory frameworks threatens to give rise to new forms of injustice—cognitive exploitation, privacy erosion, and a fragmented public discourse [31].

Recognizing historical parallels and theoretical lessons, however, can inspire more proactive and equitable interventions. Just as earlier observers realized that clarifying the land's distinctiveness and taxing its unearned increments could counter exploitative rent extraction, we can now apply similar principles to the digital realm. Insights from institutional resource regimes [15], land value capture experiments [32,33], and sustainable development frameworks [34,35] equip us to manage intangible digital resources ethically. Where reformers once proposed land value taxation and betterment levies, contemporary policymakers might envision data dividends, platform cooperatives, and regulatory standards, ensuring that digital platforms operate in the public interest rather than as vehicles of private enrichment [36,37].

Although the socio-economic and ecological inequalities tied to historical land exploitation were often severe [6,22], the commodification of human cognition and expectation—finite and fragile intangible resources—introduces a profound socio-intellectual challenge [38]. If this historical neglect enabled powerful actors to appropriate natural and communal wealth without redistribution, inaction today risks allowing them to appropriate intangible cognitive resources at the expense of human agency, creativity, and collective wisdom. The potential corrosion of intellectual autonomy and cultural resilience remains a pressing concern [39]

This study employs a multi-tiered literature synthesis to elucidate how classical, land-based exploitation persists and mutates in modern, data-driven contexts. First, key economic and historical sources on rent formation—spanning classical traditions (e.g., Ricardo, Marx, George) and modern critiques (e.g., mass appraisal studies)—were collected to clarify how the ambiguities in land value and valuation fueled the appropriation of unearned increments. Next, the debate between "omeletists" (who contend that the land and improvements are inseparable) and "separatists" (who advocate for isolating the land's intrinsic value) was systematically compared in order to grasp how diverse theoretical positions rationalize or resist exploitative patterns. The inquiry then integrated this foundation with contemporary scholarship on digitization, platformization, and cognitive exploitation to reveal the parallels between the historic "land rent" dynamic and the emerging "digital rent" models, predicated on user data and communal knowledge. Crucially, rather than conducting novel empirical measurements, the methodology emphasized weaving the scattered, yet thematically connected, literatures into a coherent analytical framework, illustrating how the unresolved valuation disputes and inadequate governance in classical land debates reappear—often amplified—in intangible, knowledge-based economies. By charting these conceptual linkages across eras, the research highlights both the enduring logic of exploitation, and the potential solutions, adapted from land-focused policy and regulatory instruments.

Building on these foundational insights, this paper develops three core arguments: first, that unresolved conceptual and legal definitions of land contributed to historical exploitation; second, that the analogous, definitional gaps now drive modern rent-seeking around user-generated data and intangible digital resources; and third, that institutionalized solutions from the physical realm—such as land value taxation or community-driven governance—can inform equitable structures for "digital land", thereby mitigating contemporary exploitative practices.

Faced with these evolving conditions, policymakers, scholars, activists, and communities are called to critically examine the complexities of digital exploitation, where powerful actors—conglomerates, tech giants, and other monopolistic entities—appropriate unearned value. This article critically analyzes the parallels between historical land exploitation and modern digital dynamics, emphasizing how monopolization and inequitable value distribution persist across the domains. By revisiting centuries of land debates—distinguishing the land's intrinsic worth, addressing the inequities in rent distribution, and integrating the ecological and social dimensions—we aim to advance a deeper understanding of the risks to cognitive and informational commons posed by unchecked appropriation and systemic injustice, while also providing insights into potential challenges and pathways toward equitable solutions.

In addition, this paper advances a novel theoretical perspective by bridging the classical rent theory with the contemporary "digital rent" phenomena. While prior works have examined land exploitation or digital data monopolies separately, our approach highlights how the unresolved conceptual ambiguities in land valuation now reappear in digital "land" platforms, thus offering a fresh contribution to the discussions on governance, equity, and sustainable resource management. Rather than conducting empirical measurements or presenting original quantitative data, we focus on mapping the conceptual, historical, and policy-oriented facets of exploitation across both soil and servers—ultimately revealing how older debates inform modern frameworks of extraction.

In the following sections, we delve deeper into the foundational concepts that frame these issues. First, we examine the definition, attributes, and economic significance of land, providing a basis for the critical debate on its separability from human-made improvements. This analysis highlights how the ambiguities in defining the land's intrinsic value facilitated historical exploitation, shaping the frameworks that persist in modern contexts. Building on this, we explore how the concept of digital rent extends the classical rent-seeking patterns into intangible domains, exposing new vulnerabilities. Finally, we discuss institutional mechanisms—both historical and contemporary—that offer insights into how the benefits of physical and digital resources can be distributed more equitably and sustainably.

2. Definition of Land

Although the term "land" may appear straightforward when a child describes it as "the garden where tomatoes grow", experts quickly discovered that defining land encompasses a wide range of dimensions and usage types—from residential, commercial, and industrial to agricultural and more. Each category can further branch into sub-classifications, with geographers, geologists, lawyers, urban planners, and economists each applying distinct or overlapping frameworks. Considering natural versus capital-improved land, public versus private tenure, or ecological versus strictly economic perspectives adds yet another layer of complexity. In line with this diversity, this paper does not attempt to address every specific form of land usage or related issues; rather, it adopts a general perspective (often focusing on urban or capital-improved contexts) to specifically examine land exploitation, regardless of how it may vary across diverse typologies and scenarios, while still acknowledging that broader variations exist in practice.

Real estate, encompassing both land and buildings, has long served as a central pillar of wealth accumulation, socio-political power, and economic development across diverse societies [1–3,40,41]. Land, unlike constructed assets, retains defining attributes—permanence, inextensibility, and immobility—that distinguish it from buildings, which inevitably depreciate and demand ongoing maintenance [19,42]. These inherent characteristics highlight the land's singular capacity to shape political influence, social relations, and the trajectories of urban and economic expansion. Although conceptualizations of land's value have evolved with shifting historical and cultural contexts, its essential nature as a finite, non-reproducible resource, intertwined with environmental, infrastructural, economic, and cultural dimensions, has never lost significance [43–45].

Classical economists, like Ricardo [2], positioned agricultural productivity and natural fertility at the heart of land rent formation, emphasizing that its finite availability and differential qualities allowed landlords to capture unearned income. Initially linked to agrarian contexts, this reasoning now extends to urban environments, where land value and rent reflect taxation systems, infrastructural investments, legal frameworks, and access to services [19,21]. Unlike buildings, which can be constructed, upgraded, and ultimately replaced, the land endures. Its inelastic supply and location-specific advantages frequently lead to appreciation driven by communal efforts and shifting market conditions [46,47]. Recognizing these durable attributes underscores the importance of distinct legal, economic, and policy frameworks that honor the land's fundamental differences from man-made capital [18].

The land's importance transcends material dimensions. It can be examined through economic, legal, cultural, and ecological lenses, each offering insights into how the land's value and function are constructed and perceived [48]. Physically, land underpins human habitation, production, and infrastructure, encompassing essential elements like soil, water, air, and light [49]. Legally, property rights often extend vertically, including subsurface minerals and air rights, thus requiring continual updates to cadastral systems and regulatory frameworks [50]. Different jurisdictions vary in whether they treat buildings, vegetation, and minerals as integral to the land or as separate taxable and regulable entities, reflecting evolving definitions shaped by economic and environmental priorities [51].

From an economic perspective, land anchors production, commerce, housing, public services, and cultural activities. Initially valued for agriculture and raw materials, it now hosts urban centers, commercial hubs, industrial complexes, institutional campuses, and multifaceted infrastructures [19,41]. Public and private investments, ranging from roads and communication networks to cultural amenities and green spaces, continuously transform land into a dynamic asset, influencing housing markets, business development, agricultural productivity, and resource extraction. As urban economies grow more complex, classical agricultural models and simplistic urban assumptions no longer suffice to explain land's evolving definition, value, and function. Scholars recognize the need to address disequilibrium, spatial discontinuities, and nonlinear relationships between location and productivity [52,53]. Nevertheless, the core distinction between non-reproducible land and depreciable improvements remains crucial for understanding the origins and distribution of value [54].

This distinction matters because the land's scarcity, immobility, and cultural resonance make it a focal point of competition, speculation, and state intervention [55,56]. Regulatory instruments—zoning ordinances, urban planning regulations, heritage protections, taxation regimes, and construction codes—jointly shape the land's meaning and allocation, determining permissible uses, identifying beneficiaries, and integrating environmental considerations into development decisions [48]. Tenure arrangements, from freehold own-

ership to leaseholds and time-sharing schemes, express shifting social contracts and moral economies regarding access, utilization, and profit distribution.

Valuation highlights the interplay of physical attributes and locational advantages. Factors like size, shape, topography, soil fertility, and drainage influence baseline suitability [57,58]. Accessibility to transportation, utilities, educational institutions, healthcare, and leisure amenities refine the value, while noise, pollution, or poor aesthetics diminish it [59]. Over time, the determinants of land value have broadened—from simple agricultural productivity to a rich range of infrastructure, amenities, social capital, and cultural identity. Modern societies increasingly prize well-located parcels that align with shifting incomes, consumer preferences, and ecological priorities, underlining the land's central role as both a resource base and a stage for human activity and environmental protection [60].

A range of theoretical frameworks illuminates these complexities. Classical theories, rooted in productivity differentials [2], were refined by neoclassical approaches, emphasizing marginal utility and subjective preferences [61,62]. Geographic models—from von Thünen's [63] location rent paradigm to Alonso's [64] bid-rent theory—stressed the spatial distribution and transport costs. Meanwhile, urban sociology, institutional economics, and neo-Marxist perspectives examined class structures, public investments, and socio-political conflicts shaping land values [5,65,66]. Political economists and reformers, influenced by George [67], demonstrated how governance and redistributive policies—such as land value taxation—can better align private gain with collective benefit [18,68–70].

Together, these frameworks confirm that land value emerges from a composite of natural attributes, infrastructural inputs, cultural influences, and institutional choices. Spatial analysis using GIS, spatial econometrics, and hedonic modeling further refines the understanding by examining how values vary across economic centers, infrastructure corridors, environmental gradients, and socio-political environments [70–72]. Yet, integrating fine-grained, property-level insights with macro-scale models remains challenging, underscoring the need for nuanced approaches to valuation and policy.

Valuation practices reveal structural, temporal, and spatial intricacies. Market comparisons provide snapshots of present conditions, while long-term assessments must consider demographic shifts, technological advances, environmental pressures, and infrastructure upgrades [59,71]. Properties slated for infrastructure projects, such as highways or rail lines, create unique appraisal challenges as interventions reshape land uses and socio-economic geographies. In densely developed areas, the rarity of vacant land transactions complicates the isolation of the intrinsic land value. Appraisers employ residual income approaches, cost-based extractions, and allocation techniques to estimate the land component apart from improvements [72,73]. Although these methodologies are imperfect, they remain indispensable for discerning how much of a property's worth derives from land itself rather than from constructed capital.

Determining the land's highest and best use (HBU) involves assessing legal permissibility, physical feasibility, economic viability, and maximal productivity [74,75]. Optimal uses shift as market conditions, regulatory reforms, cultural preferences, and sustainability imperatives evolve. The land once suited for agriculture may now host residential or mixed-use developments, or eventually revert to more ecologically restorative functions as social and environmental values change. By connecting the theoretical principles to real-world constraints, HBU analysis shows that valuation is never purely technical, but also politically and ethically charged, reflecting a broader need for environmental resilience and social responsibility.

Managing land's multifaceted nature demands effective administrative systems. Secure tenure, transparent registration, and efficient markets depend on robust cadastral data, clear property rights, and reliable governance institutions [76–78]. Integrating cadastral

records with GIS enhances analytical precision and informs policymaking, but also raises questions about data governance, privacy, and equitable information access [79].

Notably, the breadth of land types extends beyond purely 'constructive' land. Agricultural fields, forests, wetlands, and ecologically protected areas face parallel challenges when their intrinsic value—often tied to ecosystems or community heritage—becomes subject to speculative interest and capital-driven allocation [14,16].

In summary, the land's scarcity and permanence contrast starkly with the volatility of built capital, while its multi-dimensional significance far exceeds mere economic metrics. Legal instruments define accessibility and profit-sharing, and administrative systems ensure traceability and credibility. Economically, land underpins production, commerce, and development; culturally and environmentally, it preserves identities, ecosystems, and community cohesion. Recognizing these dimensions explains why land lies at the center of persistent policy debates, ideological conflicts, and theoretical inquiries. Understanding land's definition, attributes, and valuation complexities establishes a foundation for exploring how inseparability or separability of land and improvements influenced historical exploitation, and how these insights can guide contemporary and future resource management in both physical and digital domains.

3. Separation Thesis

Building upon the conceptual foundations established in the previous section, the longstanding debate over whether land and its improvements—encompassing buildings, infrastructure, and other enhancements—can or should be distinctly recognized becomes crucial. This "separation thesis" extends well beyond theoretical abstraction, directly influencing our understanding of how the land's intrinsic value is formed, how wealth derived from it is distributed, and how governance structures might ensure fairness and sustainability. The core question is whether the unique value and rent generated by land can be meaningfully measured and disentangled from the structures placed upon it.

Historically, discussions pivoted on the notion of land as a natural, immutable resource, contrasted with improvements resulting from human labor and capital investment [2,9,49]. Proponents of separability ("separatists") argue that since land value often arises from natural attributes and communal contributions—such as location advantages, infrastructural accessibility, and ecological endowments—it should be acknowledged and distributed accordingly, rather than absorbed primarily by private interests [19,54]. In contrast, the opponents ("omeletists") maintain that the land and the improvements form an indivisible whole, both physically and economically [80,81]. This inseparability stance, by reinforcing complexity and obscuring the origins of the value, often benefits those exploiting current practices to secure unearned rents.

These opposing perspectives reflect not only the theoretical divergences but also the deeper socio-economic, political, and ethical dimensions. To the separatists, conflating the land and the improvements conceals the rent sources, rightfully belonging to communities and the environment [9,82]. Such concealment enables wealth concentration, as the land-derived value, shaped by nature and collective endeavor, flows into private hands without accountability. Omeletists, by insisting on inseparability, sidestep the pressing questions of equitable distribution and ecological responsibility. From their viewpoint, isolating the land value appears theoretically flawed and practically unfeasible, thereby preserving entrenched advantages and the status quo [41,72].

In practice, the urgency of addressing separability varies. Urban planners, spatial economists, and real estate analysts often apply models that treat "land" as a conceptual factor without attempting to isolate rents or confront deeper equity issues [32]. Spatial analyses frequently reduce land to a neutral substrate, focusing on optimization or devel-

opment potential while neglecting the empirical measurement and political dimensions of rent capture [65,66]. As a result, moral and socio-political concerns remain obscured beneath layers of theoretical complexity, allowing entrenched patterns to persist.

At the parcel level, however, the debate gains tangible significance. Property ownership, value attribution, and the role of land and community as value creators become more transparent [51]. Excessive practices flourish in conditions of ambiguity: by blurring the distinction between land and improvements, beneficiaries claim increments originating from natural and communal inputs without acknowledging rightful claimants. This paradox reveals a contradiction: analytical exercises or planning models may implicitly treat land as separable, yet the ethical and practical implications of doing so remain underexplored. Consequently, unearned increments derived from land continue flowing away from communities and ecosystems toward private entities, protected by theoretical and methodological vagueness [18,21].

To clarify these complexities, the following subsections examine the separation thesis through three complementary lenses: physical, value, and evaluation grounds. Together, these dimensions highlight how separability influences conceptual understanding, economic theory, policy-making, and real-world decision-making.

3.1. Physical Grounds

Physical grounds consider whether land and improvements can be inherently distinguished as tangible entities. Historically, before development altered the landscapes, land existed in its natural state—unimproved, finite, and easily identified. In modern urban environments, land often lies beneath layers of constructed infrastructure and buildings, complicating this once-clear boundary [48]. Omeletists argue that such physical intermingling renders separation impossible, while the separatists counter that despite their functional fusion, each component retains distinct attributes meriting conceptual and analytical differentiation.

Classical economics provide an initial template. Ricardo's [2] treatment of land, labor, and capital as separate production factors recognized the land's immobility and uniqueness. Yet as economies matured, this clarity diminished. Although land remains immobile, rents accrue to developers and landlords who effectively appropriate what could be deemed land's intrinsic reward. Neoclassical economics decomposed the property into measurable attributes, but seldom isolated the land's specific contribution from that of improvements [61,62]. Without explicit criteria, conceptual ambiguity persisted.

Urban development theories often treat land as a passive substrate. The "omelette" metaphor—popularized to illustrate American land economist Richard Theodore Ely (1854–1943) position and those of others who supported him, such as Dorau & Hinman [80] and Hendriks [81]—suggests that once land and capital are mixed, they cannot be "unscrambled". Critics view this analogy as a strategic evasion of ethical and economic accountability, as the issue of separation is not inherently tied to the physical nature of land. Physical inseparability need not imply value inseparability: advanced econometric and practical methods can, in principle, disentangle the distinct contributions of land and improvements even when physical boundaries appear blurred [83,84].

Recognizing the land's immutable traits strengthens the case for separability. Unlike buildings, which depreciate and can be replaced, the land remains fixed. Studies show that prevailing models often fail to reconcile the buildings' attributes with the land's spatial qualities [47,70]. Land usually appreciates due to communal investments, infrastructure enhancements, and locational advantages—features unrelated to private improvements. Distinguishing the permanent, naturally endowed element from the perishable, human-made one is essential to prevent conflation and its attendant injustices.

3.2. Value Grounds

Value grounds shift focus from physical characteristics to the economic essence of rent attribution. The central question is whether the land's economic value can and should be separated from that of improvements. Classical theory [2] envisioned rent arising from land's inherent productivity and scarcity, allowing for, at least theoretically, a clear line between rent and other forms of income. Yet, the classical frameworks offered limited practical methodologies [9,54].

Subsequent thinkers expanded rent to encompass infrastructure and cultural elements [49], further blurring distinctions between intrinsic land qualities and capital-based enhancements. Neoclassical approaches decomposed property values into components without consistently identifying which pertain to land and which to improvements [19,61,62]. Hedonic pricing models attempt to isolate marginal contributions, but their underlying assumptions and complexity often hinder definitive separations [85].

Composite rent concept intensifies the debate. Cameron [86] noted that land, labor, and capital all generate rents, diluting land's uniqueness. Omeletists leverage such complexities to frame inseparability as inevitable. Separatists assert that ignoring land's unique, immobile contribution perpetuates unjust outcomes. Land value commonly stems from communal infrastructure, public services, and natural advantages, so when socially created increments accrue solely to private owners, inequity deepens [32,82].

Empirical realities add another layer. In urban contexts, proximity to services and amenities raises both land and building values, complicating exclusive assignment of increments to land. Although classical theories acknowledge the land's uniqueness, they seldom supply detailed criteria for operationalizing it. This methodological gap allows private interests to flourish amid confusion, capturing the wealth produced by communities and ecosystems. Separatists contend that overlooking the land's distinct contribution legitimizes rent extraction that offers minimal return to its true creators.

Though omeletists remain skeptical, it is conceptually feasible to separate attributes like location-based advantages and public investment contributions. Because land typically appreciates as buildings depreciate, distinguishing permanent, naturally endowed qualities from replaceable, human-made structures is both logical and imperative. Such clarity underpins fair taxation, equitable urban planning, and prudent investment strategies, ensuring that collectively generated value does not disappear into private hands.

3.3. Evaluation Grounds

Evaluation grounds offer insights to address practical challenges in implementing the separation thesis. Even if the theory supports separability, how can it be realized in practice? Traditional appraisal methods—Cost Summation Approach (CSA), Income Capitalization Approach (ICA), and Sales Comparison Approach (SCA)—face inherent limitations. The CSA requires active land markets, often scarce in developed areas. The ICA attempts to isolate land by deducting the operating costs and building returns, while the SCA struggles with limited comparable vacant land sales in dense urban contexts [72,73].

Alternative techniques—extraction, allocation, and advanced hedonic modeling—offer potential solutions. Although these methods rely on assumptions and encounter estimation challenges, scientific approaches, such as triadic estimates [87], suggest pathways toward a more objective distribution of value. While no flawless method exists, these efforts indicate that perfect inseparability is not inevitable.

Public governance illustrates both the complexity and necessity of separation. Some North American municipalities, including those in Quebec, attempt separate land and building assessments for taxation [88]. In practice, however, aggregated values persist, hindering effective land market management, speculation control, or the encouragement of optimal

land use. Implementing differential taxation—heavier rates on land than on buildings—reinforces the importance of credible separations. Quebec's Pacte 2000 report [88] and advocates like George [9] stress that landowners, benefiting disproportionately from communal inputs, owe a social debt best recaptured through targeted taxes [89].

Beyond taxation, credible separation matters for insurance valuations, mortgage underwriting, inheritance settlements, and eminent domain proceedings [90,91]. Although no universal solution has emerged, ongoing research, enhanced data collection, and refined econometric techniques suggest that practical separability may be achievable. Greater analytical precision can reduce exploitation and ensure that the wealth derived from land's innate characteristics benefits the communities and ecosystems that create its value.

These evaluation challenges confirm that the separation thesis is not merely academic; it has profound policy implications. If governments and communities cannot confidently distinguish land value from improvements, they struggle to favor equitable wealth distribution, sustainable growth, and balanced development. Addressing these hurdles requires innovative policymaking, improved data governance, and transparent market operations.

By examining physical value and evaluation grounds, the separability thesis emerges as central to debates in land governance. At stake is the ability to identify and attribute land's distinct contributions, recognize its collective origins, and prevent unjust appropriation. While omeletists assert that land and improvements form an inseparable whole, separatists counter that this stance conceals entrenched inequalities and perpetuates exploitative practices. Understanding this tension is essential for redressing historical inequities and for anticipating how unresolved land governance issues may shape new forms of resource exploitation, including those in digital domains.

4. Transition to Digital Rent

Although land-centered exploitation and its legacy might seem specific to physical terrains, the same underlying mechanisms increasingly shift into digital venues. By examining how rent-seeking patterns extend beyond soil and urban spaces into intangible realms of user engagement, data, and communal knowledge, we can better understand—and potentially mitigate—the parallel risks of unearned income capture in "digital land". Accordingly, this section draws explicit connections between historic frameworks of land exploitation and modern platform-based resource appropriation, illustrating how rent extraction adapts when physical fields give way to servers and algorithms.

The prolonged failure to safeguard nature and communities from the enduring impacts of land exploitation created a legacy of deeply entrenched injustices. For more than a century, the absence of conceptual clarity and decisive policy intervention allowed powerful interests to capture and commodify land rent. This persistent neglect left communities and ecosystems vulnerable, their contributions appropriated by actors skilled in using regulatory ambiguities and reinforcing their privileges through political and intellectual influence. Even the separatists—those who insisted on distinguishing land value from improvements—could not reverse these trends, as vested interests adapted, refined strategies, and maintained dominance through strategic confusion.

Had land exploitation been effectively constrained, some relief might have followed. Instead, capital derived from land rent was not merely amassed; owing to its mobility, it could be redirected into new spheres of activity. As the natural world and local communities continued bearing the brunt of the often unchecked extraction, the most sought-after resource gradually evolved from tangible land to less visibly finite yet equally monopolizable domains: knowledge, information, and human attention. This shift introduced a new frontier of exploitation, where intangible elements of cognition and expectation are appropriated—much as fertile soil or mineral-rich deposits once were. Although the un-

derlying logic remains—capturing and commodifying essential but previously unmanaged resources—the target has moved from the earth's surface to the human mind.

Over centuries, land rents thrived under opaque frameworks and uneven power relations, enabling landlords to capture disproportionate gains. Such dynamic underscores how exploitation can shift as the underlying systems evolve. In transitioning from physical land to intangible, data-driven spheres, similar exploitative logics reemerge in "digital land" platforms, where human cognition, information, and communal knowledge replace soil or geographic space as the core sources of unearned increments. Just as the conceptual ambiguities in defining the land's intrinsic value historically empowered landlords to extract excessive rents, today's definitional and regulatory gaps in digital ownership rights equip platform owners to appropriate user data, attention, and communal inputs. In effect, the digital era parallels older conditions of insufficient oversight, fueling rent-like accumulation at the top while limiting the public's rightful share in newly created wealth.

Notably, the shift from tangible fields to servers does not merely substitute one resource for another; it represents a deeper recalibration of exploitative mechanisms. Traditional land exploitation leveraged unclear boundaries and minimal regulations to maximize private gains at public expense; likewise, digital platforms exploit algorithmic opacity and sparse governance in user-generated ecosystems. Where once capital derived from differential soil fertility or prime location, modern digital rent flourishes in network effects and user participation, subtly mirroring how spatial advantages once conferred economic privilege. While intangible, "digital land" nonetheless harbors finite elements—for instance, limited user attention or specialized data—and thus the same structural inequities arise: dominant owners collect disproportionate rents, communities lose out on returns they help create, and beneficial competition or innovation is stifled. Recognizing these parallels clarifies that digitized exploitation not only matches older patterns, but can also intensify them through technology's global reach and immense data asymmetries.

Understanding how digital rent emerges requires a renewed perspective on "digital land". Although physical land cannot be literally transposed into bits, the spatial logic that once governed fields and cities is mirrored in virtual domains. These platforms mimic physical attributes by allowing users to navigate, interact, and co-create value within digital "locations" regulated by algorithms, interfaces, and data policies. While they can seem boundless, digital spaces nonetheless remain constrained by factors such as cognitive attention and network congestion—just as land was limited by fertility or location. The familiarity of spatial metaphors facilitates commodification: behaviors, relationships, and expectations are measured, influenced, and monetized. Just as physical location once dictated who collected land rent, control over digital "terrain"—namely data infrastructures and platform governance—now determines who profits from collective engagement and informational resources.

Historically, land rent originated from natural advantages—fertility, strategic proximity, environmental abundance—and from public investments that enhanced these attributes. Over time, it detached from natural productivity and became aligned with speculation and legal artifices. In the digital sphere, value generation often lacks any direct link to natural qualities, emerging instead from platforms designed to shape user behavior, direct attention, and harvest data. Marx's [8] caution about rent drifting from its natural basis reverberates, as "value" today is increasingly manufactured from human cognition, social participation, and algorithmic operation.

Technological complexity further obscures the origins of digital value creation. In physical contexts, natural ecosystems and communal traditions anchored moral and legitimacy claims. In digital contexts, platform owners can disguise the roots of value creation behind intricate technical layers. Just as land speculation once allowed a select few to profit

from collective labor and ecological richness, digital rent enables powerful entities to exploit communal knowledge and user engagement. Cognitive resources—finite and vulnerable, like any ecosystem—are extracted as raw material for accumulation. The outcome repeats a familiar cycle: wealth and influence consolidate at the top, reinforcing dependency, limiting autonomy, and narrowing opportunities for genuine self-determination.

The repercussions are substantial. By monopolizing data ecosystems and shaping user interactions, new "Mindowners" [29] recreate historical asymmetries. The same structural imbalances that once characterized land exploitation resurface in digital form: communal benefit is displaced by private gain, natural and social contributions are concealed, and power is entrenched via control of a fundamental resource. Users, collectively producing immense value, receive scant returns, while platform owners leverage network effects, cultural influence, and regulatory gaps to consolidate their advantages.

Historical lessons from land exploitation underscore the perils of allowing such transformations to proceed unchecked. Just as unregulated physical land exploitation fueled environmental degradation, social upheavals, and broad wealth disparities, digital rent extraction threatens cognitive well-being, cultural diversity, and democratic institutions. Where communities once struggled to claim their share of land-derived value, they now face intangible challenges in defending cognitive resources and their intellectual commons. The historical record shows that ignoring moral and ecological considerations leads to harm not easily reversed.

The shift to digital rent does not sever ties with the past; it extends embedded patterns into a new medium. Fundamental resources are once again enclosed and monetized, and once again a gap emerges between creators of value and those its capturers. Although these resources are no longer anchored in soil, they remain subject to inequalities in access, knowledge, and power. Recognizing this continuity is crucial: the logic of exploitation flows from fields and forests into servers and search queries, demonstrating that extractive practices adapt to emerging vulnerabilities.

Highlighting these parallels reveals that the transition to digital rent is neither accidental nor anomalous, but rather the logical outcome of historical trajectories. The unresolved questions of land exploitation—who owns value, how it should be distributed, how to ensure stewardship—remain no less pressing in digital contexts. Ambiguities around defining land's distinctiveness and limiting unearned rent have a modern counterpart online, where intangible resources remain poorly understood and under-regulated.

Addressing digital exploitation also involves revisiting formal–legal structures. Just as zoning laws and land-use regulations determine who benefits from prime physical locations, data ownership frameworks and platform governance policies now shape the distribution of digital rents. Policymakers might consider data dividends, cooperative models, or mandatory transparency protocols to ensure that "communal inputs"—user data, engagement, and creativity—are not absorbed solely by platform owners. By highlighting how legal systems initially devised for physical land use (e.g., zoning, taxation, or betterment levies) parallel current needs in digital resource governance, this perspective underscores the urgency of developing robust, equitable structures for intangible domains.

This perspective prepares us for the next section, which explores institutional frameworks, policy instruments, and conceptual innovations necessary to address both old and new forms of exploitation. By understanding how historical patterns inform current digital dynamics, we can better anticipate the need for equitable, transparent, and sustainable governance strategies, that guard against replicating past injustices in intangible realms.

5. Institutionalization

For decades, policymakers, economists, and urban planners have sought institutional solutions to capture and redistribute land rent in ways that align private incentives with public benefits. Historically, attempts to distinguish land from its improvements in taxation and regulatory frameworks aimed to ensure that unearned increments—arising from the land's inherent qualities rather than labor or capital—serve the broader community. By doing so, these efforts sought to correct a fundamental imbalance: if land's unique attributes and communal inputs create additional value, then the resulting rent belongs to the society whose collective endeavors and natural endowments shaped these advantages.

Efforts to implement differential taxation, where higher tax rates are imposed on land rather than on buildings, have attracted sustained interest for their potential to reshape urban development patterns and mitigate inequalities. Conventional property taxation often conflates land and improvements, yielding counterproductive outcomes [92,93]. Such uniformity can discourage building maintenance and new construction [94], while failing to address the speculative withholding of land that inflates property values, displaces vulnerable populations, and distorts urban economies [95]. In contrast, a tax system placing heavier burdens on land than on improvements can promote building activity, guide land toward more sustainable uses, and support urban vitality [32,96].

Empirical evidence supports these theoretical claims. Pittsburgh's 1979 decision to double its land tax rate while leaving the building tax unchanged led to a substantial rise in construction activity, with building permits increasing by 70% in the 1980s, whereas comparable cities experienced declines [97]. In Sydney, an exclusive land tax system produced building activity rates notably higher than in Melbourne, which continued taxing buildings more heavily [98]. Although factors like latent demand [99] also influence outcomes, these examples illustrate that distinguishing land from improvements can direct the development and discourage speculative landholding.

The theoretical efficiency of taxing land rests on its immobility and fixed supply. According to Tideman [82], this levy imposes no deadweight loss on the economy, as landowners cannot shift the tax burden. Land value taxation thus encourages productive land use while reducing resource misallocation. Many cities worldwide, including regions in Scandinavia, New Zealand, Australia, and the United States, have experimented with differential land taxation. While results vary and concerns persist about implementation, administration, and political feasibility [99,100], these initiatives underscore global interest in refining taxation policies to improve equity and efficiency.

Beyond generating revenue, land taxation can function as a deliberate planning tool. By influencing the relative costs of holding land, tax policies can guide investment toward denser, more sustainable urban forms, conserving resources and limiting sprawl. The efficacy of these measures depends on governance capacities, administrative structures, and institutional contexts [101,102]. Although separating land and building values remains challenging and politically sensitive [98], the notion that taxing land more heavily than improvements can stimulate rational urban growth and fulfill public objectives remains compelling.

Institutional solutions extend beyond taxation. Throughout history, land rent extraction—as analyzed by economists from Ricardo [2] to George [9], and observed by Cord and Andelson [12]—allowed elites to accrue wealth without proportional productive contributions. Such rent extraction thrived on monopolizing scarce resources, legitimized through cultural narratives, legal frameworks, and political influence. George [9] called for land value taxation to restore fairness; Ostrom [15] emphasized that community-driven governance can mitigate mismanagement and unchecked exploitation. Nonetheless, landowners often shaped laws and policies to protect their interests, and Ely's [103,104]

inseparability thesis helped to obscure land's distinct value, facilitating continued rent extraction. These entrenched patterns reflect how deeply wealth and power influence institutional outcomes.

Addressing these inequities demands reassessing cultural and legal norms that have long enshrined private land ownership. Harvey [105] and Shiva [14] underscored how the narratives framing landowners as natural stewards masked their privileged access to communal wealth. Legal systems historically codified property rights in ways that privileged the few, reinforcing the need for renewed scrutiny of property institutions and moral claims [2]. Rethinking these frameworks is integral to ensuring that collective contributions to land value are acknowledged and shared.

Speculation, scarcity, and socio-economic divides magnify the urgency of reform. Unchecked speculative markets inflate property values, exclude vulnerable populations, and distort urban growth [4,12]. Environmental degradation follows, as exploitative practices erode soil fertility, water supplies, and urban ecosystems [14,16]. Indigenous communities face disproportionate dislocation and loss of cultural continuity. These patterns highlight the need for institutional measures that restore balance, protect communal well-being, and incorporate environmental considerations into land governance.

In response, policymakers and scholars increasingly advocate for sustainability and equity in land governance. Sustainable development frameworks [35] and international approaches to non-renewable resource management [106] guide new strategies that limit overuse and capture unearned increments for public services. Alterman [107], Stiglitz [108], and Mattauch et al. [109] argue that reclaiming and redirecting land rent toward infrastructure, environmental protection, and social investments can redress historical injustices and address current urban pressures. Piketty [21] and Munoz Gielen and Van der Krabben [110] propose integrating private wealth accumulation with public infrastructure spending to advance more inclusive urban landscapes.

Land's immobility, scarcity, and cultural resonance demand governance that respects ethical, communal, and environmental values [23,24]. Mattei's [111] concept of the commons characterizes land as both economic and non-economic, meeting diverse societal needs. When public investments enhance land's worth, moral considerations arise: should private owners claim all the gains, or do communities deserve their share [112]? Institutional Resource Regimes (IRR) blend insights from political science, economics, and institutional theory to distinguish sustainable from unsustainable practices [113,114]. IRR frameworks clarify property rights and responsibilities, encouraging cooperation and aligning private incentives with sustainability goals. Overcoming fragmented regulations and coordination gaps [115] requires coherent legal structures, robust enforcement, and long-term commitments to ecological and social well-being.

In practice, numerous mechanisms—such as differential taxation, public land leasing, development rights trading, and betterment levies—can help capture and redistribute land-based wealth. Impact fees, joint development ventures, and targeted state acquisitions can finance infrastructure and services, as documented by Barnett and Morse [68], Lindholm and Lynn [116], and Higgins [117]. Garza and Lizieri [118] and Kresse et al. [119] emphasize recognizing the moral and legal foundations of requiring landowners to return part of their unearned gains, guiding more equitable planning and market regulation.

Moreover, multi-functional land use research highlights the importance of ecological resource management and sustainable urban expansion [35]. By integrating agricultural practices, conservation corridors, and recreational spaces within broader governance frameworks, these approaches mitigate soil degradation, protect biodiversity, and allow more balanced urban–rural interactions [14,16]. Such strategies also complement the value-capture mechanisms discussed above, enabling policymakers to move beyond traditional zoning

or property taxation models. As Raworth's Doughnut Economics framework posits [34], land governance reforms should simultaneously respect environmental thresholds and social imperatives, thereby promoting a more inclusive and resilient development. Over time, adopting these multi-dimensional approaches may bridge theoretical debates on land governance with practical solutions, ultimately extending their relevance even to intangible domains such as digital rent.

Building on these multi-functional land use strategies, interest in Land Value Capture (LVC) intensifies as governments confront fiscal constraints, inequality, and environmental pressures [120]. By focusing on the land rather than buildings, split-rate taxes and related instruments address housing affordability, promote inclusive urban planning, and reduce distortions [109]. Such policies encourage compact, resource-efficient city forms that protect agricultural lands and support ecosystems [121,122]. Recognizing that public investments and natural advantages generate land value underscores the fairness argument: if collective inputs create additional value, society should recoup a portion to sustain the infrastructure and services that uphold it [123].

Urban planners must consider not only the exchange value but also the use values communities rely upon [124]. While developers capture potential gains, communities bear externalities like congestion, pollution, and housing cost inflation. Institutional reforms can correct these imbalances. Adjusting zoning laws, refining planning guidelines, and implementing transparent governance can ensure that land uses align with socially beneficial and environmentally sustainable priorities. Over time, pricing mechanisms, regulatory instruments, and rigorous oversight can mitigate negative externalities, ensuring that land's communal benefits endure.

Developers often transfer costs onto communities, extracting private wealth while limiting public returns [125]. Without adequate checks, they exploit loopholes—minimal renovations, underdevelopment, rapid resale—evading taxes, inflating private gains, and depriving communities of essential revenues. This divergence between market and societal value results in economic inefficiencies and environmental harm. Public authorities can intervene through tailored policies, recovering diverted wealth for social housing, infrastructure, and environmental protection [126,127]. By doing so, communities can redirect rents into public goods and reduce wealth disparities.

Sustainable land governance thus requires varied reforms. It must address historical injustices, embed ethical considerations into property law, and utilize economic tools that realign private interests with public welfare. By integrating classical theories [2,9] with modern sustainability frameworks, IRR approaches, and international best practices, we can treat land as a shared, socially constructed resource rather than as merely private property. Such recognition supports just development, ecological resilience, and long-term social stability.

In this context, interventions once considered radical—like land value taxation or state participation in recapturing land-based wealth—acquire renewed legitimacy as responses to well-documented historical injustices and environmental strains. Grounding the reforms in established economic theories, empirical evidence, and shared ethical principles can garner broader support. Although challenges persist, global experimentation and scholarly discourse suggest that more equitable, sustainable land governance is attainable.

These lessons from the land domain also influence approaches to digital ecosystems. Just as sustainability policies arose to curb the depletion of natural resources, analogous frameworks emerge for responsible digital resource management. In digital environments, the need to safeguard users, ensure fair compensation, protect privacy, and maintain transparent governance mirrors the moral reasoning behind land value capture. By extending principles of accountability, equity, and communal benefit into intangible, knowledge-based

economies, policymakers can prevent online platforms from replicating the entrenched patterns of resource exploitation.

When effectively institutionalized, land value capture and related strategies can transform rent extraction from a driver of private enrichment into a source of public good. These insights guide parallel efforts in digital governance, reducing speculation, mitigating environmental harm, and restoring fairness to the distribution of collectively generated value. Viewed through a historical lens, ongoing developments reflect enduring questions over who should benefit from communal wealth. Applying intellectual traditions from economics, political science, environmental studies, and law across both physical and digital domains offers a path toward balanced, enduring, and human-centered resource management.

6. Discussion and Conclusions

This study traced the historical and theoretical evolution of land-based exploitation, demonstrating how rent extraction from finite, non-renewable land resources fueled inequalities and shaped governance structures. By treating land as both foundational and indivisible, a privileged minority leveraged conceptual ambiguities and institutional inertia, ensuring that rents captured from these resources remained concentrated. Although various frameworks and analytical tools were proposed over time to clarify land's distinctive attributes, entrenched interests resisted reforms. As a consequence, conceptual confusion—particularly the inability to separate land value from human-made improvements—sustained unequal patterns that marginalized ecological systems and the communities that enhanced land's worth.

The contention that land and its improvements can be analytically separated—physically and economically—long remained obscured by layers of political, financial, and institutional complexity, as well as academic debate. Favorable capital access for those positioned to exploit land-based surpluses reinforced traditional urban planning models, valuation practices, taxation systems, and legal constructs aligned with landowner interests. Although many thinkers, from Ricardo to George, maintained that unearned increments belong to nature and society, these insights rarely led to transformative policies. Over time, even as buildings depreciated and infrastructure aged, the land values steadily rose, buoyed by communal investments and natural endowments. Meanwhile, communities bore increasing fiscal burdens and lost their rightful share of accruing rents, and environmental conditions deteriorated as development proceeded without proportional ecological compensation. Thus, the debate over the separability of land and improvements transcends technical appraisal, reaching into core questions of fairness, justice, and sustainable stewardship.

Today, these historic logics migrate into the digital realm. Instead of centering on physical land, rent-seeking strategies now infiltrate intangible domains—data, attention, and collective cognition. Where once rent was extracted from soil, location, and natural fertility, it now derives from user participation, personal data, and intellectual contributions. Contemporary "Mindowners" refine historical methods, exploiting definitional gaps, outdated taxation models, minimal oversight, and opaque valuation techniques to appropriate digital resources. As with physical land, communities and ecosystems were historically denied fair returns on their contributions; now, users and the public are similarly deprived of equitable benefits generated from cognitive inputs.

Acknowledging these continuities presents an opportunity. History shows that complexity in distinguishing land value from improvements persisted not because it was impossible, but because vested interests opposed clarity. Recognizing that separability is both conceptually and practically feasible, and applying analogous principles to digital

contexts, can help identify and redistribute rents captured by today's information economy. Just as earlier reformers championed land value taxation, betterment levies, and public leasing, current policymakers might consider data dividends, platform cooperatives, and regulatory standards ensuring that digital platforms serve the public good rather than exclusive private gains.

Intelligent systems, fueled by collective intelligence, cultural nuances, and sensitive private information, evolve over time and geography, ultimately becoming proprietary assets of those who own the underlying architectures. This ownership enables wealth and power concentration, rendering digital settings increasingly opaque and abstract. Compared to earlier exploitation of non-renewable, communal resources, the stakes are now higher: extracting value from human cognitive systems jeopardizes public debate, democratization efforts, and collective awareness. In these virtual domains, human expectations and intellect meld into proprietary systems controlled by a few, potentially at great cost to humanity and the planet.

Past struggles against land exploitation offer valuable lessons. Without public engagement, conceptual clarity, and political resolve, exploitative practices endure and adapt. In the digital sphere, the stakes are even greater. While misallocated land rents once undermined economic security and ecological stability, unchecked cognitive rent extraction now imperils human agency, creativity, and intellectual flourishing. Just as it once seemed natural for land-based exploitation to accompany industrialization, today's presumption that digital exploitation is inevitable can be contested. The century-long discourse on land's distinctiveness, rent formation, and the moral imperatives of redistribution can guide efforts to contain cognitive exploitation in digital spaces.

Although this discussion often focuses on urban land or "constructive" sites, the same fundamental principles apply to agricultural regions, forests, and ecologically sensitive areas, where community and ecosystem inputs similarly shape land value and are at risk of under-compensation. Future research could further examine how specific land typologies—and their unique socio-environmental conditions—intersect with the frameworks discussed here, offering comparative insights into how institutional mechanisms and governance strategies may vary across different usage scenarios.

By combining these well-established land exploitation debates with the emerging concept of "digital rent," this paper makes a unique scholarly contribution. It provides a theoretical lens that reveals how unresolved land-valuation issues—such as ambiguous property rights, unearned increments, and inequitable rent capture—are replicated in today's data-centric platforms. This approach not only clarifies the parallels between material and intangible resource domains but also emphasizes the adaptability of proven institutional solutions—like land value capture and communal governance—to modern digital ecosystems. In doing so, we offer policymakers and researchers a more integrated framework for understanding and addressing rent-seeking across both physical and virtual frontiers.

Meeting these challenges requires a renewed conceptual clarity, interdisciplinary collaboration, and decisive institutional reforms. Land, once viewed as an inseparable blend of natural substrate and human labor, can be disentangled to reveal nature- and community-created value. Similarly, digital platforms—often perceived as inscrutable, algorithm-driven systems—can be dissected to expose user data, communal knowledge, and collective participation as fundamental value sources. Accurate value attribution and accountable governance can restore agency to contributors, mirroring the unfinished project of ensuring fair returns on land's unearned increments.

Recognizing that unjust patterns simply migrate into new mediums—from physical land to digital "land"—serves both as a warning and a guide. The historical struggle to

clarify the land's unique status and redistribute its rents illustrates that conceptual precision and principled intervention are potent strategies. By adapting these lessons to the digital age, we can anticipate and prevent another era of unchecked appropriation in intangible domains. The same impetus that once inspired efforts to combat land-related inequalities can now drive initiatives to create more equitable digital ecosystems.

Ultimately, this analysis suggests that resource exploitation is not static but adaptive, shifting to whichever substrates—physical or intangible—promise unexamined opportunities for value extraction. The contest that began over nature and community now extends into cognitive and informational realms. Understanding this continuity, acknowledging the adaptability of exploiters, and reimagining governance frameworks are vital steps toward a future in which knowledge empowers society rather than undermines it. By applying lessons from historical land debates to modern digital challenges, we move closer to realizing what earlier generations envisioned: a more equitable distribution of value produced by communities and nature, ensuring that genuine progress benefits all rather than an elite few.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The author declares no conflict of interest.

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Article

Assessing the Effects of Climate Change and Anthropogenic Contributions in Parishan Wetland, Iran

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Abstract: Wetlands provide essential benefits, including flood control, water quality enhancement, shoreline erosion prevention, natural resource conservation, recreational opportunities, and esthetic value. However, climate change and human activities have recently posed significant threats to these ecosystems. To address this issue, we employed an integrated approach combining remote sensing and the cloud-free Google Earth Engine (GEE) to monitor the impacts of climate change and human activities on Parishan Wetland in Iran. In this study, various climatic and anthropogenic factors, including air temperature (AT), precipitation, built-up area, croplands, and groundwater storage, were analyzed over the period from 2001 to 2010 to explore their potential effects on wetland conditions. The Pearson correlation test was used to assess the relationships between these variables and wetland health. Also, non-parametric Mann–Kendall (MK) and Pettitt tests were employed to identify monotonic trends and shifts in the time series. The findings suggest a complex interplay of climatic and anthropogenic factors impacting the wetland's ecosystem. Groundwater availability emerged as the most influential factor, with a very strong positive correlation of 0.92, highlighting the critical role of groundwater in sustaining wetland ecosystems. Air temperature values in recent years have shown a significant increasing trend, while precipitation exhibits a statistically significant decreasing trend. These factors, along with the slightly increasing built-up area, which negatively impacts the natural ecosystem, indicate an urgent need to restore the wetland.

Keywords: wetland; climate change; anthropogenic effects; Google Earth Engine (GEE); Parishan

1. Introduction

Wetlands contribute to approximately 40% of the total value of ecosystem services, which are the benefits provided by natural systems that enhance social welfare, including food supply, biodiversity preservation, and flood control [1,2]. Wetlands serve as transitional areas between terrestrial and aquatic ecosystems, where the water table is typically at or near the surface or the land is covered by shallow water [3]. These ecosystems play an

essential role in supporting the environment, providing critical habitats for many unique species of plants and animals [4,5].

Wetlands offer numerous benefits, such as water purification, natural hazard protection, soil and water conservation, and recreational opportunities [6,7]. However, in recent decades, both human activities and climate change have impacted ecosystems, particularly in semi-arid and arid regions. Human-induced factors such as urban expansion and intensified agriculture have led to a 35% global loss of natural wetlands since the 1970s, while artificial wetlands have increased by 233% [8,9]. As urban areas expand, impervious surfaces such as roads, buildings, and parking lots multiply, preventing rainwater infiltration, which is essential for recharging local aquifers and sustaining wetlands [10]. Moreover, agricultural practices in these dry regions rely heavily on irrigation, often drawing water from local sources such as rivers, aquifers, and wetlands. Given the naturally low rainfall, the additional demand for irrigation further exacerbates water scarcity [11]. Climate change poses additional threats, including declining freshwater availability and rising sea levels [12]. The warming trend associated with climate change has raised concerns about global ecosystems, particularly wetlands, which are highly sensitive to changes in temperature and precipitation patterns [13]. These changes affect rainfall distribution and evaporation rates, leading to fluctuations in wetland water levels. Many wetland species are adapted to specific environmental conditions, and variations in temperature and water availability threaten their survival, resulting in population shifts, altered migration patterns, and, in some cases, local extinctions [14,15]. Consequently, monitoring wetlands to assess the effects of human activities and climate change is essential to obtain accurate, consistent, and up-to-date data on key attributes such as changes in size, type, and condition.

Remote sensing techniques have proven invaluable in wetland identification and monitoring, offering satellite-based data to track changes in wetland extent, vegetation cover, and water quality [16,17]. These techniques are essential for effective wetland management and conservation, as they reduce the need for extensive fieldwork, provide broad spatial coverage, and are both cost effective and time efficient [18]. Recent advancements in remote sensing have significantly improved the spatial, spectral, and temporal resolution of satellite imagery, providing a golden opportunity for the spatiotemporal monitoring of wetlands [19,20]. However, less attention has been given to using remote sensing to monitor the combined effects of anthropogenic and climatic factors on wetlands. Multispectral satellite imagery, especially from the Landsat series, is widely used for wetland mapping due to its extensive coverage, moderate resolution, long historical record, and free accessibility, making it a primary resource for tracking wetland dynamics [21,22]. With advancements in big data, cloud computing, and artificial intelligence, the ability to extract meaningful wetland-related information from remote sensing data has significantly evolved, necessitating the development of efficient processing tools for handling large datasets [23]. Google Earth Engine (GEE), a cloud-based geospatial data processing platform developed by Google in 2010, leverages Google's server capacity to enable large-scale, long-term geospatial analysis [24,25]. GEE provides access to vast amounts of global remote sensing data, including Landsat, MODIS, Sentinel, and GF-1 imagery, along with thematic datasets covering climate, temperature, ecology, and socioeconomic factors [26]. Additionally, GEE offers free access to anthropogenic data, such as urban development, land use/cover, and surface water consumption, making it a powerful tool for comprehensive, long-term monitoring of human impacts on wetlands [27].

A brief review of the literature shows that numerous studies have evaluated the effects of climate change on wetlands [28–33]. However, despite an increasing number of studies on the combined impacts of climate change and anthropogenic factors on wetlands, existing research often considers a limited range of indicators, such as temperature and land cover

changes [34–36]. In contrast, the present study intends to provide a more comprehensive analysis by examining various climatic and anthropogenic factors, including air temperature (AT), precipitation, built-up areas, croplands, and groundwater storage. This study focused on the Parishan Wetland in Iran and investigated environmental challenges from 2001 to 2010, a period chosen due to the near-complete drying of the wetland in 2010. Furthermore, this study aimed to employ the cloud-based capabilities of GEE to monitor the impacts of climate change and human activities on wetlands, offering a data-driven approach to sustainable wetland management.

2. Location of Study Area

The Parishan Wetland, a permanent freshwater lake fed by springs and seasonal streams, is located in Fars Province, approximately 12 km southeast of Kazeroun (Figure 1). The wetland's average depth fluctuates between 2 and 2.5 m, depending on annual rainfall variations. Situated at an elevation of 820 m above sea level, Parishan Wetland experiences warm, dry summers and mild winters [37]. It plays a crucial role as a habitat for a diverse range of wintering waterfowl, as well as breeding waterfowl populations, especially during wetter years. Located in an enclosed drainage basin within a broad valley, the wetland's water ranges from brackish to saline, with salinity levels varying according to the wetland's size [38].

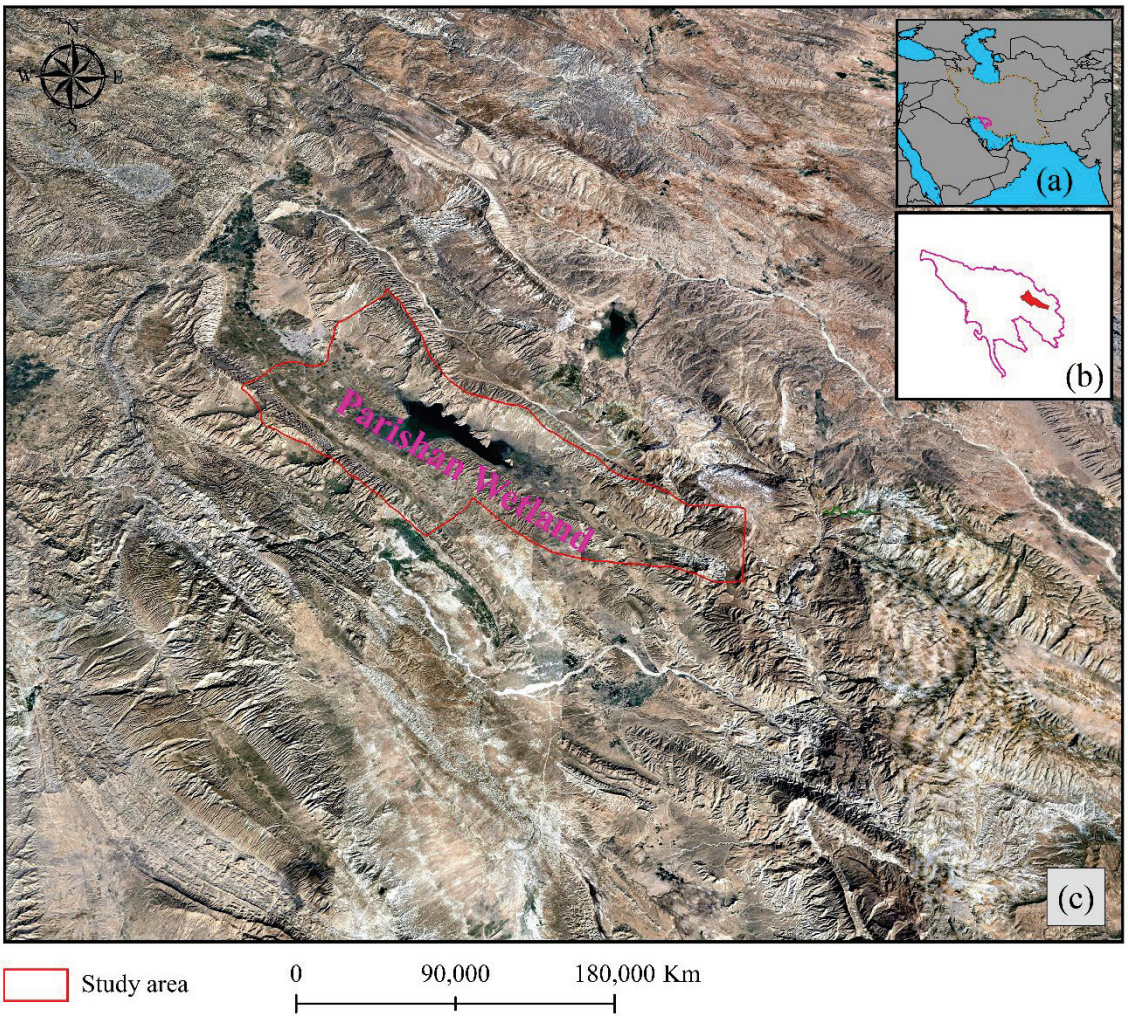


Figure 1. Location of study: (**a**) in the southwest of Iran, (**b**) basins, and (**c**) Parishan Wetland represented on the satellite image for the year 2002, when water was available.

From a climatic perspective, Parishan Wetland lies within the warm zone of Fars Province, specifically in the Persian precipitation zone. This zone extends from the central region near the Persian Gulf to southern Kerman and Fars and receives approximately 60% of its precipitation during winter, making it the region with the highest winter rainfall concentration in Iran [39]. In recent years, declining annual rainfall has caused the wetland's water levels to drop significantly, bringing it close to drying up. Seasonal temperature fluctuations range from approximately 4 °C in winter to around 32 °C in summer. In addition to climatic challenges, anthropogenic activities have significantly impacted the wetland over the past few decades, exacerbating its environmental challenges [40].

3. Materials and Methodology

3.1. Materials

The present study investigated the relationship between wetland and various climatic and anthropogenic factors over the period from 2001 to 2010. The analyzed variables included AT, precipitation, built-up areas, croplands, and groundwater storage. Table 1 provides detailed information on these selected variables, while Figure 2 illustrates the range of climatic and anthropogenic factors used to assess the impacts of climate change and human activities on wetlands during this period.

Table 1. Further details on the various climatic and anthropogenic variables employed, including their full names, products, and spatial resolutions, to assess their effects on Parishan Wetland.

Name	Product	Spatial Resolution (m)	Reference
Air temperature	ERA5-Land	11,132	[41]
Precipitation	Global Precipitation Measurement (GPM)	11,132	[42]
Built-up areas	Global Human Settlement Layer (GHSL)	100	[43]
Cropland	MCD12Q1	500	https://doi.org/10.5067/MODIS/MCD12Q1.061 (accessed on 1 November 2024)
Groundwater storage	NASA Global Land Data Assimilation System	27,830	[44]

3.2. Methodology

- To assess the impacts of climate change and human activities on wetlands, various climatic and anthropogenic variables were analyzed within GEE. GEE supports two geographic data structures: raster-based Images and vector-based Features. This flexibility enhances the interpretation of environmental phenomena [45]. For this study, *Images* were chosen to represent our datasets due to their suitability for handling large-scale environmental data and performing extensive analyses. *Features* in GEE, in contrast, consist of geometric elements such as points, lines, or polygons, each accompanied by a property dictionary that provides detailed spatial attributes. This dual structure in GEE provides flexibility in manipulating geographic data, making it easier to analyze environmental changes [46]. We began by delineating both the study area and the study period. Using QGIS Desktop version 3.30.3, we outlined Parishan Wetland as the area of interest. The study period was set from 2001 to 2010, covering a decade of data that reflect both climate variability and human influences. Next, we extracted key variables from GEE that are critical for understanding the impacts of climate and human activities on wetlands. These included AT, precipita-

tion, built-up areas, cropland extent, and groundwater storage. Each variable was sourced from specialized satellite products and environmental datasets, ensuring a comprehensive analysis of the relationships between climate factors, human activity, and wetland health. All variables were exported in GeoTIFF and CSV formats to enable detailed analysis. The implemented code facilitated the execution operations, including (a) spatial subset on the interested area, (b) temporal subset on the collection datasets, (c) selecting the targeted datasets, and (d) exporting the selected datasets to perform further analysis. Figure 3 shows an overview of the applied methodology.

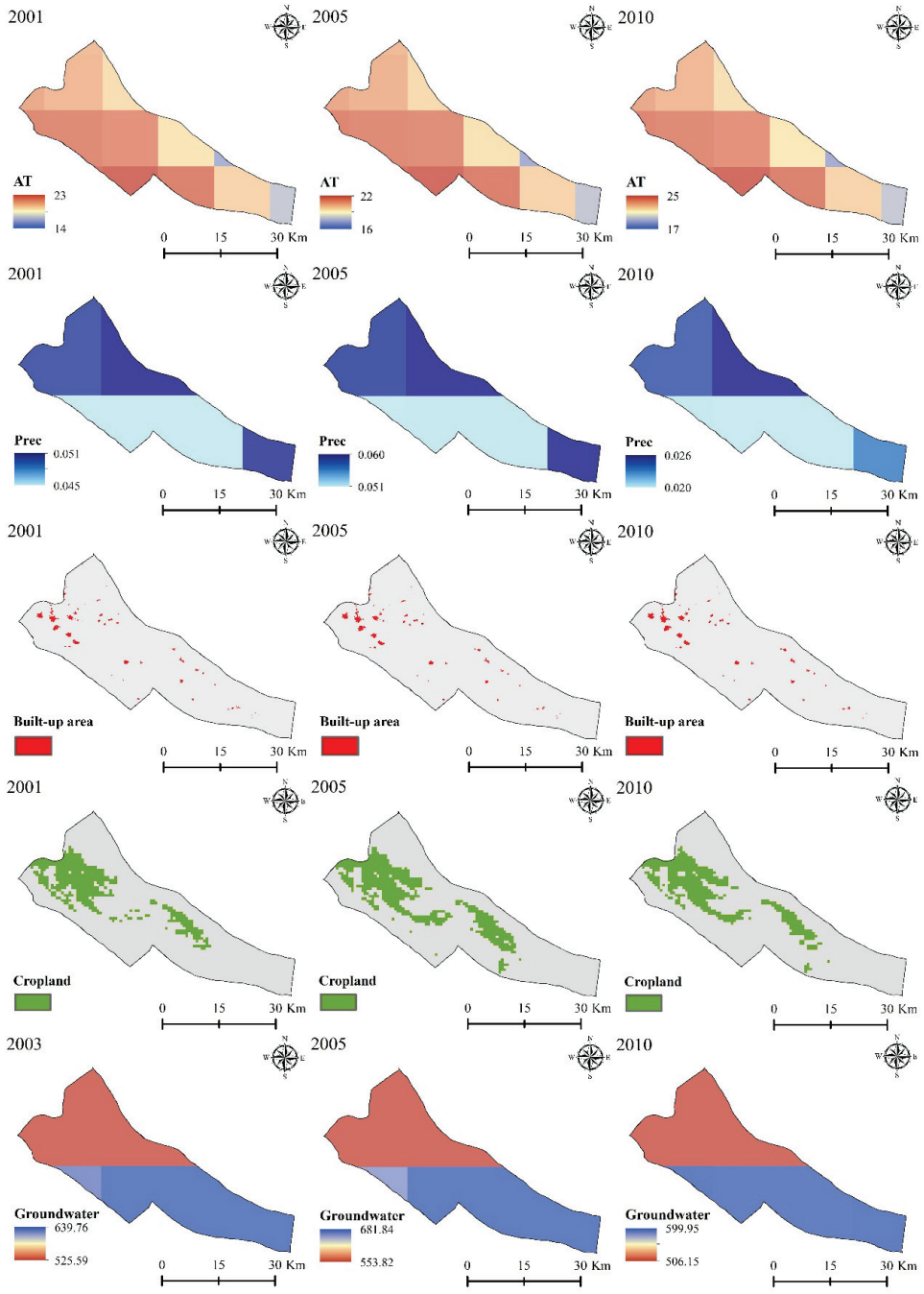


Figure 2. Examples of the climatic and anthropogenic variables employed for the years 2001, 2005, and 2010, along with their respective ranges in different units, were used to assess their effects on Parishan Wetland.

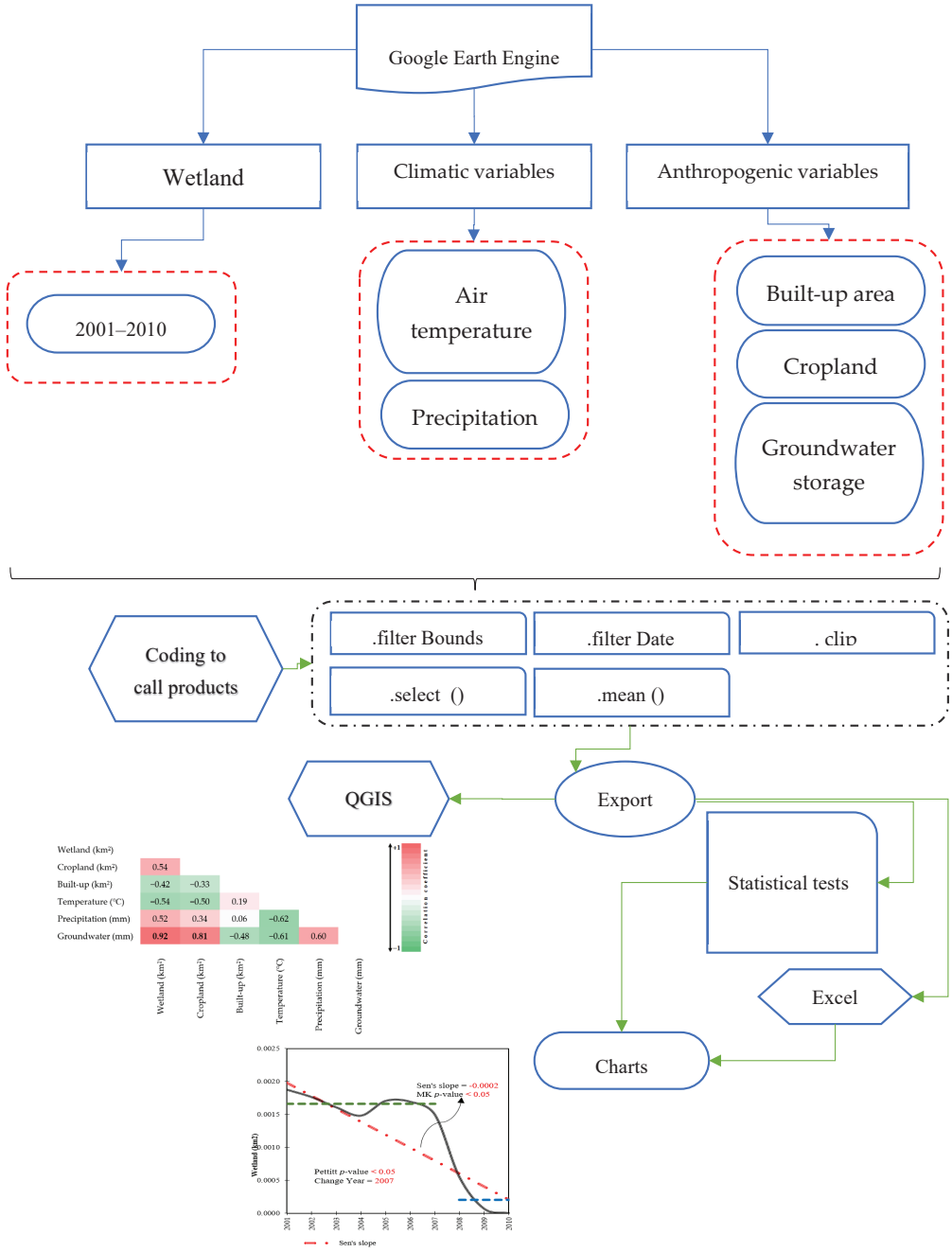


Figure 3. An overview of the applied methodology for detecting the effects of climate change and anthropogenic activities on wetlands.

Statistical Analysis

To assess the relationships between climate, anthropogenic variables, and wetlands, we applied the Pearson correlation coefficient. Furthermore, the Mann–Kendall (MK) test was used to detect significant long-term trends. The effect of autocorrelation was addressed using the modified MK test proposed by Hamed and Rao [46]. The magnitude of the trend was quantified using Sen's slope estimator [47]. The Pettitt test [48] was employed to identify abrupt shifts in the time series. These tests have been extensively applied in numerous studies investigating the impacts of climate change on Earth's natural systems and processes [49–51]. All these statistical methods are comprehensively described in Sadeqi et al. [52].

4. Results

An integrated approach combining remote sensing and GEE is employed to monitor the impacts of climate change and anthropogenic activities on wetlands in southwest Iran. The results demonstrate significant correlations between climatic factors, namely AT and precipitation, and wetland conditions, as shown in Figure 4. This study found that AT negatively correlated with wetland area (−0.54) from 2001 to 2010. This suggests that as AT increased, the wetland area decreased. These findings align with [53], which also reported the harmful effect of rising AT on wetland health in Iran. Furthermore, a positive correlation coefficient of 0.52 was found between precipitation and Parishan Wetland conditions, indicating that decreased rainfall negatively impacted wetland preservation. This result is consistent with the findings of [54], which documented a similar relationship between precipitation and wetland sustainability. In terms of anthropogenic variables, a negative correlation of −0.42 was identified between the expansion of built-up areas and wetland health, highlighting the detrimental impact of urbanization on wetlands. Groundwater availability was identified as the most influential factor, with a very high positive correlation coefficient of 0.92 with wetland conditions, indicating that groundwater plays a crucial role in maintaining wetland ecosystems in the Parishan Wetland ecosystem. Previous studies showed the adverse effects of groundwater decline in water resources in Iran [55,56].



Figure 4. Correlations between various climatic and anthropogenic variables and Parishan Wetland. Bold values indicate statistically significant correlations (p-value < 0.05).

From 2001 to 2010, Parishan Wetland underwent significant changes due to both climatic and human-induced factors, as illustrated in Figures 4 and 5. These influences led to a reduction in the wetland area by 2.041 km^2, with a noticeable decline beginning in 2007, signaling a dramatic shift in the region's environmental health. Prior to this critical year, the wetland's average area was approximately 2.043 km^2, which gradually shrank over time, eventually decreasing drastically to just 0.002 km^2 by the end of the decade, highlighting a severe loss in wetland habitat. Regarding average AT, the study found an increase of 1.38 °C over the same period, with the highest temperature recorded in 2009. Before this peak year, the average AT was around 20.47 °C, which subsequently rose to 21.85 °C, reflecting a clear upward shift in regional temperatures. Conversely, precipitation data from 2001 to 2010 showed a statistically significant negative trend. Additionally, no

significant changes were observed for the built-up areas and croplands within the study region. In stark contrast, groundwater storage exhibited a statistically significant decrease of 47.54 mm ($p < 0.05$), indicating a worrying decline in the region's water resources. The average groundwater storage level dropped from 637.60 mm to 590.06 mm during this period, contributing further stress to the wetland ecosystem. Groundwater in Iran is frequently used for agricultural and domestic purposes, highlighting the significant anthropogenic impacts on natural resources. This comprehensive analysis highlights the diverse and interconnected impacts of both climatic and anthropogenic factors on the Parishan Wetland, underscoring the urgent need for integrated management strategies to ensure its sustainability and mitigate the adverse effects of ongoing environmental changes.

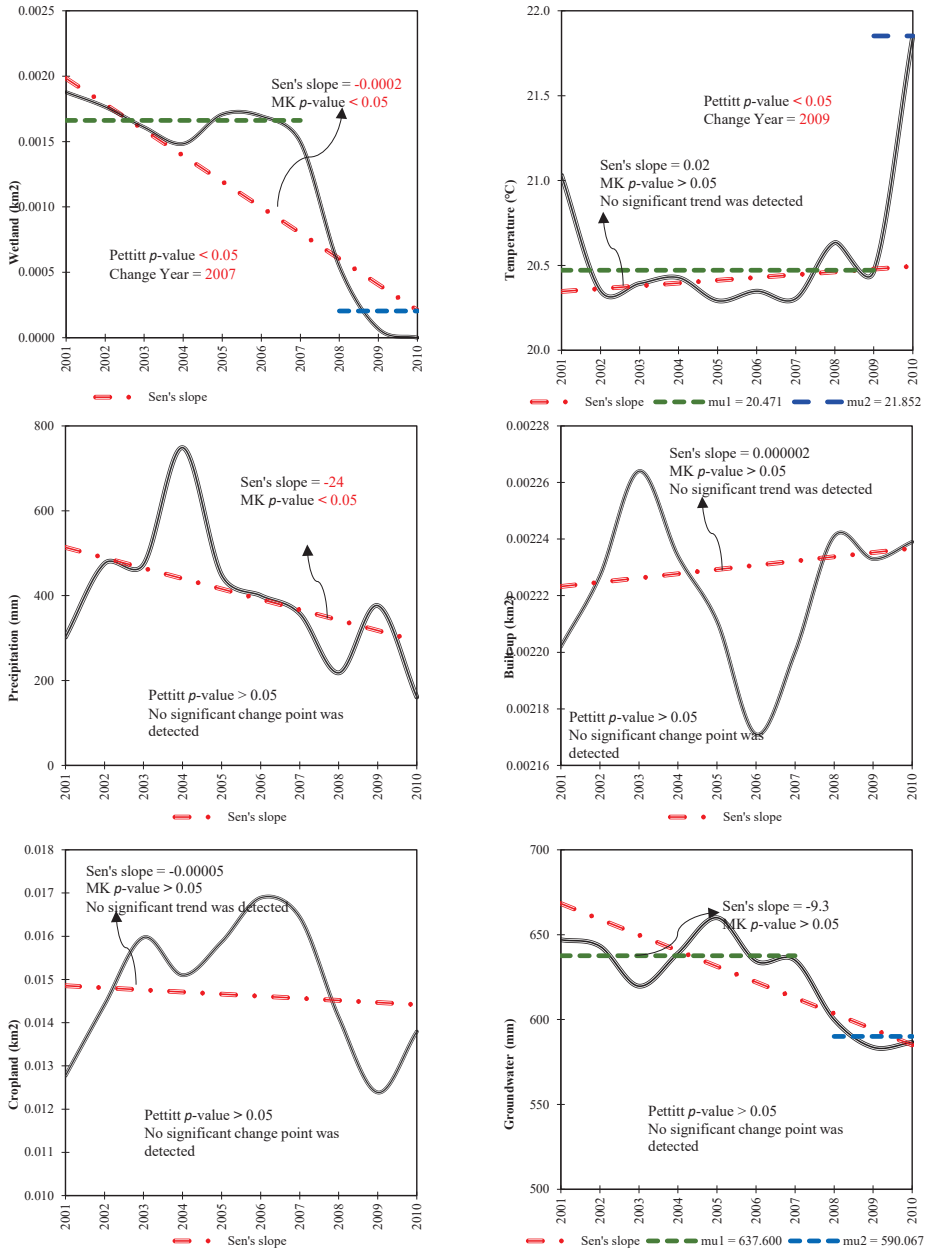


Figure 5. Time series monotonic analysis depicting the annual variations and trends in climatic and anthropogenic variables throughout the Parishan Wetland from 2001–2010. Mu denotes the average of the pre- and post-breakpoint sub-series.

5. Discussion

Wetlands are recognized for the valuable benefits they provide to society, such as enhancing food supply, preserving biodiversity, and offering flood control. Understanding the changes in wetlands and their impacts, driven by climate change and human activities, is, therefore, of great importance. Previous research [30–36] has typically focused on a limited number of climatic and anthropogenic variables when assessing the effects of climate change and human activities on wetlands. Chen et al., [34] analyzed the spatiotemporal changes in land use and land cover (LULCC), focusing particularly on the conversion of marshland to other LULCC types (e.g., croplands) in northeast China from 1980 to 2015. The relative impacts of human activities and climatic changes on wetland and agricultural dynamics were quantitatively distinguished and evaluated across different periods using a seven-stage LULC dataset. Their findings indicated that human activities such as population expansion, socioeconomic development, and institutional policies related to wetlands and agriculture were the primary driving forces of LULCC over the past decades. However, this study also identified an increasing contribution of climatic changes. Yan et al., [36] also examined the impact of climatic and anthropogenic pressures on the net primary production (NPP) of wetlands on the Zoige Plateau from 1990 to 2015. They assessed and quantified the effects of various climatic and anthropogenic factors such as NDVI, precipitation, temperature, and solar radiation on NPP using a simulated process model (LPJ_WHyMe) and a remote sensing model (CASA). Their simulations indicated that the annual average potential net primary production (NPPp) fluctuated throughout the study period, peaking in 2008 at 347.37 g C m^{-2} $year^{-1}$, while the total wetland NPPp peaked in 2000 at 1.75 Tg C $year^{-1}$. The results also revealed that the annual average actual net primary production (NPPa) reached its lowest value of 206.04 g C m^{-2} $year^{-1}$ in 2000. The total wetland NPPa ranged from 0.97 to 1.15 Tg C $year^{-1}$ and exhibited a continuous decline over the study period. Their research demonstrated that human activities contributed to 22.37–36.45% of the reduction in wetland NPP. These findings suggest that minimizing human interventions can enhance the NPP of wetlands. In contrast, the present study focuses on analyzing various climatic and anthropogenic indicators, including AT, precipitation, built-up areas, croplands, and groundwater storage, to provide a comprehensive approach to examining the effects of climate change and human activity on the Parishan Wetland and its associated environmental issues from 2001 to 2010. Additionally, we applied an integrated approach combining remote sensing and GEE to monitor the effects of climatic and anthropogenic variables on wetlands. This approach provides a faster and more efficient method for analyzing the trends and impacts of these variables on wetlands compared with previous research. Besides the applied methodology, developing a framework that identifies key climatic and anthropogenic indicators such as temperature, precipitation, land use changes, and groundwater storage can enhance the efficiency of this approach, making it more applicable to various wetlands worldwide. The results demonstrate that both climatic and human-induced factors significantly influence wetlands, with groundwater storage emerging as a key variable impacting changes in the Parishan Wetland. Additionally, our research highlights the effectiveness of integrating remote sensing with GEE for long-term monitoring of climate change and wetland patterns. The use of GEE enables access to a wide array of free datasets and provides a user-friendly, cloud-based environment, making it an ideal platform for conducting extensive, long-term studies across various scales.

The analysis of various climatic variables highlights their impact on the Parishan Wetland, revealing notable trends in precipitation over the years. Findings show a significant upward shift in temperature values in recent years. Higher temperatures cause more water to evaporate from the wetland's surface. In the case of Parishan Wetland, which is already

experiencing water stress, increased evaporation could significantly lower water levels, worsening the drying process. This also disrupts the regional hydrological cycle. As a result, the amount of water entering the wetland is further limited, leading to prolonged dry periods. Higher temperatures not only accelerate evaporation but also reduce the volume of water in wetlands, which may increase the concentration of salts and other minerals in the remaining water. This salinization can make the wetland inhospitable for many species of plants and animals, leading to a loss of biodiversity. Wetlands like Parishan rely on both groundwater and surface water for replenishment. As temperatures rise, groundwater levels may also decline due to increased evaporation and higher water consumption, causing the wetland to dry out more quickly. As temperatures continue to increase, the types of vegetation and animals that can survive in the wetland will change. Species adapted to cooler, wetter conditions may no longer survive, reducing the diversity of the wetland's ecosystem and negatively affecting both local wildlife and regional environmental health [57].

The analysis of various anthropogenic factors has revealed significant effects on the Parishan Wetland. Among these factors, changes in cropland and groundwater storage appear to be particularly influential. A closer look at the built-up area shows a steady increase over time. In 2001, the built-up area comprised 9.00% of the study region. This proportion rose gradually, reaching 10.80% by 2010. The expansion of urban areas is a critical factor contributing to the degradation of the wetland, as urbanization typically leads to the reduction in natural habitats and changes in water drainage patterns. The expansion of built-up areas around the Parishan Wetland in Iran has significantly contributed to its drying through various direct and indirect impacts. Urbanization and infrastructure development in the surrounding region have disrupted natural hydrological and ecological dynamics, accelerating the wetland's degradation. This expansion reduces water inflows, disrupts hydrological processes, introduces pollution, and increases water demand, all of which exacerbate the drying of the wetland. Implementing sustainable urban planning, effective water management, and robust wetland conservation policies is crucial to mitigating these effects and preserving the wetland's ecological integrity [58]. Similarly, the cropland area within the study zone also experienced significant fluctuations during the period from 2001 to 2010. In 2001, cropland covered 8.64% of the area, and this figure increased over the following years, reaching 11.13% by 2007. This growth can be attributed to the intensification of agricultural practices and the expansion of irrigated lands, which often results in a higher demand for water and contributes to the alteration of local hydrological cycles. However, by 2008, the area under cropland began to decline, dropping to 9.33% by 2010. This decrease may reflect shifting agricultural priorities, land-use policies, or environmental factors such as water scarcity, which may have affected agricultural productivity. The most significant anthropogenic factor impacting the Parishan Wetland, however, is the variation in groundwater storage. Groundwater is a critical resource for the region, particularly in arid and semi-arid areas like the study zone, where it plays a key role in maintaining both agricultural and ecological balance. The study revealed a noticeable decline in groundwater storage from 2001 to 2010. In 2001, the mean annual groundwater storage was 638.55 mm. This value initially increased, reaching 659.97 mm by 2005, possibly due to enhanced recharge from precipitation or changes in water management practices. However, from 2006 onwards, groundwater storage began to decrease sharply, dropping to 586.55 mm by 2010. This significant reduction in groundwater levels could be linked to factors such as over-extraction for agricultural irrigation, reduced precipitation, or ineffective groundwater management practices, all of which exacerbate the stress on the wetland ecosystem. The overall trends observed suggest that the combined pressures of urbanization, agricultural expansion, and declining groundwater storage are

contributing to the degradation of the Parishan Wetland. These factors not only alter the local landscape but also disrupt the delicate ecological balance, further threatening the sustainability of the wetland. A decrease in groundwater storage has a profound impact on the drying of Parishan Wetland in Iran. Wetlands like Parishan depend heavily on groundwater to maintain their hydrological balance, particularly in arid and semi-arid regions where surface water is scarce. Groundwater contributions are especially critical during dry seasons or periods of low rainfall. When groundwater storage declines, these inflows are directly reduced, causing water levels in the wetland to drop. Additionally, the regional water table lowers as groundwater storage diminishes, making it more difficult for water to naturally seep into the wetland. This disruption to the wetland's hydrological balance accelerates the desiccation process [59]. In conclusion, the Parishan Wetland is facing multiple anthropogenic challenges. The continued expansion of built-up areas and cropland, coupled with the decline in groundwater storage, underscores the urgent need for integrated land-use and water management policies to mitigate these negative impacts. Effective conservation strategies are essential to ensure the long-term preservation of the wetland ecosystem, which provides important ecological services such as biodiversity support, water filtration, and climate regulation.

The Parishan Wetland, spanning nearly 4300 hectares at an elevation of 820 m above sea level, is internationally recognized as a Ramsar Convention wetland (https://www.ramsar.org, accessed on 3 November 2024) and designated as a protected area. However, in recent years, it has nearly dried up due to inadequate rainfall and the proliferation of authorized and unauthorized wells drilled for agricultural purposes. Despite its historical resilience and self-regeneration in the absence of human interference, the wetland now faces significant challenges. Although seasonal rains during winter and spring temporarily replenish it, excessive groundwater extraction, deep-well digging, year-round agricultural activities, and high evaporation rates hinder its long-term revival. The dry bed of the Parishan Wetland has been plagued by numerous issues, including land subsidence, soil erosion, encroachment on national lands, unauthorized grazing, illegal wells, and water diversion beyond its boundaries. Rising air temperatures in this arid desert region and declining annual rainfall have exacerbated these problems. Additionally, road construction near the wetland has caused irreparable harm to its ecosystem, further contributing to its desiccation. Another major factor in the wetland's decline is the operation of a combined-cycle power plant located nearby. While plant officials claim their water sources come from distant wells, the heat generated by the facility significantly increases evaporation in the wetland. Furthermore, unauthorized wells drilled around the wetland to support surrounding agriculture have intensified the crisis. These combined pressures have devastated the Parishan Wetland, threatening its ecosystem and highlighting the urgent need for comprehensive conservation efforts [60]. Therefore, recovering the Parishan Wetland in Iran requires an integrated approach that encompasses water resource management and land-use planning. To enhance water inflows, it is essential to identify and secure natural water sources, such as springs and rivers. Groundwater extraction should be regulated by implementing monitoring systems and restricting well drilling. In terms of land-use planning, establishing protected areas around the wetland is crucial to prevent urban encroachment and limit industrial development in its vicinity. Additionally, promoting the use of drip irrigation and other water-saving techniques can serve as an effective strategy for restoring the wetland ecosystem.

Despite the efficiency of the applied methodology for analyzing the effects of climatic and anthropogenic factors on wetlands, there are two limitations. First, the spatial resolution of some applied products (e.g., groundwater storage) may not be as helpful as other products with medium spatial resolution for understanding trends in small-scale wetland

dynamics across various variables. Although accuracy assessments have generally been conducted for each product, it would be better to evaluate the accuracy of the applied data specifically for different regions worldwide before processing using ground control points. Several factors, including spatial and temporal resolution, data collection methodology, classification algorithms, and sensor limitations and calibration, affect data in GEE. Some limitations, such as sensor constraints, cannot be resolved by users. However, others, like classification algorithms, can be improved or at least mitigated by users. In general, using ground control points is the most effective way to check and validate the accuracy of GEE products. Future research is recommended to incorporate high-spatial-resolution data for monitoring small-scale wetlands. Additionally, to gain a deeper understanding of the effects of climate change and anthropogenic factors on wetlands, it is crucial to consider a broader range of ecological and hydrological features. This approach would enhance the efficiency of the results and provide a more comprehensive understanding of how integrated factors impact wetland ecosystems.

6. Conclusions

We monitored the Parishan Wetland from 2001 to 2010 to explore the effects of climatic and anthropogenic variables using an integrated approach of remote sensing and GEE. Our findings highlight that both climatic and anthropogenic factors have a significant effect on the wetland. Groundwater availability was identified as the most significant factor, showing a strong positive correlation of 0.92 with wetland conditions. This highlights the critical role of groundwater in sustaining the Parishan Wetland ecosystem. The results of this study demonstrate the effectiveness of the cloud-free GEE platform in monitoring wetland trends and assessing the impacts of climate change and human activities. Additionally, our findings highlight the efficiency of this integrated approach for large-scale and long-term wetland monitoring. This methodology offers valuable insights for researchers studying the impacts of climate change on Earth's features, particularly wetlands. The findings of this research can contribute to developing effective management strategies to mitigate the impacts of climate change and anthropogenic activities on wetlands, particularly in semi-arid and arid regions.

Author Contributions: Conceptualization, writing—original draft, and methodology: M.K.G.; methodology, investigation, writing—review and editing, and supervision: K.V.K. and B.F.; formal analysis, data curation, and writing—original draft: O.G.A. and M.S.; methodology and validation: A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be made available on request from the corresponding author.

Acknowledgments: We thank the anonymous reviewers for their comments and suggestions, which contributed to improving this work.

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

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The Road to 2030: Evaluating Europe's Progress on Sustainable Ecosystem Protection and Restoration

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Abstract: The 2030 Agenda for Sustainable Development emphasizes the interconnectedness of its economic, social, and environmental dimensions, recognizing their essential role in promoting human well-being. This study provides an in-depth analysis of EU Member States' progress towards Sustainable Development Goal (SDG) 15—Life on Land—as outlined in the 2030 Agenda. Using official data from Eurostat, this study applies the AAA (Holt–Winters) exponential smoothing algorithm to analyze trends in key indicators from 2011 to 2021 and project these trends to 2030. The results reveal notable progress in the first years since the adoption of the 2030 Agenda but also highlights drought and soil erosion as escalating risks, particularly in Mediterranean regions and areas of intensive agriculture (Spain, Cyprus, Greece). Water quality emerges as a critical concern, and, alongside the ongoing rise in soil sealing, presents an added threat to ecological stability, agricultural productivity, and overall well-being.

Keywords: sustainable development; 2030 agenda; SDG 15; life on land; terrestrial ecosystems

1. Introduction

The sustainable development of society, the economy, and the environment is one of the most pressing and complex challenges of our time, focused on securing essential resources without compromising the needs of future generations. Sustainable development is a holistic concept, pursuing a balanced and sustainable approach that integrates three essential dimensions: economic growth, environmental protection, and social well-being. It involves meeting present needs while preserving the ability of future generations to meet theirs, thus promoting a resilient and equitable society. This concept is a central goal of the 2030 Agenda for Sustainable Development, a global initiative adopted by United Nations (UN) member states in 2015 [1].

In addition to promoting the sustainability of human actions and the economy, protecting the environment and terrestrial ecosystems through sustainable practices is a key objective for contemporary society. In all regions and nations, governments, organizations and various entities have a responsibility to implement solutions that protect life on Earth and promote long-term well-being.

Achieving sustainability, especially from the perspective of terrestrial ecosystems, means maintaining a balance with nature in all human activities. This goal is increasingly important as we face growing challenges such as climate change, pollution, soil degradation, desertification, deforestation, resource overexploitation, urban sprawl, and habitat frag-

mentation. These negative phenomena collectively threaten biodiversity, environmental health, and the fundamental capacity of ecosystems to sustain life.

In this context, restoring and promoting the sustainable use of terrestrial ecosystems is undoubtedly the central pillar of the whole society, an aspect supported, as stated above, by the 2030 Agenda, the 17 specific Sustainable Development Goals, especially SDG 15 ("Earth Life") through the sustainability of all economic, social, physical, and ecological aspects of the Earth so as to mitigate climate change but also pollution. It is undoubtedly recognized that restoring the health of degraded land is essential for human development, as land is a vital life support system that directly or indirectly influences the achievement of the Sustainable Development Goals and beyond. These considerations are all the more important given that more than 33% of the global land surface is degraded, which is increasingly affecting the livelihoods of billions of people across the planet [2].

Reviewing the available literature, it is noticeable that there is a knowledge gap in terms of forecasting the potential evolution of the specific SDG 15 indicators until 2030, even though 8 years have already passed since the adoption of the 2030 Agenda with the definition of its specific targets. Therefore, we aimed to fill this knowledge gap through the results presented in this research in a synthetic way, bringing together all the key indicators tracked in the EU member countries. In order to understand the current status of SDG 15's target achievements, as well as the challenges related to the achievement of these targets, we individually analyzed the representative literature published to date.

This research study aims to critically assess the progress made by EU Member States in achieving the goals of SDG 15—Life on land—as committed to in the 2030 Agenda. Our analysis is based on an in-depth examination of relevant data published by the Statistical Service of the European Union (Eurostat) on the key indicators established to monitor the pursuit of SDG 15 by the 28 EU Member States.

The increased interest in the protection of ecosystems is justified, considering that it was necessary to urge all governments and specific bodies to develop strategies and measures to stabilize climate disruptions, to reduce carbon emissions, greenhouse gases, and all aspects that cause degradation of the environment, ecosystems, and quality of life [3,4].

We can recognize a large number of projects, actions, policies, and strategies in this regard, such as the actions undertaken by the United Nations (e.g., the restoration of more than 68 million hectares of degraded land and coastlines). However, identifying priority areas, developing appropriate technologies, adopting best practices and policies, and assessing the environmental, climate, and social benefits and costs are still significant global and regional challenges that require investments but also different measures depending on the level of local and regional degradation of terrestrial ecosystems [3,5].

In the same spirit of common global policies and efforts, we also identify the post-2020 Kunming-Montreal Global Biodiversity Framework (GBF) which was developed as a consequence of the Convention on Biological Diversity (CBD) on the conservation of biodiversity and ecosystem services for the next three decades. It set ambitious targets for ecosystem restoration, particularly in light of SDG 15, which aims to restore ecosystems. The Kunming-Montreal Global Biodiversity Framework (GBF) was adopted during the fifteenth meeting of the Conference of the Parties (COP 15) with key targets for both 2030 and 2050 [6].

Equally important are strategies such as reforestation, revegetation, revegetation, invasive species removal, wetland rewetting, direct seeding, and soil remediation, applied in different regions of the world. However, there are notable differences globally, particularly in the timing of the implementation of these measures, depending on the degree of degradation of each area. The correct identification of priority areas for ecosystem restoration is also essential, as this provides a solid basis for the use of innovative technologies, particularly focused on combating soil erosion and desertification. In addition, ecosystem stability and resilience are key factors used to assess the effectiveness and success of these restoration efforts [3].

Not to be neglected is also the fact that ecosystem restoration actions and targets focus on positive outcomes for biodiversity, even if there is still considerable disagreement and confusion about the different types of terrestrial ecosystem restoration actions. It is therefore essential to distinguish different types of restoration, monitoring, and reporting. This action will be essential for effective ecological restoration, as current commitments are insufficient to meet the GBF (Kunming-Montreal Global Biodiversity Framework) targets to increase the area and integrity of the natural ecosystem [4,7].

Based on these considerations related to the necessity of protecting the terrestrial ecosystem, this paper aims to identify how Europe, namely, the Member States of the European Union, is prepared to achieve the objectives of the 2030 Agenda for Sustainable Development on protecting, restoring, and promoting the sustainable use of terrestrial ecosystems.

Therefore, this paper will identify in the first part the current state of knowledge from the perspective of SDG 15 ("Life on land") that tracks the evolution of terrestrial ecosystems and the evolution of specific indicators. The second part of this paper will focus on a critical assessment of the progress made by EU Member States in achieving SDG 15 targets, in line with the commitments made through the adoption of the 2030 Agenda.

This research is grounded in the analysis of relevant data published by the Statistical Office of the European Union (Eurostat) on the key indicators established for monitoring the achievement of SDG 15 by the 27 EU Member States [8]. The time series was deliberately chosen to cover an extended period, at least five years before the implementation of the Paris Agreement in 2015. This longer time span is designed to allow a detailed analysis of the selected indicators, taking into account significant events that could have had a considerable impact on their evolution.

Furthermore, this paper focuses in particular on the successful experiences of European Union Member States, which have demonstrated exceptional performance in protecting terrestrial ecosystems, and, from this perspective, a successful model can be created for lagging countries and beyond. Issues such as current policies and strategies, climate change impacts, ecosystem restoration initiatives, innovative technologies for ecosystem management, etc., are just some of the benchmarks for analyzing the current State-of-the-Art methods in protecting terrestrial ecosystems.

2. Materials and Methods

The forecasting model used in this study was based on data reported by the EU countries on the evolution of the nine specific indicators of SDG 15, covering the full period from 2011 to 2021. In the case of indicators for which data were reported at a 3-year interval, the interpolation method was used to calculate the missing values from the selected reference years. The time series was deliberately selected to cover an extended period, including five years prior to the implementation of the Paris Agreement in 2015. This wider time scope was intended to allow a comprehensive examination of the selected indicators, incorporating significant events that could have had substantial implications for their evolution.

The existing literature shows a clear separation between two main categories of forecasting models, which were grouped into traditional and contemporary models. Traditional models (ETS, ARMA, ARIMA, SARIMA) have been fundamental in time series forecasting. Contemporary models (LSTM, FBProphet, DNN), on the other hand, have emerged with technological advances, with the intention of surpassing the predictive capabilities of traditional models, but each of them has distinct drawbacks that limit their effectiveness in certain contexts [9–13].

Reviewing the advantages and disadvantages of models appropriate to the context of this research, we opted for a traditional approach, specifically the AAA (Holt–Winters) exponential smoothing algorithm. ETS algorithms, including Holt–Winters, are widely recognized for their adaptability and simplicity, making them indispensable tools in time series forecasting. This adaptability is particularly advantageous in situations where data

exhibit varying levels of seasonality or where the seasonal pattern undergoes dynamic changes over time. The flexibility of ETS models arises from their three core components: error, trend, and seasonality. These components enable ETS to effectively capture and model complex patterns within data, offering a nuanced representation of intricate temporal structures [9,11,14,15].

The robustness of traditional time series forecasting models, such as ETS, is rooted in their well-established statistical foundations and proven reliability across a variety of applications. These models are built on sound mathematical principles that have been rigorously studied and tested over decades, ensuring their capacity to deliver consistent and accurate forecasts across a wide range of conditions. A critical aspect of their robustness lies in their interpretability; the selected model provides clear insights into how different components—such as trend, seasonality, and noise—contribute to the overall behavior of the time series.

Moreover, traditional models' reliance on prior values and straightforward parameter estimation processes allows them to perform reliably even with relatively small datasets or limited computational resources. This property makes them a practical choice in many real-world scenarios where data may be noisy, incomplete, or challenging to model using more complex methods [16,17]. In general, the robustness of traditional models is derived from their simplicity, interpretability, and strong theoretical foundations, all of which contribute to their enduring relevance in time series forecasting.

In the AAA (Holt–Winters) iteration of the ETS exponential smoothing algorithm, weights are systematically assigned to time-varying variables based on a geometric progression sequence of the form $\{1, (1-\alpha), (1-\alpha)^2, (1-\alpha)^3, \ldots, \infty\}$ [18–20]. This exponential weighting mechanism ensures that more recent observations have a greater influence on the forecast, while older data points contribute less significantly. The forecast value generated by this method extends the historical data forward to the target date, adhering strictly to the time sequence and structure as dictated by the core equations of the Holt–Winters multiplicative approach. This approach not only models the seasonality as a proportion of the level but also adjusts dynamically for both trends and seasonal variations, thereby enhancing the precision of the forecasts.

The use of multiplicative components in this iteration allows the model to accommodate variations in seasonality that change in proportion to the level of the series, making it particularly effective for datasets where the amplitude of seasonal fluctuations evolves over time. Consequently, the Holt–Winters method within the ETS framework improves both the accuracy and reliability of forecasts, particularly in contexts where capturing complex seasonal patterns is crucial [16]. This methodological rigor and adaptability underscore the efficacy of the AAA iteration in producing robust forecasts across diverse time series applications:

$$\text{level}: \quad L_t = \alpha \frac{Y_t}{S_{t-m}} + (1-\alpha)(L_{t-1} + B_{t-1}) \tag{1}$$

$$\text{trend}: \quad B_t = \beta(L_t - L_{t-1}) + (1-\beta)B_{t-1} \tag{2}$$

$$\text{seasonal}: \quad S_t = \gamma \frac{Y_t}{L_{t-1} + B_{t-1}} + (1-\gamma)S_{t-m} \tag{3}$$

$$\text{forecast}: \quad F_{t+m} = (L_t + B_t m) + S_{t-s+m} \tag{4}$$

where

L_t = level;
B_t = trend;
S_t = seasonal component;
F_{t+m} = forecast for m periods ahead;
α, β, γ = smoothing parameters;
s = length of seasonality;
m = frequency of the seasonality.

3. Empirical Results

Based on the research methodology described previously, this section presents the findings related to each of the nine key indicators for SDG 15. The results of the forecasting models are summarized in separate tables. Each table includes the reported values of the indicators for the years 2011, 2015, and 2021 in the first three columns, to facilitate the tracking of relevant data at key periods. The subsequent columns present projected estimates for 2025 and 2030, as well as the rate of change in 2025 and 2030 compared to the reference year 2015. The final column illustrates the estimated trend for the analyzed indicator, facilitating the visualization of the projected trend up to 2030, based on the data available to date.

The first SDG 15 key indicator included in this research provides essential data on the extent and health of forest ecosystems and wooded areas, which are vital for biodiversity, climate regulation, and ecosystem services (Table 1). Forests and wooded lands play a significant role in sequestering carbon dioxide, thus mitigating climate change, while also supporting diverse flora and fauna, preserving water cycles, and providing resources and livelihoods for many communities. Tracking this indicator enables policymakers to assess progress towards maintaining and enhancing forest cover, address deforestation and land degradation, and implement effective conservation strategies, thereby contributing to the broader goals of environmental sustainability, climate action, and the preservation of natural resources. As can be seen from the data summarized in Table 1, the expected trend up to 2030 for almost all EU countries is positive, i.e., an increase in the area occupied by forests and other wooded land is expected.

Table 1. SDG 15–10—Share of forest and other wooded land (% of total land area).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	40.2	41.9	43.5	44.7	46.4	1.07	1.11	UP
Belgium	22.2	23.1	25.1	26.3	27.8	1.14	1.20	UP
Bulgaria	n.a.	44.7	50.8	54.6	60.1	1.22	1.34	UP
Czech Republic	37.3	37.7	38.2	38.6	39.0	1.02	1.04	UP
Denmark	13.5	15.6	17.3	18.7	20.6	1.20	1.32	UP
Germany	31.0	32.2	33.1	33.7	34.7	1.05	1.08	UP
Estonia	56.9	58.2	59.3	60.3	61.6	1.04	1.06	UP
Ireland	19.9	22.4	21.0	21.3	22.1	0.95	0.99	UP
Greece	39.7	44.5	50.5	54.8	60.5	1.23	1.36	UP
Spain	35.6	39.2	43.9	47.2	51.6	1.20	1.32	UP
France	30.4	31.0	33.4	34.7	36.3	1.12	1.17	UP
Croatia	n.a.	50.6	65.4	75.3	89.0	1.49	1.76	UP
Italy	34.5	35.6	37.9	39.5	41.5	1.11	1.17	UP
Cyprus	n.a.	39.7	48.5	55.2	63.9	1.39	1.61	UP
Latvia	54.4	56.4	57.5	58.7	60.3	1.04	1.07	UP
Lithuania	37.3	38.3	40.6	42.0	43.8	1.10	1.14	UP
Luxembourg	34.1	36.3	36.5	36.9	37.4	1.02	1.03	UP
Hungary	22.9	25.2	27.6	29.3	31.8	1.16	1.26	UP
Malta	n.a.	11.5	9.0	7.2	4.8	0.62	0.42	DOWN
Netherlands	7.4	8.0	11.6	13.4	15.6	1.67	1.94	UP
Austria	45.1	46.7	47.3	47.7	48.5	1.02	1.04	UP
Poland	34.1	36.1	37.7	39.1	40.9	1.08	1.13	UP
Portugal	40.2	46.6	54.5	60.2	67.6	1.29	1.45	UP
Romania	n.a.	34.1	37.0	39.0	41.6	1.14	1.22	UP
Slovenia	62.0	63.4	63.0	63.0	63.1	0.99	1.00	UP
Slovakia	46.6	48.7	49.8	51.0	52.6	1.05	1.08	UP
Finland	69.9	71.3	70.8	71.0	71.5	1.00	1.00	UP
Sweden	65.9	66.5	67.9	68.8	70.0	1.03	1.05	UP

Source: Eurostat, own calculations. # forecasted values. n.a. not reported data.

A notable exception to the general upward trend is Malta, where research indicates a downward trend if immediate action is not taken to halt the downward trend. Although

Malta has limited woodland cover—only 5% of the island's landmass—significant portions of arable land are being repurposed for property development and national infrastructure projects. A positive example was expressed in 2020, when Malta signed, with 100 other countries at COP 26 in Glasgow, a commitment against deforestation, trying to limit the negative effects of deforestation [21].

The second key indicator of SDG 15 is vital for assessing the effectiveness of conservation efforts and ensuring the protection of ecosystems and biodiversity. By measuring the extent of land designated for conservation, this indicator reflects the commitment to preserving natural habitats, safeguarding endangered species, and maintaining ecosystem services that are critical for environmental health and human well-being. Protected areas serve as refuges for wildlife, help mitigate climate change by maintaining carbon sinks, and offer opportunities for sustainable tourism and recreation. Monitoring this indicator allows for the evaluation of progress towards global conservation targets, informs policy decisions, and supports the sustainable management of terrestrial resources.

As was the case for the previous indicator, the evolution of the terrestrial protected areas is on an upward trend until 2030 in all EU countries, without exception (Table 2).

Table 2. SDG 15–20—Surface of the terrestrial protected areas (% of terrestrial protected area).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27		25.1	26.0	26.8	27.6	1.07	1.10	UP
Belgium	13.0	13.0	14.7	14.7	15.4	1.13	1.19	UP
Bulgaria	34.0	34.0	41.0	41.4	44.7	1.22	1.32	UP
Czech Republic	14.0	14.0	21.9	22.1	25.7	1.58	1.83	UP
Denmark	9.0	8.0	14.9	15.5	18.8	1.94	2.35	UP
Germany	15.0	15.0	37.4	37.8	47.9	2.52	3.20	UP
Estonia	18.0	18.0	20.9	20.9	22.2	1.16	1.23	UP
Ireland	13.0	13.0	13.9	13.9	14.3	1.07	1.10	UP
Greece	27.0	27.0	34.9	35.1	38.7	1.30	1.43	UP
Spain	27.0	27.0	28.0	28.0	28.5	1.04	1.05	UP
France	13.0	13.0	28.0	28.1	34.9	2.16	2.68	UP
Croatia	n.a.	37.0	38.1	38.5	39.3	1.04	1.06	UP
Italy	19.0	19.0	21.4	21.5	22.5	1.13	1.19	UP
Cyprus	28.0	29.0	37.7	39.3	44.2	1.35	1.52	UP
Latvia	12.0	12.0	18.2	18.3	21.2	1.53	1.76	UP
Lithuania	12.0	12.0	17.1	17.5	19.9	1.45	1.66	UP
Luxembourg	18.0	27.0	55.8	62.9	81.6	2.33	3.02	UP
Hungary	21.0	21.0	22.2	22.2	22.8	1.06	1.08	UP
Malta	13.0	13.0	29.0	29.3	36.6	2.26	2.82	UP
Netherlands	15.0	15.0	26.5	26.8	32.0	1.79	2.14	UP
Austria	15.0	15.0	29.2	29.4	35.8	1.96	2.39	UP
Poland	20.0	20.0	39.6	40.0	48.9	2.00	2.45	UP
Portugal	21.0	21.0	22.4	22.4	23.1	1.07	1.10	UP
Romania	23.0	23.0	23.4	23.5	23.7	1.02	1.03	UP
Slovenia	36.0	38.0	40.5	41.1	42.9	1.08	1.13	UP
Slovakia	29.0	29.0	37.4	39.4	44.0	1.36	1.52	UP
Finland	13.0	13.0	13.3	13.3	13.4	1.02	1.03	UP
Sweden	13.0	12.0	15.0	13.9	14.5	1.16	1.21	UP

Source: Eurostat, own calculations. # forecasted values. n.a. not reported data.

The third SDG 15 indicator included in this research is essential for understanding and managing the effects of drought on ecological systems. This indicator measures the extent and severity of drought-induced damage to ecosystems, which can lead to significant biodiversity loss, reduced water availability, and compromised ecosystem services such as soil fertility and carbon sequestration (Table 3).

Table 3. SDG 15–42—Drought impact area on ecosystems (%).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	3.1	3.2	1.4	10.3	13.7	3.22	4.28	UP
Belgium	13.5	0.1	0.0	61.2	88.7	100.0	100.0	UP
Bulgaria	0.2	0.1	0.2	4.6	6.5	45.63	64.49	UP
Czech Republic	0.1	7.8	0.1	7.8	9.4	1.01	1.21	UP
Denmark	0.1	0.1	0.1	15.0	21.6	100.0	100.0	UP
Germany	4.0	2.7	0.1	21.4	29.5	7.94	10.93	UP
Estonia	0.0	0.4	1.5	11.0	15.3	27.38	38.21	UP
Ireland	0.0	0.1	0.2	2.6	3.8	25.94	38.03	UP
Greece	0.1	0.1	3.9	3.5	5.4	35.59	54.22	UP
Spain	1.8	1.7	0.5	0.0	0.0	0.0	0.0	NONE
France	13.0	0.2	0.2	30.5	44.0	100.0	100.0	UP
Croatia	9.5	1.1	0.9	5.7	5.2	5.14	4.71	UP
Italy	1.9	0.9	2.6	5.7	7.6	6.31	8.44	UP
Cyprus	0.4	0.1	6.2	6.0	4.1	59.60	40.98	UP
Latvia	0.0	0.4	2.6	8.3	11.6	20.73	29.01	UP
Lithuania	0.0	2.0	0.4	16.6	22.9	8.32	11.44	UP
Luxembourg	42.7	0.1	0.1	85.5	100.0	100.0	100.0	UP
Hungary	0.5	3.6	1.3	0.4	0.0	0.11	0.0	DOWN
Malta	0.0	0.1	0.8	0.6	0.0	5.57	0.0	NONE
Netherlands	0.0	0.1	0.1	22.4	31.2	100.0	100.0	UP
Austria	2.1	7.2	1.1	4.4	8.7	0.60	1.21	UP
Poland	0.0	21.3	1.5	8.9	17.0	0.42	0.80	UP
Portugal	2.8	4.3	0.1	4.6	3.3	1.07	0.78	NONE
Romania	0.2	2.1	0.1	0.8	2.2	0.38	1.05	UP
Slovenia	6.0	0.6	2.0	22.4	30.9	37.30	51.54	UP
Slovakia	0.0	9.8	0.2	3.7	2.2	0.38	0.23	DOWN
Finland	1.6	0.4	4.0	6.4	8.7	16.10	21.65	UP
Sweden	0.4	1.9	3.8	7.8	10.7	4.09	5.64	UP

Source: Eurostat, own calculations. # forecasted values.

By tracking these impacts, stakeholders can better assess the resilience of ecosystems to climate variability, implement targeted mitigation and adaptation strategies, and enhance preparedness for future drought events. These actions are crucial for sustaining natural resources, supporting agricultural productivity, and ensuring the overall health and functionality of ecosystems that underpin human well-being and economic stability.

The fourth relevant indicator is essential for assessing the vulnerability of land to soil degradation processes, which can have profound implications for agricultural productivity, ecosystem health, and water quality. Soil erosion by water can lead to the loss of fertile topsoil, reduced crop yields, and the sedimentation of water bodies, affecting aquatic habitats and water management (Table 4).

By identifying areas at risk of severe erosion, this indicator helps inform land management and conservation strategies to prevent soil loss, protect soil health, and maintain ecosystem stability. Effective monitoring and mitigation efforts guided by this indicator are essential to promote sustainable land use practices, enhance food security, and ensure long-term environmental resilience.

In terms of the aggregated EU-wide indicators, Eurostat publishes data on two such indicators specific to SDG 15. The Common Bird Index monitors trends in bird populations, which serves as a key indicator of overall ecosystem health and biodiversity, while the Grassland Butterfly Index assesses the health of grassland ecosystems and their biodiversity (Table 5).

Table 4. SDG 15–50—Area at risk of severe soil erosion by water (%).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	5.31	5.32	5.30	5.29	5.29	1.00	0.99	DOWN
Belgium	0.42	0.41	0.44	0.44	0.44	1.06	1.08	UP
Bulgaria	3.31	3.07	3.91	4.09	4.21	1.27	1.37	UP
Czech Republic	1.31	1.33	1.28	1.27	1.26	0.96	0.95	DOWN
Denmark	0.00	0.01	0.00	0.00	0.00	n.a.	n.a.	NONE
Germany	1.31	1.36	1.20	1.16	1.14	0.88	0.84	DOWN
Estonia	0.00	0.00	0.00	0.00	0.00	n.a.	n.a.	NONE
Ireland	0.67	0.68	0.65	0.65	0.65	0.97	0.95	DOWN
Greece	9.57	9.44	9.89	9.98	10.04	1.05	1.06	UP
Spain	8.99	8.88	9.28	9.36	9.42	1.04	1.06	UP
France	3.29	3.37	3.09	3.03	2.99	0.92	0.89	DOWN
Croatia	5.45	6.75	2.20	1.22	0.57	0.33	0.08	DOWN
Italy	24.88	24.66	25.41	25.57	25.68	1.03	1.04	DOWN
Cyprus	6.43	6.17	7.10	7.30	7.43	1.15	1.21	UP
Latvia	0.01	0.01	0.01	0.01	0.01	1.00	1.00	NONE
Lithuania	0.02	0.02	0.02	0.02	0.02	1.00	1.00	NONE
Luxembourg	2.63	2.65	2.60	2.59	2.58	0.98	0.98	DOWN
Hungary	2.52	2.56	2.42	2.39	2.37	0.95	0.93	DOWN
Malta	10.93	12.24	7.64	6.66	6.00	0.62	0.49	DOWN
Netherlands	0.01	0.01	0.01	0.01	0.01	1.00	1.00	NONE
Austria	15.51	15.55	15.41	15.38	15.36	0.99	0.99	DOWN
Poland	1.13	1.10	1.22	1.24	1.26	1.11	1.14	UP
Portugal	4.14	4.38	3.54	3.36	3.24	0.81	0.74	DOWN
Romania	7.34	7.48	7.01	6.91	6.84	0.94	0.92	DOWN
Slovenia	18.99	18.97	19.04	19.05	19.06	1.00	1.01	UP
Slovakia	4.58	4.68	4.33	4.25	4.20	0.93	0.90	DOWN
Finland	0.01	0.01	0.01	0.01	0.01	1.00	1.00	NONE
Sweden	0.68	0.68	0.68	0.68	0.68	1.00	1.00	NONE

Source: Eurostat, own calculations. # forecasted values. n.a. not reported data.

Table 5. SDG 15–60 and SDG 15–61—EU aggregates (index, 2000 = 100).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
Common bird index	93.10	91.16	88.40	86.63	84.40	0.95	0.93	DOWN
Grassland butterfly index	114.02	106.73	68.27	37.10	5.71	0.35	0.05	DOWN

Source: Eurostat, own calculations. # forecasted values.

Birds are sensitive to changes in their environment, and shifts in their populations can reflect broader ecological changes, such as habitat loss, climate change, and pollution. Tracking the Common Bird Index helps in assessing the impact of these environmental pressures on avian species and ecosystems, guiding conservation efforts and informing policies aimed at preserving biodiversity. By understanding and responding to changes in bird populations, stakeholders can better address the underlying environmental issues, promote sustainable land use, and support the conservation of various species and habitats.

In a relatively similar way, butterflies are sensitive to changes in their habitat. This indicator provides insights into the quality of grassland habitats, which are essential for maintaining plant–pollinator interactions and overall ecosystem stability. Changes in the Grassland Butterfly Index can signal shifts in habitat quality due to factors such as land use changes, climate change, or pollution, thereby informing conservation strategies and management practices.

The next key indicator included in this research is the level of biochemical oxygen demand in rivers. This indicator measures the mean annual five-day biochemical oxygen demand (BOD5) in rivers, weighted by the number of measuring stations. Elevated levels signal higher pollution, which can deplete oxygen in the water, leading to adverse effects on aquatic life, such as fish die-offs and disruptions in food chains. Constant monitoring of the

biochemical oxygen level allows for the evaluation of wastewater treatment effectiveness, the identification of pollution sources, and the implementation of necessary measures to safeguard and restore river ecosystems. Ensuring low biochemical oxygen levels is crucial for maintaining water quality, supporting biodiversity, and protecting water resources for both human and ecological needs (Table 6).

Table 6. SDG 6–30—Biochemical oxygen demand in rivers (mg O_2 per liter).

Countries †	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	2.58	3.13	2.77	2.79	2.79	0.89	0.89	DOWN
Belgium	2.53	2.91	2.27	2.29	2.16	0.79	0.74	DOWN
Bulgaria	2.87	2.74	3.03	2.76	2.76	1.01	1.01	UP
Czech Republic	2.69	2.75	2.60	2.54	2.49	0.92	0.91	DOWN
Estonia	1.74	1.73	1.64	1.62	1.61	0.94	0.93	DOWN
Ireland	1.49	1.16	1.11	0.85	0.63	0.73	0.54	DOWN
Spain	1.59	4.56	3.59	4.20	4.81	0.92	1.05	UP
Croatia	1.83	1.92	1.89	1.76	1.69	0.92	0.88	DOWN
Italy	1.96	1.84	1.60	1.28	0.98	0.69	0.53	DOWN
Cyprus	3.94	2.00	2.41	0.78	0.89	0.39	0.45	DOWN
Latvia	1.47	1.18	2.19	2.52	2.95	2.13	2.50	UP
Lithuania	2.23	2.05	1.98	1.90	1.76	0.93	0.86	DOWN
Austria	2.33	1.88	1.13	0.76	0.20	0.40	0.11	DOWN
Poland	3.87	2.76	2.66	2.45	2.18	0.89	0.79	DOWN
Romania	4.35	3.97	3.48	2.81	2.21	0.71	0.56	DOWN
Slovenia	0.97	0.84	0.78	0.69	0.61	0.83	0.73	DOWN
Slovakia	2.58	2.75	1.89	1.61	1.21	0.58	0.44	DOWN
Finland	2.60	1.91	1.57	1.07	1.00	0.56	0.53	DOWN
Sweden	5.34	5.98	6.11	6.40	6.71	1.07	1.12	UP

Source: Eurostat, own calculations. # forecasted values. † Countries not listed in the table have not reported data.

The eighth SDG15 indicator included in this research quantifies the concentration of phosphate in the dissolved phase of water. Phosphates, when present in high concentrations, can lead to nutrient pollution, which stimulates the excessive growth of algae and aquatic plants, a process known as eutrophication. This process can result in harmful algal blooms, decreased oxygen levels, and the degradation of aquatic habitats, which negatively affects fish and other aquatic organisms. The effective management of phosphate concentrations is crucial for maintaining balanced and healthy river ecosystems, supporting biodiversity, and ensuring clean water resources for both ecological and human uses (Table 7).

The last specific indicator for SDG 15 considered for this research is critical for understanding the impact of urbanization and land use changes on soil health and ecosystem functionality. Soil sealing refers to the process by which natural land surfaces are covered by impermeable materials such as asphalt and concrete, which prevents water infiltration, disrupts natural drainage patterns, and reduces soil fertility. High levels of soil sealing can lead to increased surface runoff, a higher risk of flooding, the loss of agricultural land, and diminished habitats for plants and animals. Unfortunately, as can be seen from the data presented in Table 8, the forecasted values for this indicator for all EU Member States are on an upward trend until 2030, which represents a warning signal to all stakeholders (Table 8).

In order to achieve a broader perspective on the potential evolution of the values of the specific indicators for SDG 15 by 2030, as well as on the potential of the EU Member States to achieve the targets assumed, Table 9 summarizes the main expected trends until 2030 for each specific indicator included in the analysis. The table does not include the evolution of the indicators 15–60 and 15–61, as these are aggregated at the level of the whole European Union (Table 9).

Table 7. SDG 6–50—Phosphate in rivers (mg PO_4 per liter).

Countries †	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	0.057	0.063	0.074	0.088	0.097	1.39	1.54	UP
Belgium	0.217	0.188	0.174	0.187	0.187	1.00	0.99	NONE
Bulgaria	0.133	0.094	0.189	0.290	0.405	3.09	4.30	UP
Czech Republic	0.109	0.126	0.085	0.072	0.057	0.57	0.46	DOWN
Denmark	0.051	0.051	0.053	0.053	0.055	1.05	1.08	UP
Estonia	0.029	0.023	0.022	0.023	0.024	1.02	1.03	UP
Ireland	0.034	0.023	0.022	0.019	0.014	0.81	0.63	DOWN
Spain	0.052	0.159	0.199	0.267	0.328	1.68	2.06	UP
Croatia	0.032	0.022	0.018	0.013	0.006	0.59	0.28	DOWN
Italy	0.037	0.071	0.055	0.057	0.061	0.80	0.86	DOWN
Latvia	0.021	0.013	0.017	0.016	0.014	1.22	1.10	UP
Lithuania	0.053	0.080	0.205	0.264	0.349	3.30	4.36	UP
Romania	0.090	0.105	0.087	0.096	0.097	0.92	0.93	DOWN
Slovenia	0.032	0.045	0.029	0.030	0.030	0.67	0.66	DOWN
Slovakia	0.081	0.092	0.050	0.036	0.017	0.39	0.19	DOWN
Finland	0.016	0.016	0.015	0.013	0.010	0.84	0.62	DOWN
Sweden	0.012	0.008	0.007	0.004	0.002	0.52	0.22	DOWN

Source: Eurostat, own calculations. # forecasted values. † Countries not listed in the table have not reported data.

Table 8. SDG 11–32—Soil sealing index (index, 2006 = 100).

Countries	2011	2015	2021	2025 #	2030 #	2025/2015	2030/2015	Trend
EU-27	102.2	102.6	104.3	105.4	106.7	1.03	1.04	UP
Belgium	101.6	101.9	103.3	104.1	105.2	1.02	1.03	UP
Bulgaria	102.0	102.3	103.7	104.6	105.8	1.02	1.03	UP
Czech Republic	102.0	102.3	103.8	104.7	105.9	1.02	1.04	UP
Denmark	101.6	101.8	103.2	104.1	105.2	1.02	1.03	UP
Germany	101.8	102.1	103.4	104.2	105.3	1.02	1.03	UP
Estonia	101.8	102.2	103.2	104.0	105.0	1.02	1.03	UP
Ireland	101.8	102.1	104.1	105.9	107.6	1.04	1.05	UP
Greece	101.3	101.6	102.8	103.6	104.6	1.02	1.03	UP
Spain	103.5	104.2	106.4	108.0	110.0	1.04	1.06	UP
France	102.3	102.8	104.5	105.6	107.1	1.03	1.04	UP
Croatia	101.5	101.9	103.7	105.0	106.5	1.03	1.04	UP
Italy	101.6	101.9	103.0	103.8	104.7	1.02	1.03	UP
Cyprus	106.3	107.9	113.7	117.5	122.2	1.09	1.13	UP
Latvia	101.1	101.5	102.4	103.0	103.9	1.01	1.02	UP
Lithuania	101.1	101.3	102.0	102.6	103.2	1.01	1.02	UP
Luxembourg	103.0	103.6	105.6	107.0	108.8	1.03	1.05	UP
Hungary	102.3	102.7	104.3	105.4	106.8	1.03	1.04	UP
Malta	100.4	100.4	104.4	106.0	107.7	1.06	1.07	UP
Netherlands	102.3	102.6	104.6	105.7	107.3	1.03	1.05	UP
Austria	101.7	101.9	103.3	104.2	105.3	1.02	1.03	UP
Poland	103.9	104.6	106.9	108.2	110.0	1.03	1.05	UP
Portugal	102.1	102.6	104.1	105.2	106.6	1.03	1.04	UP
Romania	102.7	103.2	105.0	106.2	107.7	1.03	1.04	UP
Slovenia	101.8	102.1	103.5	104.7	106.0	1.03	1.04	UP
Slovakia	103.5	104.1	106.2	107.6	109.5	1.03	1.05	UP
Finland	101.5	101.7	102.9	103.7	104.6	1.02	1.03	UP
Sweden	101.2	101.4	102.6	103.5	104.5	1.02	1.03	UP

Source: Eurostat, own calculations. # forecasted values.

Table 9. Estimated trends for key SDG 15 indicators towards 2030.

Countries	SDG 15–10	SDG 15–20	SDG 15–42	SDG 15–50	SDG 6–30	SDG 6–50	SDG 11–32
EU-27	↗	↗	↗	↘	↘	↗	↗
Belgium	↗	↗	↗	↗	↘	→	→
Bulgaria	↗	↗	↗	↗	↗	↗	↗
Czech Republic	↗	↗	↗	↘	↘	↘	↗
Denmark	↗	↗	↗	→	n.a.	↗	↗
Germany	↗	↗	↗	↘	n.a.	n.a.	↗
Estonia	↗	↗	↗	→	↘	↗	↗
Ireland	↗	↗	↗	↘	↘	↘	↗
Greece	↗	↗	↗	↗	n.a.	n.a.	↗
Spain	↗	↗	→	↗	↗	↗	↗
France	↗	↗	↗	↘	n.a.	n.a.	↗
Croatia	↗	↗	↗	↘	↘	↘	↗
Italy	↗	↗	↗	↘	↘	↗	↗
Cyprus	↗	↗	↗	↗	↘	n.a.	↗
Latvia	↗	↗	↗	→	↗	↗	↗
Lithuania	↗	↗	↗	→	↘	↘	↗
Luxembourg	↗	↗	↗	↘	n.a.	n.a.	↗
Hungary	↗	↗	↘	↘	n.a.	n.a.	↗
Malta	↘	↗	→	↘	n.a.	n.a.	→
Netherlands	↗	↗	↗	→	n.a.	n.a.	↗
Austria	↗	↗	↗	↘	↘	n.a.	↗
Poland	↗	↗	↗	↗	↘	n.a.	↗
Portugal	↗	↗	→	↘	↘	n.a.	↗
Romania	↗	↗	↗	↘	↘	↘	↗
Slovenia	↗	↗	↗	↗	↘	↘	↗
Slovakia	↗	↗	↘	↘	↘	↘	↗
Finland	↗	↗	↗	→	↘	↘	↗
Sweden	↗	↗	↗	→	↗	↘	↗

Source: own calculations. "↗" denotes upward trend, "↘" denotes downward trend, "→" denotes no trend, "n.a." means not available data.

4. Discussions

The in-depth analysis of the research results indicates that European countries are actively working to protect and conserve terrestrial ecosystems, dedicating various human and financial resources toward achieving the goals outlined in the 2030 Agenda. However, the findings also reveal the existence of concerning trends that could significantly hinder efforts to restore and promote these ecosystems. While commendable progress is being made in aligning with the 2030 Agenda goals, this research uncovers specific challenges and negative trends that could obstruct progress across Member States. This dual perspective underscores the need to not only recognize the achievements but also to address emerging challenges, ensuring a comprehensive and resilient approach to sustainable development in European countries.

4.1. Share of Forest Area (sdg_15_10)

The SDG 15–10 indicator, "Share of forest and other wooded land," is critical because it reflects the overall health and extent of terrestrial ecosystems, which are essential for biodiversity, carbon sequestration, and the livelihoods of millions. Forests play a pivotal role in mitigating climate change by absorbing carbon dioxide, supporting diverse species, and preserving soil and water quality. This indicator helps monitor the conservation and sustainable management of these ecosystems, making it fundamental in assessing countries' efforts to protect natural resources, which are crucial to achieving the broader sustainability and environmental goals outlined in the 2030 Agenda.

Forested areas, covering 31% of the world's land, are vital to long-term sustainability, but their extent has significantly decreased over time [22]. The conversion of forests to

agricultural land has often brought negative consequences, including global warming and environmental imbalances [23–25]. Europe, with about 40% of its land covered by forests, is one of the most forested regions in the world [26]. Despite relatively extensive management practices, European forests face threats such as pollution, habitat loss, and growing urbanization. Additionally, the increasing demand for biomass puts further pressure on these critical ecosystems, making sustainable management even more essential [27,28].

As the analysis shows, most EU countries, with the exception of Malta, are expected to increase their forest and other wooded land area by 2030, with varying rates of increase. Thus, an example of good practice is Portugal, which is estimated to increase, by 45%, the area allocated to forests and other wooded land by 2030 [29]. Portugal has been increasing its forested areas due to a combination of reforestation efforts, sustainable land management practices, and policies aimed at enhancing biodiversity and combating climate change. The country's focus on forest expansion is driven by the recognition of the critical role that forests play in carbon sequestration, soil protection, and water regulation. Additionally, Portugal has been working to restore degraded lands and convert abandoned agricultural areas into forests, contributing to an increase in forest cover. Efforts to manage and prevent forest fires, which have historically been a significant challenge in Portugal, also support this increase by promoting healthier, more resilient forest ecosystems. These results are in line with research published by Nunes et al. [30] and Reboredo and Pais [31].

4.2. Surface of the Terrestrial Protected Areas (sdg_15_20)

The extent of terrestrial protected areas (SDGs 15–20) reflects the extent of land designated for biodiversity conservation and the protection of natural habitats. These areas are vital for protecting ecosystems, species, and genetic diversity from human pressures and environmental degradation. By providing a refuge for endangered species and supporting ecological processes, protected areas play a crucial role in monitoring environmental health and promoting recovery.

The expansion of protected areas is a global priority, contributing directly to restoring biodiversity, mitigating the impacts of climate change and combating habitat loss. The high rates of climate change but also the frequent changes in land use through the spatial adaptive management of natural resources become key points in the actions undertaken by many of the world's governments to achieve sustainable development and biodiversity goals and beyond. From this perspective, unfortunately, by 2070, most countries are expected to fail to conserve their climate at current levels by 90% [32,33].

Despite these efforts, biodiversity loss remains a significant social and ecological emergency. Many existing protected areas are too small or poorly connected to provide adequate protection for endangered species, highlighting the need for more strategic siting and better management [34,35]. In the European Union, 26% of land was protected in 2021, and the EU Biodiversity Strategy aims to increase this amount to 30% by 2030 [36]. However, if the current rate of increase of 1.7 percentage points per decade persists, this target may not be met. To ensure success, EU Member States need to accelerate their efforts to designate and manage new protected areas, focusing on effective environmental management rather than just expanding land cover [37,38].

As indicated by current research results, at the current rate of growth, achieving the 30% target by 2030 appears very challenging. Nonetheless, EU Member States are actively preparing pledges to designate additional protected areas by the target date, which will provide critical information on the feasibility of reaching the 2030 Agenda goal and identify any significant gaps in the current conservation strategy. We can underline the efforts of Germany and Poland, for which growth rates well above the EU average are estimated, proving that remarkable results can be achieved even for more ambitious targets. In fact, the results of our research correspond to the research published by Schumacher et al. [39], who state that the goals for more wilderness areas in Germany are ambitious but achievable. Brackhane et al. [40], Cazzolla Gatti et al. [41], and Zbierska [42] also reached similar conclusions.

4.3. Drought Impact Area on Ecosystems (sdg_15_42)

The impact of drought on ecosystems (SDG 15–42) is a crucial indicator, especially in the context of the recent climate emergencies in Europe. Droughts severely affect biodiversity, water resources, and soil quality, disrupting ecosystem services essential for human well-being and environmental stability. Monitoring these impacts helps to understand ecological disturbances, guide effective adaptation strategies, and promote sustainable land and water management.

The impact of drought on socio-economic activities but also on life on the planet is certainly becoming more and more evident, an aspect that calls for government policy measures with immediate applicability that prioritize the elimination/reduction in greenhouse gases and the adaptation of ecosystems to climate change. Drought impacts may increase further if national adaptation strategies are not effectively implemented [43,44]. Also, droughts and extreme heat cause rapid declines in vegetation with large impacts on biodiversity, aridity, and vegetation cover. These aspects emphasize the large role that vegetation dynamics play in the drought phenomenon and highlight the phenomenon that soil water depletion, due to future warming-induced vegetation increases, could cause more frequent and severe droughts [45,46].

Within the EU, monitoring the impacts of meteorological droughts underpins policy measures aimed primarily at eliminating greenhouse gases as well as adapting ecosystems to climate change. In recent years, Europe has experienced the hottest summers on record, with more than 630,000 km^2 of land affected by drought. It is also evident that drought impacts may increase further if global mitigation and EU's national adaptation strategies are not effectively implemented [47].

According to the results obtained through this research, if the trend of past years will remain unchanged, the general situation is expected to worsen in EU countries, with an increase in the areas affected by drought estimated for most Member States. The few countries for which no clear trend can be defined, or for which slight decreases are expected, are most likely to be affected by droughts in the future, given the accelerating climate change. We emphasize the importance of adopting firm and immediate measures at the level of all EU countries in order to reduce the rate of increase in the areas affected by drought as well as for the mitigation of side effects. The results of our research are in line with numerous published studies on this topic, which emphasize the level of urgency and the need for immediate measures to reduce and even stop this phenomenon.

4.4. Area at Risk of Severe Soil Erosion by Water (sdg_15_50)

SDG indicator 15–50, 'Area at risk of severe soil erosion by water', is critical because it highlights a major threat to environmental and agricultural sustainability. Water erosion reduces soil fertility, decreases agricultural productivity, and increases sedimentation in water bodies, affecting food security, biodiversity, and ecosystem health. Despite extensive research, quantifying large-scale erosion remains a challenge as millions of hectares worldwide are at risk from erosion, making the identification of spatial patterns an urgent issue [48].

Changes in future soil erosion rates are determined by local or regional climatic conditions, land use patterns, the socio-economic development of regions, farmer/investor choices, and, last but not least, by agri-environmental policies. In this sense, for the EU, the Common Agricultural Policy (CAP, 2023–2027) has an important role in supporting farmers and improving agricultural productivity, ensuring a stable supply of food at affordable prices, protecting the right of EU farmers to earn a reasonable living, contributing to combating climate change, and the sustainable management of natural resources [49].

The results of our research indicate positive estimates for most European countries, which are expected to reduce the areas potentially affected by severe soil erosion by water, suggesting that public authorities are making efforts in this direction, especially in the current context of the negative effects induced by climate change. The results obtained for a number of European countries (Belgium, Greece, Spain, Greece, Cyprus, Poland,

Spain) indicate a potential increase in the areas affected by floods by 2030, if no preventive measures are taken. Belgium faces increasing erosion due to climate change, intensive agriculture, and land use changes, particularly in its hilly Wallonia region. Mediterranean countries like Spain, Cyprus, and Greece suffer more severe issues due to their climate patterns of dry periods followed by intense rainfall, coupled with mountainous terrain. These nations struggle with deforestation, overgrazing, and the abandonment of traditional practices like terracing. Spain's southern and eastern regions, Cyprus's mountains, and Greece's islands and coasts are especially vulnerable. Poland, while generally less affected, contends with erosion in its southern hills and along river valleys, mainly due to intensive agriculture. Across all five countries, human activities exacerbate natural erosion processes, with climate change expected to intensify these challenges. The mix of climatic, topographic, and anthropogenic factors creates a complex erosion landscape, requiring tailored approaches to soil conservation and sustainable land management.

Currently, unsustainable management practices and climate change are threatening soil quality to an increasing extent, which is why rapid changes in land use and socio-economic activities associated with climate change are imposing high pressures on the soils of the region. In this regard, we identify biodiversity management as one of the necessary solutions to mitigate risks and reduce damage, coupled with increasing soil organic matter by covering with crop varieties with higher residue and root production as well as reducing dependence on fossil fuels by avoiding the use of synthetic chemicals [50,51].

4.5. Common Bird Index by Type of Species (sdg_15_60) and Grassland Butterfly Index–EU Aggregate (sdg_15_61)

Birds are highly sensitive to environmental pressures, making their populations a reliable indicator of changes in their natural habitats. Unfortunately, in the EU, the index of 168 common bird species declined by 12% between 1990 and 2021. Given this trend, it is unlikely that the decline in common bird populations will be reversed by 2030 [37,52,53].

Similarly, butterflies play a crucial role in ecosystems, providing services such as pollination and serving as indicators of environmental health due to their sensitivity to change. Their declining numbers signal wider environmental problems, as they are key indicators for other insects essential for ecosystem functioning. Their decline also threatens the pollination of wildflowers and some crops, endangering habitats and biodiversity. [54,55].

EU-wide data show that, between 1991 and 2020, populations of 15 grassland butterfly species declined sharply by 29.5%. Population restoration, therefore, includes improving pollinator diversity and reversing the decline of pollinator populations by 2030 at the latest, which requires Member States to implement appropriate restoration measures in different ecosystems [56,57].

The results of our research indicate a clear and worrying worsening of the current situation by 2030. These indices track population trends of widespread bird and butterfly species, serving as sensitive barometers of habitat quality and overall environmental conditions. Birds and butterflies respond quickly to changes in land use, climate, and pollution levels, making them excellent proxies for broader biodiversity trends.

The decline in values for the Common Bird Index and Grassland Butterfly Index projected to 2030 can be attributed to a combination of factors, including habitat loss, climate change, and agricultural intensification. Habitat degradation, driven by urban expansion and agricultural practices, results in the fragmentation of critical areas necessary for the survival and reproduction of these species. Climate change exacerbates this issue by altering the availability of resources and shifting habitats, making it increasingly difficult for species to adapt or migrate. Additionally, the intensification of agriculture, including the use of pesticides and fertilizers, negatively impacts the quality of grassland ecosystems, further threatening the populations of both birds and butterflies. These results are correlated and confirmed by research published by Zingg et al. [58] and Herrando et al. [59], suggesting that the abandonment of traditional land use practices could be considered one of the main causes of the decline of species in open habitats.

4.6. Biochemical Oxygen Demand in Rivers (sdg_06_30)

Environmental pollution is a growing threat to sustainable development and quality of life, with biological oxygen demand becoming a key challenge in assessing water quality to ensure environmental and human health. Tackling this environmental crisis and monitoring biochemical oxygen demand is an ongoing challenge, although some innovative technologies can mitigate the harmful effects of pollution on ecosystems [60–62].

Biochemical oxygen demand in rivers (SDG 6–30) measures the oxygen required by microorganisms to break down organic matter in water. High levels indicate organic pollution, leading to oxygen depletion, which can harm aquatic life. Monitoring BOD5 levels helps assess organic pollution and river health, guiding better management strategies. Clean rivers have a BOD5 of less than 1 mg/L, while moderately polluted rivers range from 2 to 8 mg/L [60].

The results of our research indicate Latvia as one of the European countries most affected by the increase in BOD5. This increase can be attributed to several interrelated factors. Firstly, agricultural runoff contributes significantly to higher BOD5 levels due to the influx of organic matter, such as fertilizers and animal waste, into water bodies [63]. Additionally, industrial activities and inadequate wastewater treatment infrastructure further exacerbate this issue, as untreated or poorly treated effluents release high amounts of organic pollutants into rivers [64].

4.7. Phosphate in Rivers (sdg_06_50)

The phosphate in rivers indicator (SDG 6–50) is also very important for assessing the health of aquatic ecosystems because phosphates are key nutrients that can influence the growth of algae and aquatic plants. While phosphates are essential in small amounts, excessive concentrations, often resulting from agricultural runoff, sewage discharge, and industrial effluents, can lead to eutrophication. This process triggers excessive algal blooms, which can deplete oxygen levels in the water as the algae decompose, causing hypoxia and creating "dead zones" where aquatic life cannot survive [65–67].

As the results suggest, for a significant part of the countries that have reported values of this indicator, a downward trend in the values is forecast until 2030, which is good news in the context of meeting the 2030 Agenda targets. However, based on the data recorded so far and without significant interventions, unfavorable developments are estimated for a few countries, the most affected being Bulgaria, Spain, and Lithuania, for which values are forecast to be more than 300% higher than the EU average in 2030.

The key factors potentially influencing these potentially negative developments are primarily related to agricultural practices, urbanization, and inadequate wastewater treatment. In these countries, agricultural runoff is a major source of phosphate pollution, as fertilizers rich in phosphates are commonly used to enhance crop yields. When it rains, these phosphates are washed into rivers, increasing their concentrations [68,69]. Urbanization also plays a significant role, with expanding cities leading to greater sewage discharge, often containing phosphates from household detergents and industrial processes. In cases where wastewater treatment facilities are outdated or insufficient, untreated or poorly treated sewage can enter waterways, further elevating phosphate levels [70].

4.8. Soil Sealing Index (sdg_11_32)

The increase in soil surfaces sealed with impermeable materials generated by urban development, mainly buildings, to a very large extent leads to an imbalance in the ecosystem, especially when areas change their use. Therefore, in order to respond to the targets set by the 2030 Agenda on the terrestrial ecosystem, it is necessary to create different remote sensing techniques to monitor this process and to create soil sealing maps at local and national levels so that the degree of soil sealing can be permanently monitored [71,72].

Soil sealing reduces carbon and nutrient stocks compared to green spaces but can increase soil carbon and nitrate content, particularly in areas with an industrial past. Anthropogenic additions may lead to higher urban soil carbon stocks, contributing significantly to

urban soil carbon budgets. More research is needed to understand these processes in both sealed and unsealed soils and their effects on ecosystem services [73,74]. In the EU, soil sealing often affects fertile land, harms biodiversity, increases flooding and water scarcity risks, and contributes to global warming, with urban areas expanding by 78% since the 1950s [75].

The results of our research indicate a unanimous worsening of this indicator in European countries by 2030. There are numerous published studies pointing to this phenomenon, both at micro and macro level, the negative effects of which are widely debated in the literature [50,76]. The results clearly suggest that the targets set by the 2030 Agenda for this indicator will not be met by any of the EU countries.

The implications of this research for SDG 15 highlight both progress and current challenges in protecting, restoring, and promoting the sustainable use of terrestrial ecosystems in the European Union. The findings show that European countries are increasingly allocating resources to achieve the objectives of SDG 15, as evidenced by notable efforts to expand forest cover, designate protected areas, and improve water quality indicators. However, several negative trends, such as increased soil erosion, the lingering effects of drought and urban-induced soil sealing, highlight critical obstacles that could hamper the region's overall success. Thus, while substantial efforts are being made, addressing these negative trajectories is essential for the effective realization of the ambitions of SDG 15.

To increase the effectiveness of EU policies in achieving SDG 15, stronger enforcement mechanisms at the Member State level are essential. While the EU sets ambitious environmental targets, differing levels of commitment and capacity among countries often lead to inconsistent implementation. Strengthened monitoring and accountability measures at the Member State level could ensure that ecosystem protection and restoration objectives are consistently met. Increased funding and investment in green infrastructure is also essential as many initiatives, such as reforestation and waterway rehabilitation, require sustained financial support. Expanding financial resources, possibly through public–private partnerships and increased support from the European Investment Bank, would strengthen restoration efforts in the long term.

Moreover, fostering closer collaboration between government agencies, local communities, and research institutions can accelerate the adoption of sustainable practices and technologies, creating a more comprehensive, community-centered approach to ecosystem conservation and improving the overall resilience of these initiatives.

This research recognizes several limitations, primarily related to the variability of available data and differing rates of progress between EU Member States. Relying on indicators reported from sources such as Eurostat may not capture all the nuances of regional environmental degradation or the socio-economic factors influencing each country's performance. In addition, the challenges of establishing causality and comprehensively assessing long-term impacts suggest the need for further investigation and data integration at both local and regional scales.

Given these limitations, future research should prioritize improving data quality and developing more refined indicators that reflect the complex dynamics affecting ecosystem health. Other areas for exploration may include assessing the effectiveness of current policy interventions, investigating the socio-economic dimensions of ecosystem degradation, and advancing technological solutions to mitigate soil erosion and restore biodiversity. Expanding research on adaptive land management practices tailored to the specific climatic and geographical conditions in Europe could provide valuable information for targeted actions and strengthen the resilience of ecosystems to climate change.

5. Conclusions

Achieving the goals of SDG 15, as committed to by EU countries through the 2030 Agenda, is not only important for environmental sustainability but also for achieving broader socio-economic goals, including poverty reduction, food security, and global health, making it a cornerstone of global sustainable development.

The analysis of this research results reveals both progress and challenges in the conservation and restoration of terrestrial ecosystems in European countries. While substantial efforts are being made to align with the 2030 Agenda, particularly in terms of increasing forests and other wooded land, significant obstacles remain that could hinder these efforts. Countries such as Portugal have made notable progress in afforestation and sustainable land management, setting an example for other Member States. However, progress is uneven, with some regions facing greater challenges in achieving their conservation goals.

In addition, research highlights growing environmental threats that could undermine these conservation efforts. Drought and soil erosion are emerging as significant risks, particularly in Mediterranean regions and areas with intensive agriculture. These problems, exacerbated by climate change, threaten biodiversity, agricultural productivity, and the overall health of ecosystems. If current trends continue, areas affected by drought and soil erosion are expected to increase, posing a serious challenge to sustainable development.

Water quality is also emerging as a critical concern, with indicators such as phosphate levels and biochemical oxygen demand (BOD5) showing worrying trends in countries such as Latvia, Bulgaria, Spain, and Lithuania. These problems are largely caused by agricultural run-off, urbanization, and inadequate wastewater treatment, leading to pollution that threatens aquatic ecosystems and human health. Tackling these problems will require stronger water management and pollution control measures across the EU.

While European countries are making commendable progress in some areas of ecosystem conservation, significant challenges remain. The increasing threats posed by drought, soil erosion, and water pollution need to be addressed through targeted and coordinated efforts to ensure that the 2030 Agenda goals can be met. A comprehensive and resilient approach to sustainable development is needed to overcome these challenges and preserve the health of Europe's ecosystems.

Our research contributes to filling knowledge gaps regarding the potential for achieving the 2030 Agenda goals for protecting, restoring, and promoting the sustainable use of terrestrial ecosystems. The findings can inform decisions and actions by relevant parties and will hopefully inspire further research and improve understanding, thereby promoting the protection of terrestrial ecosystems.

Author Contributions: Conceptualization, D.F., G.H.I., C.P., R.P., C.M.C. and M.P.C.; Methodology, D.F., G.H.I. and R.P.; Writing—original draft, D.F. and G.H.I.; Writing—review and editing, D.F., G.H.I., C.P., R.P., C.M.C. and M.P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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

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Identifying Potential Urban Greenways by Considering Green Space Exposure Levels and Maximizing Recreational Flows: A Case Study in Beijing's Built-Up Areas

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Abstract: Urban greenways are pivotal in enriching urban quality and fostering socio-ecological sustainability. Previous studies on urban greenway networks have often overlooked user-based experience efficiency, leading to the underutilization and insufficient translation of cultural services into human well-being. In this study, we introduce a user behavior-driven assessment framework for planning multifunctional urban greenways that connect parks with high green space exposure and maximize recreational mobility. Beijing's built-up urban areas (BBUA) were selected as the case study area. Firstly, we evaluated the green space exposure of 331 parks in BBUA using an integrated "Availability–Accessibility–Adaptability" assessment framework as potential carriers. Then, through spatially explicit workflows and the least-cost path methodology, we leveraged a vast dataset of 70 million public transportation swipe records to optimize the alignment of multifunctional greenways, prioritizing the criterion of maximizing recreational footfalls. The results showed that the potential greenways network spans 1566.36 km in BBUA, encompassing 93.88% of parks and offering six diverse functions. It can serve 34.39–35.92% of bus recreation passengers, with this ratio tending to be higher on weekends. However, we identified obstacle points (non-greenway sections) in the networks based on residents' view perceptions and panoramic street images, primarily located in densely built-up central areas and along southern trunk roads. By addressing these disconnections, the integrity and connectivity of urban greenway networks in BBUA will be improved. Overall, the framework we present can be used to construct greenway networks that maximize the perceived accessibility for bus-based visitors, with valuable implications for sustainable urban planning and regeneration initiatives.

Keywords: greenways; public transportation; green space exposure; street panoramic view; BBUA

1. Introduction

Cities worldwide are vigorously expanding urban green spaces [1–3]. These spaces, which encompass greenways, parks, urban forests, waterfronts, and open green areas, are essential components of urban systems [4,5]. They offer diverse ecosystem services, such as regulating urban microclimates [6] and mitigating floods [7], providing cooling down services [8], and carbon sequestration [9], thereby contributing to resilient and sponge-like cities [10,11]. Unlike other static green spaces, greenways are a form of linear green infrastructure that connects various types of open space, such as ecological parks and green parks [12]. Greenways also provide numerous socioeconomic benefits, including enhancing physical and mental health [13], reducing household health costs [14], and offering intangible physiological benefits [15]. Scientific and systematic planning of greenways is crucial for fostering sustainable cities and strengthening social pillars.

Currently, a considerable number of theoretical frameworks for greenway systems planning have emerged [16], most of which integrate environmental, geographic, climatic, and socioeconomic data [17,18]. In terms of greenway planning, there are robust frameworks based on questionnaires [19], the analytic hierarchy process (AHP) approach [18], human-based flows [19], and others [20]. Methods for greenways routing include the greenways network preparation program [21], geographic information models [22], the least cumulative resistance model [23], and the multifactor superposition method [5], as well as spatially explicit approaches [24], network analysis method [25], and landscape connectivity for greenways network routing [26].

The integration of big data into greenways identification is gaining increasing traction [18,27]. Leveraging extensive datasets on recreational flows, such as those derived from shared bicycle trajectories [28], taxi movements [29], and mobile signaling data [30], holds immense potential to optimize the delivery of ecosystem cultural services [31,32]. Moreover, social network data sourced from platforms like TikTok and Facebook, showcasing users' green experiences, serve as pivotal indicators for greenways route selection [33].

Furthermore, high-resolution remote sensing imagery at the tree level, encompassing technologies like LiDAR and drone imagery [34], has emerged as a critical input for urban greenway spatial analysis, facilitating point-based evaluation of green space quality [35]. Notably, the adoption of user-generated street-level view imagery has garnered widespread recognition in greenways planning endeavors [36,37]. This imagery provides insights into citizens' firsthand experiences and engagement opportunities within greenways [38]. Indeed, the amalgamation of diverse big data sources has become the prevailing approach in greenways planning, underscoring interdisciplinary methodologies spanning geographic information technology, deep learning algorithms, remote sensing data analytics, and model optimization techniques [39].

China's urbanization and urban sprawl have been unprecedented over the past two decades [40,41]. Fragmentation of urban landscapes [42,43], significant urban heat island effects [44], as well as scarcity and inequality of green space [45], have been widely observed in China's cities. China's greenway planning exhibits certain deficiencies, marked by uneven spatial distribution and low use frequency [46]. To proactively address the knock-on effects of the dissonance between man and nature, the Chinese government has launched ambitious greenways planning policy package (Figure A3). Mature greenway initiatives predominantly thrive on the fringes of urban areas, while rejuvenating green corridors in old urban area remains a pressing need [47]. Furthermore, a prevalent mismatch between populace and greenway spaces underscores the need for an effective strategy to enhancing access efficiency [48]. Methodologically, conventional approaches suffer from insufficient sample sizes, which leads to a high degree of uncertainty when translating greenway planning blueprints into tangible realities [12]. Another challenge lies in the existing framework's neglect of user mobility-based perspectives, resulting in a reduced frequency of visitor access to greenways. This, in turn, exposes individuals to physical and mental health risks [49].

To fill the significant knowledge gap, we present a user-based driven assessment framework for identifying greenway networks. First, using the "3A" (Availability-Accessibility-Adaptability) framework, we evaluated the green space exposure of 331 parks in BBUA. Parks with high exposure levels were selected as carriers of greenway systems. Then, we used spatially explicit traffic information by filtering weekly transportation swipe data containing 70 million samples. We identified high-recreation-frequency routes as key selections for greenways. Note that the definition of urban greenways in this work is limited to systems that connect urban green spaces, distinguishing them from walking trails, waterfront greenways, etc. The functions of park nodes determine the functions of the greenway network, enabling an optimal configuration of multifunctional greenways. This study addresses the following three questions: (1) What is the spatial pattern of green space exposure level in BBUA? (2) How well laid out and multifunctional is the potential greenway network? (3) Where are the obstacle points in the greenway network located?

2. Materials and Methods

2.1. Study Areas

The Beijing's built-up urban area (BBUA), a cutting-edge metropolis in China, spans over 1088 km^2, primarily encompassing Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan districts (Figure 1a). This region boasts an exceptionally compact road and metro system for public transportation, coupled with a high level of human activity. As one of China's most densely populated metropolitan areas, the resident population of the study area has skyrocketed from 2.1 million to 10.9 million inhabitants from 2000 to 2020, which has led to higher demands on the urban green space system. The pattern of urban sprawl in the area revolves around ring patterns and encompasses a total of 4209 public transportation lines and 33,664 stations (Figure 1b).

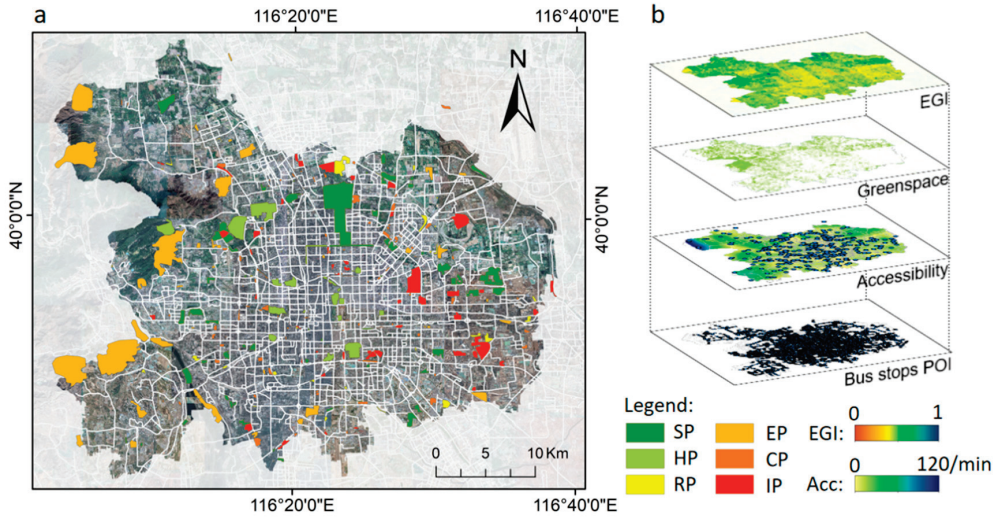


Figure 1. Spatial distribution of roads and parks in BBUA, as well as auxiliary spatial data. (**a**) A spatial map depicting the pattern of roads and parks in BBUA. The white lines indicate roads. (**b**) The diorama map provides supplementary spatially explicit patterns regarding EGI, green spaces, accessibility, and bus stop POIs. **SP:** specialized park; **EP:** ecological park; **HP:** historic park; **CP:** community parks; **RP:** recreational parks; **IP:** integrated parks; **ACC:** accessibility; **EGI:** excess green index).

Nowadays, it is increasingly evident to local residents that they favor greenways. The government has initiated old city renovation projects, whereby low impact buildings are replaced with open spaces such as parks and green areas, aiming to cater to the wishes of the residents and enhancing the sustainability of the city. In our research, we have identified 331 green space-related parks within BBUA, which can be categorized into six distinct types (Figure 1).

2.2. Data Sources and Processing

In this paper, bus traffic and parks area of interest (AOI) data are employed as crucial input variables for this research. Specifically, we captured 4254 point of interest (POI) park data from Gaode Maps (ditu.amap.com), China's authoritative map and navigation sharing platform, by using "park" as the keyword. By eliminating duplicates, removing redundant and irrelevant points, and manually reviewing each one, we initially evaluated 331 POI parks. The actual boundaries of each park AOI were determined by our co-authors using Google Earth tools (earth.google.com). In this work, we only considered green parks with large areas of green space, and excluded non-green vegetation-covered parks such as car parks and basketball parks. By comparing the Beijing Municipal Parks Directory List (https://yllhj.beijing.gov.cn), the 331 parks were categorized into six functions, as shown in Figure 1.

Furthermore, we collected weekly bus traffic data to mine high-volume recreational travel patterns, which contribute to identifying potential urban greenways. All travel data were obtained from the Beijing Public Transport Co. (www.bjbus.com) for the period of February 13th to 19th, 2023 in Beijing, including information on bus stops, times, and trip numbers, among other variables. This dataset integrates transportation cards and quick response code cards from phones, totaling over 70 million card traffic samples. It is essential for analyzing the residents' travel purposes, such as daily commuting, sightseeing, leisure, and shopping. We cleaned the bus data and visualized the bus travel map.

Auxiliary data were gathered to create a geodatabase in support of this work. The Beijing vector street data is available from www.resdc.cn, while the road system used to determine park accessibility was obtained from the OpenStreetMap platform in 2023 (openstreetmap.org). The accessibility network processing involved vector cropping and hierarchical processing implemented on ArcGIS 10.2 (Appendix A for details). We collected precise green space data, with a resolution of 1 m and for the year 2023, from prior research to satisfy the small-scale park requirements (Figure 1). To assess green space quality, we computed each park's excess green index (EGI) via the Google Earth Engine cloud platform and image analysis. All geographic data were projected onto the Krasovsky UTM 50-degree bands. In addition, the acquisition of street view panoramic images was conducted utilizing the street view imagery (SVI) from the Baidu Street View service (Refer to Appendix B). Detailed information can be seen in Table 1.

Table 1. The data list in this work.

Data Lists	Sources	URLs
Big data on bus transport swipe cards	Beijing Public Transport Co.	www.bjbus.com (accessed on 25 September 2024)
Park POI data	Gaode Map Open Platform	https://ditu.amap.com (accessed on 25 September 2024)
Beijing Parks List	Beijing Municipal Forestry and Parks Bureau	https://yllhj.beijing.gov.cn (accessed on 25 September 2024)
Vector boundary of BBUA	Resource and Environment Science and Data Center,	www.resdc.cn (accessed on 25 September 2024)
Google image raster data	a peer-reviewed paper [50] and Google Earth	https://earth.google.com (accessed on 25 September 2024)
Public transport road system	OpenStreetMap	https://openstreetmap.org (accessed on 25 September 2024)
Comments data	Dazhongdianping consumption sharing platform	www.dianping.com (accessed on 25 September 2024)
Street View images	Baidu Street View service	https://api.map.com (accessed on 25 September 2024)

2.3. Methods

To achieve scientifically informed outcomes in planning multifunctional urban greenways network systems, we assessed the human exposure to green spaces of 331 parks as potential greenways carriers using the "3A" framework and mined high-frequency recreational travel routes from transportation swipe data. This work involves four es-

sential steps: (1) assessing park exposure as potential greenway carriers; (2) extracting passenger-based recreation routes from bus transportation data; (3) overlaying each route and identifying high-frequency recreation access routes as greenways; (4) identifying the multifunctional greenways network and obstacle points based on street panoramic image. A visual flowchart is illustrated in Figure 2.

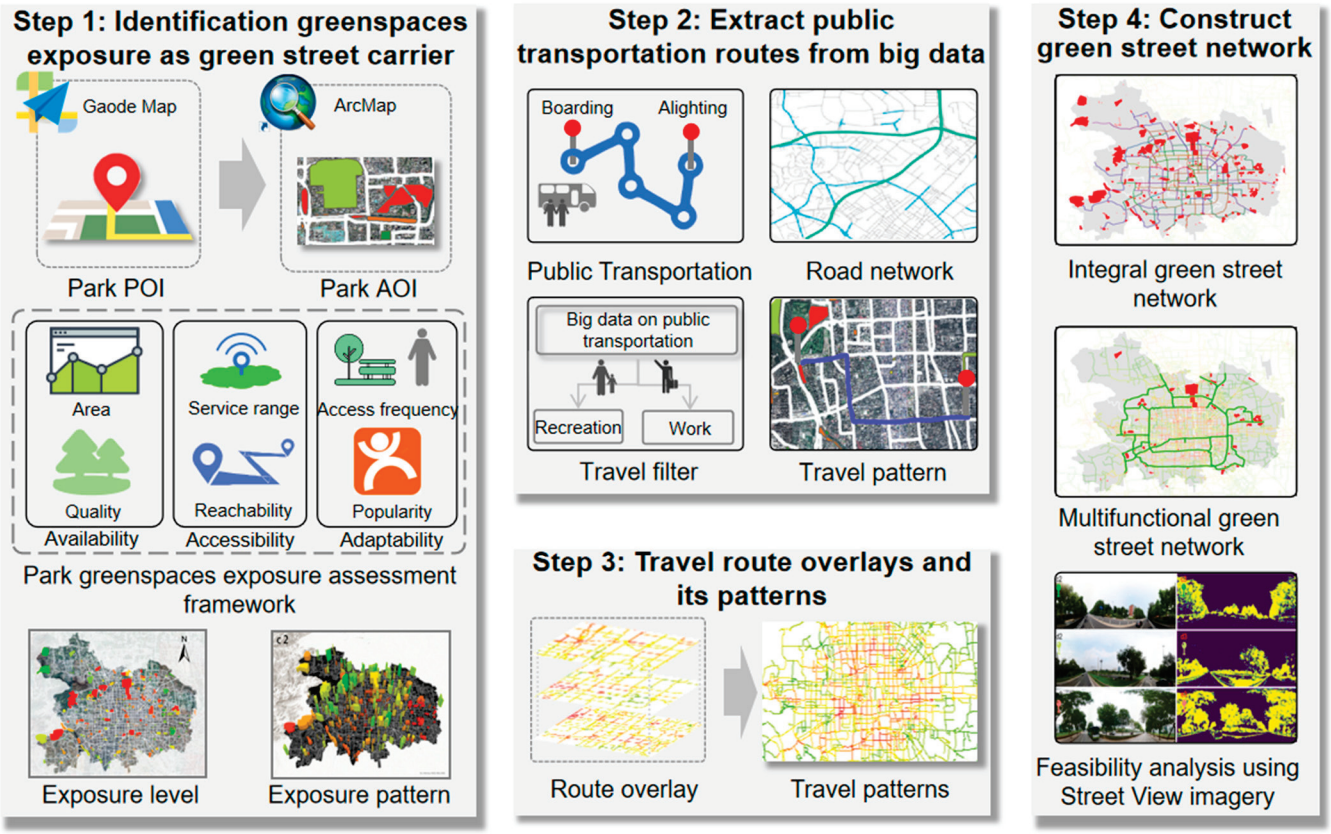


Figure 2. Visualizing technology map.

2.3.1. Park Green Space Exposure Assessment

To assess park green space exposure quantitatively, we adopted the "Availability–Accessibility–Adaptability" (3A) assessment framework, as demonstrated in previous work (Table 2), which provides a convenient and efficient method to evaluate exposure performance in urban green spaces [51]. The "3A" framework can encompass a wide range of dimensions, including natural function potential and human socioeconomic well-being. Identifying the exposure levels in 331 parks is crucial for recognizing park green space carriers, and this framework comprises three primary elements:

Availability: This component illustrates the basic state of green space in parks, encompassing two key indicators: area and quality (Table 2). The green space area is a valuable metric for quantifying green space exposure and is widely used in relevant research. We calculated the green space area of each park using zoning statistical tools in ArcGIS 10.2. Furthermore, we introduced the excess green index (EGI) to demonstrate variations in green space quality (Table 2). For example, the presence of denser vegetation is associated with more robust ecological processes. The EGI is an effective index for monitoring small green spaces such as community parks. To express accurate green space information, high-quality input data of RGB true-color Google remote sensing imagery with 1 m resolution and a time stamp of 2023 were utilized. The exact formula to use is as follows:

$$EGI = 2G - R - B \quad (1)$$

where *EGI* represents the excess green index. *G*, *R*, and *B* represent the green, red, and blue bands, respectively.

Table 2. Park green space exposure assessment system. (We have developed a "3A" framework for assessing the exposure of park's green spaces, which comprises three pillars and six indicators. Below, we provide the proxies for each indicator along with their significance.).

	Systems	Indicators	Agency	Significance
Park green-space exposure	Availability	Area	Green-space area	Larger green areas can increase park capacity and visitor acceptance levels.
		Quality	Excess green index (EGI)	This indicator helps evaluate green space quality; densely vegetated green spaces tend to be more favored.
	Accessibility	Service range	Park type	We quantified the service area of various parks, which is crucial for the surrounding residents.
		Reachability	Transport accessibility	By constructing an OD cost matrix with the road network, we quantified accessibility ranging from 5 to 120 min using Arcmap 10.2 tools.
	Adaptability	Popularity	Popularity of parks	The parks are graded according to their levels in the Beijing Parks Directory, with the high-level parks tending to be more well-known.
		Access frequency	Comments in Dazhongdianping	A greater number of comments reflects higher access frequency, which is essential for human exposure to park green spaces.

Accessibility: We aimed to measure the interaction between humans and the park through two metrics: accessibility and service coverage (Table 2). On the one hand, movement-based human behavior improves access to parks through public transportation. By defining a road network dataset (Table 1), we generated the accessibility radiation area formed by the source points along the topological road network (See Appendix A for details). Using an origin–destination (OD) cost matrix [52], we created a model of the public transportation network with a hierarchy incorporating breakpoints of 5, 10, 15, 30, 60, 90, and 120 min to determine park accessibility (Figure A1). Additionally, we examined the direct and potential impact of various parks on local human perception (Table 2). In accordance with the Chinese standards for park service areas (https://www.mot.gov.cn/), we measured the service areas of various types of parks, which range from 300 m for community parks to 2000 m for comprehensive parks (Table A1).

Adaptability: We then evaluated the impact and popularity of parks on residents (Table 2). The Beijing Municipal Bureau of Landscape Architecture categorizes green parks into four levels, with the highest to lowest levels corresponding to grades A to D. We also considered the frequency and number of parks visits within our framework (Table 2). One challenge we encountered was quantifying visit frequency in small parks. To address this, we utilized an agent-based model based on big data analysis of park evaluations. Specifically, we analyzed the quantity of ratings provided by visitors for each park through Chinese travel mobile apps from Dazhongdianping (Table 1). Parks with higher levels of comments also correspond to higher levels of visits, which is crucial in quantifying residents' exposure to parks. Using the natural segment point method, we categorized exposure levels into five classes, with the two highest exposure classes selected as the carriers for greenways (Figure A6). The "3A" assessment framework for this study is displayed visually below:

We found that the data from the "3A" framework did not follow a normal distribution; instead, it exhibited a heavily skewed left histogram. Parks that are well-known typically exhibit significantly greater amounts of green space and visitor frequency compared to other parks. To address this, we applied Equation (2) to adjust the normal characteristics of the indicator and reduce redundancy in extreme values. Additionally, normalizing the data is necessary to facilitate horizontal comparisons across dimensions [14]. All indicators show positive values, except for accessibility. The normalization formulas are as follow:

$$I_N = ln(j) \tag{2}$$

$$I_{Nj} = \frac{I_N - I_{N_{min}}}{I_{N_{max}} - I_{N_{min}}} \tag{3}$$

$$I_{Nj} = \frac{I_{N_{max}} - I_N}{I_{N_{max}} - I_{N_{min}}} \tag{4}$$

where the datasets matrix was constructed, with rows representing parks (i) and columns representing indicators (j). I_N denotes the normalized values, while I_{ij} represents the values in column j. I_{N_max} and I_{N_min} represent the initial maximum and minimum values of column j, respectively, indicating, the best and worst performance for a certain indicator. I_{Nj} is the new column after normalization. All values were scaled between 0 and 1, where 0 represents the worst and highest performance and 1 represents the highest performance.

2.3.2. Weighting

The indicators were assigned weights to determine their contribution to exposure. To ensure objectivity, we employed the entropy method for weight calculation. A lower information entropy indicates a higher level of information provided by a specific indicator, which is integral to the comprehensive evaluation system. The calculation process is as follows:

$$w_i = \frac{G_i}{\sum_{i=1}^{m} G_i} \tag{5}$$

where w_i is the weight of indicator i, i = 1, 2, 3; m represents the indicator dimension, and $m = 6$ in this work. Gi is the information utility value of indicator i.

$$G_i = 1 - E_i \tag{6}$$

where E_i is the entropy of indicator i.

$$E_i = -k \sum_{j=1}^{n} \sum_{t=1}^{r} P_{ij} \times ln(P_{ij}) \tag{7}$$

where k represents constant and $k = ln\ (m)$. j is the number of evaluation objects, j = . . . 1, 2, 3, n; there are j = 331 in this work. In addition, t is the number of indicators, t = . . . 1, 2, i, r, and $r = 6$. P_{ij} is the proportion of the value of each indicator.

$$P_{ij} = \frac{V_{ij}}{\sum_{t=1}^{r} V_{ij}} \tag{8}$$

where V_{ij} is the standardized value of each indicator.

2.3.3. Identifying Recreation Routes and Potential Urban Greenways

In this paper, the identification of the greenways network relies on the data collected from traffic swipes to spatially determine residents' recreational mobility. The efficiency optimization hypothesis posits that roads with higher numbers and frequency of public passengers for shopping and recreation would benefit more from at-grade greenways. This approach aims to maximize the ecological and aesthetic value of greenways while

enhancing invisible human well-being [2]. Additionally, the greenway community often emphasizes diversity and adaptability in an era of varied requirements. Consequently, greenway systems serving different functions have been established, utilizing six distinct park types and their priority arrangements.

We employed a flow-based process to filter and visualize patterns of passenger traffic flow for recreation and shopping. Specifically, we utilized Arcmap 10.2 software and geographic coordinate information to visualize bus stops and bus route patterns (Figure 3). Typically, work-related passenger trips exceed 8 h for round-trip travel, whereas leisure and shopping trips generally require less than 6 h. Taking this into account, we calculated the time difference from when each sample disembarked from the bus stop to their return to the starting point. Using the decision tree method, we determined the spatial line for leisure and shopping (Figure 3). We excluded some potentially interfering samples and ultimately visualized 400,000 samples (Figure 3).

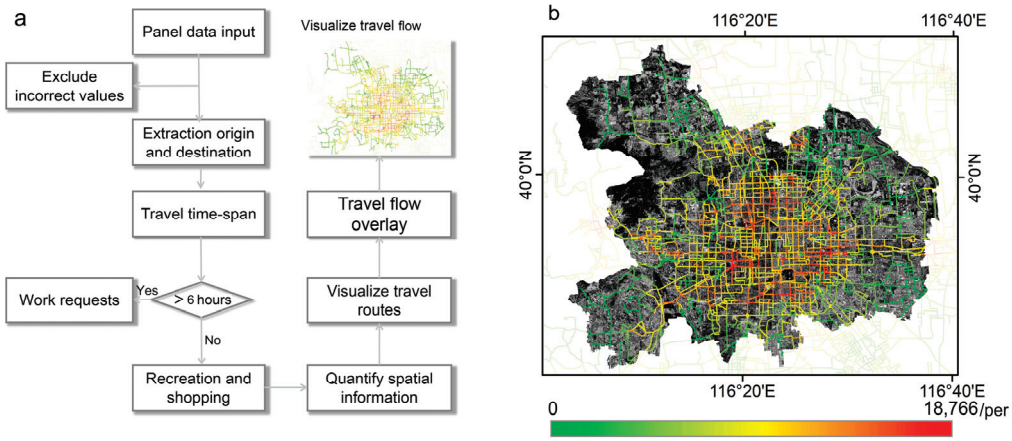


Figure 3. Travel flow extraction and visualization based on big data of bus card. (**a**) Procedure extraction steps. (**b**) Visualizing bus traffic flow map.

Greenways were identified using both qualitative and quantitative methods based on carrier priorities and the high frequency of recreational roads. This plan incorporates only the greenways with the highest pedestrian flow and valuable potential, while also considering the landscape patterns of the surrounding areas. For instance, ribbon parks along roads and waterfront paths will receive prioritization. The least-cost paths (LCP) method is a straightforward and suitable resistance-based modeling approach [53,54]. The quantitative assessment method employs the LCP, where the resistance value in off-road areas is set to converge to infinity, and the resistance value for the bus route is set lower as the passenger flow increases. Additionally, we modified some greenways while adding potentially useful ones that provide valuable ecosystem services, taking into account human requirements, patterns, and maximizing benefits.

2.3.4. Identifying Barrier Points in Greenway Networks

We attempted to use street view images to recognize the barrier points of the greenways network and discuss entry points for improving street greening in BBUA. According to the Baidu development documentation, the API service interface was called, with the field of view parameter set to 360° (fov = 360) [55]. We used Python packages to write a program to retrieve panoramic images, resulting in a total of 3235 images within BBUA. Considering that BBUA is in a temperate monsoon climate, the bare tree trunks in winter can lead to uncertainties in the results. Therefore, only images from March to October were included in the study. In the end, we obtained 1479 Baidu street view images from the last decade.

Here, we considered using the green view index (GVI) to demonstrate the greening performance of roads [56]. The GVI, as an important indicator of spatial greening quality

in urban streets, has been widely used in recent years. Panoramic images are more closely aligned with human perception. The GVI is defined as the ratio of the total green area in street panoramic photos to the total area of the photos. Previous studies have extensively demonstrated the positive effects of high GVI performance on human health and ecological urban development. The GVI, based on multi-angle greening images aligned with human sight-lines, is commonly used to reveal the relationship between green spaces and human health and well-being, and is incorporated into neighborhood environmental audits. We constructed a decision tree to evaluate the green view ratio indicators of street panoramas (Figure A2). In this article, streets with a high GVI are considered greenways within the network, while streets with a low GVI are defined as obstacle points. Overcoming these obstacle points facilitates the creation of a greenways network that is both connected and integrated, contributing to the development of a sustainable urban environment.

3. Results

3.1. The Status of Park Green Space in BBUA

We identified green-related 331 parks AOI, covering a total area of 13,248 ha, equivalent to 9.8% of BBUA (Figure 4). Administratively, Dongcheng boasts the highest number of parks, totaling 108, while Chaoyang has the least with only 18 (Figure A4). In terms of park area, Chaoyang has the largest areas at 4119 ha, while Xicheng only has 352 ha (Figure A4). The percentage difference in park area among the six districts ranges from 7.47% to 10.92%, with Shijingshan deserving particular praise (Figure A4). We observed significant average park size across different districts. Shijingshan district has the largest average park area of 48.38 ha, followed by Chaoyang and Haidian districts with 41.19 ha and 38.72 ha, respectively. Xicheng district has the smallest average park area of 8.38 ha.

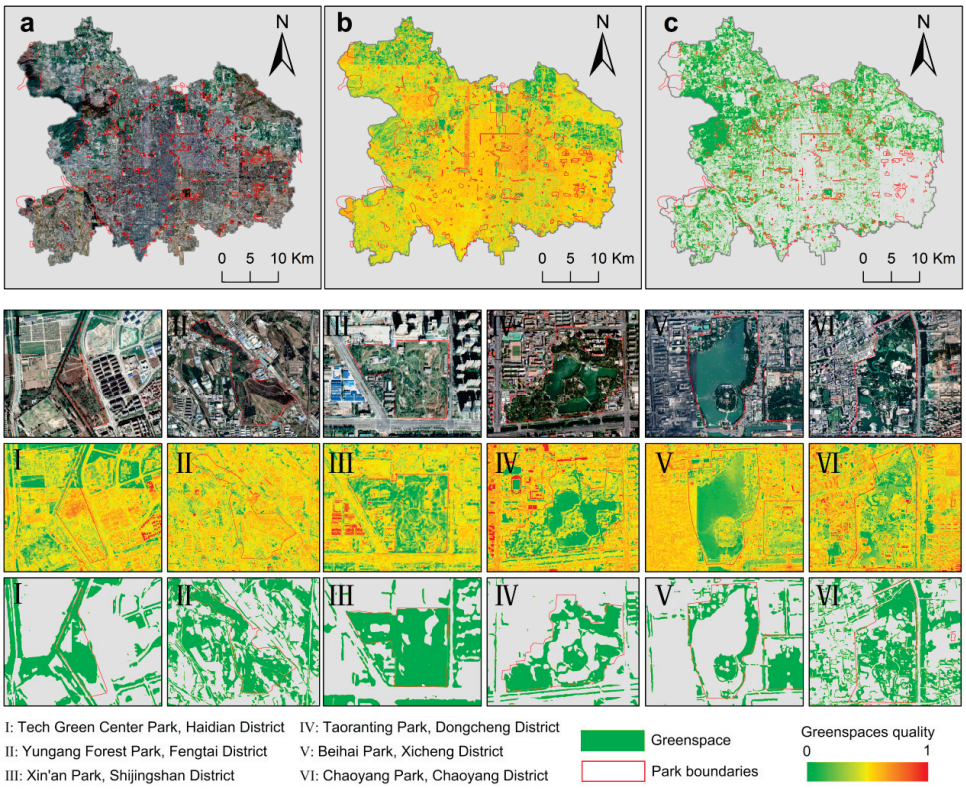


Figure 4. Spatialized referenced remote sensing images depict park patterns, green spaces, and their quality in BBUA. (**a**) Park spatial pattern map; (**b**) green space quality maps; (**c**) spatial distribution of green spaces in BBUA. All subplots display the visual accuracy of information extraction for green spaces in several parks. The remote sensing image base map is from Google Earth. See Equation (1) for the calculation of the green spaces quality indicator.

Spatially, the parks exhibited varying sizes with wide-ranging open areas (Figure 4a), primarily concentrated in the northern region and accompanied by a high EGI (Figure 4b). We reassessed the accuracy of green space data, which yielded a credible accuracy of 87.6%, facilitated by precise 1 m resolution Google Earth remote sensing imagery (Figure A5). We randomly selected six parks and observed their accuracy spatially (Figure 4). Validation results showed that these data are credible and can support further research.

3.2. Exposure Degree of Green Parks

We have presented a map portraying the spatial distribution of green park exposure (Figure 5). It is evident that significant spatial heterogeneity exists, with exposure levels ranging between 0.030 and 0.770 (Figure 5a). Geographically, the exposure performance decreases in concentric circles, from the center outwards. Notably, large-scale forest parks such as Olympic Forest Park, Beigong National Forest Park, and Xishan Park exhibit high levels of exposure (Figure 5a). In terms of quantitative data, the Summer Palace exhibits the highest level of green space exposure at 0.770, followed by Yuyuantan Park and Longtan Lake Park at 0.746 and 0.719, respectively (Figure 5a).

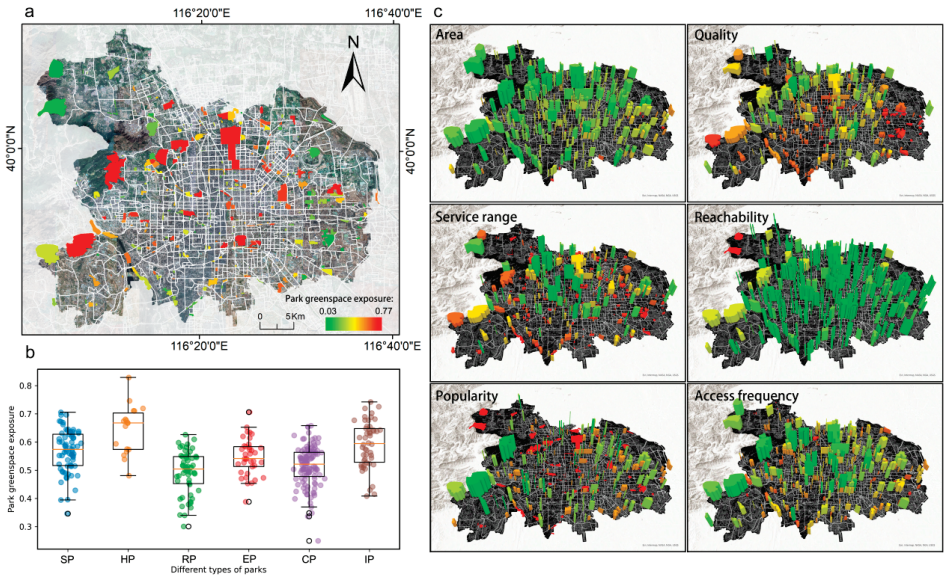


Figure 5. Spatially-explicit map illustrating the exposure performance of the parks' green space. (**a**) Spatially-explicit map of park exposure. (**b**) Exposure degree comparison between parks with different functions. See Figure 1 for abbreviations of park names on the x-axis. (**c**) Performance of different indicators under the exposure framework. In this subplot, the color gradient ranges from red to green, where high green corresponds to better performance.

We observed that six out of ten parks ranked at the top in terms of exposure are historical function parks. In contrast, community and recreational parks generally exhibit a lower level of exposure (Figure 5b). Specifically, from the sample point oscillation amplitude of the box plot in Figure 5, we found significant differences in indicator performance among specialized parks, recreational parks, and community parks, while the exposure gap was relatively smaller among ecological parks (Figure 5b). Under the "3A" assessment criteria, diverse exposure performance was observed among parks. Spatially, the center and southeast of BBUA are accompanied by smaller park areas; in contrast, the north and northwest have larger park areas (Figure 5c). Similarly, the north and northwest of BBUA have better green space quality and significant spatial heterogeneity. Central parks consistently demonstrate better performance in terms of service coverage, accessibility, and frequency of access (Figure 5c).

3.3. Potential Urban Greenways System Patterns

We have identified potential urban greenways to accommodate diverse functions by linking six park functions with transportation swipe card data using the least-cost method, as illustrated in Figure 6. Significant disparities were found in the greenways network in relation to various park functions, providing a range of greenway development options for the distinct needs of residents (Figure 6). All greenways with different functionalities have been planned, spanning a total of 1566.36 km and capable of encompassing 93.88% of the parks (Figure A7). Spatially, park greenways with integrated functions (Figure 6) are densely concentrated in the north and east, with priority given to connecting Chaoyang, Jintian, and Moqiao parks. A total of 15 greenways are in the works, covering 235.15 km (Table 3).

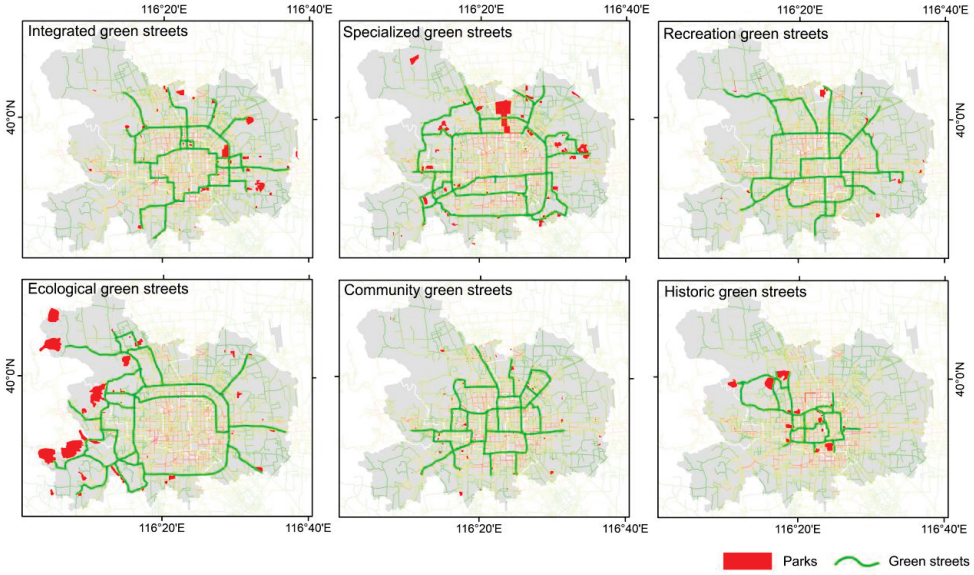


Figure 6. Greenways planning for different park functions. (Using spatial information platforms, we spatially visualized the spatial patterns of different greenways and their spatial distribution differences).

The specialized park greenways aim to connect sports, camping, and music parks primarily located in the outer ring of BBUA's Olympic Park, which spans a total of 318.36 km (Table 3). The recreational park greenways in the central area exhibit radial patterns and have an average length of 17.92 km per greenway (Table 3). The ecological park greenways (Figure 6) are concentrated in the northern and fringe areas, boasting the longest span of greenways, totaling 350.16 km. Conversely, the community park greenways are primarily located in the central area, with the highest number of greenways at 19 and an average span of only 13.08 km (Table 3). The historical park greenways (Figure 6) are also heavily concentrated in central areas, with the shortest span of only 145.22 km. It is worth noting that the average distance of the greenways is only 10.37 km.

We counted the number of recreational passengers at a total of 1167 bus stops on the greenway and compared their travel patterns over the course of a week (Table A2). Our results showed that the planned greenway network can serve between 377,000 and 609,000 passengers per day, accounting for approximately 34.39% to 35.92% of the total recreational volume (Table A2). The number of recreational passengers is particularly high on weekends. Public passengers have greater access to greenways, thereby maximizing the intangible value and benefits of these greenways.

Table 3. The quantitative data related to the various functions of greenway planning were analyzed spatially.

Data Lists	Counts	Length (km)	Mean Length
Integrated parks (IP)	15	235.15	15.68
Specialized parks (SP)	18	318.36	17.69
Ecological parks (EP)	18	350.16	19.45
Community parks (CP)	19	248.60	13.08
Recreation parks (RP)	15	268.87	17.92
Historic parks (HP)	14	145.22	10.37
Total	99	1566.36	15.82

3.4. Obstacle Point Recognition

We further assessed the street-level green view index (GVI) within the network using a street panorama image dataset. Our goal was to identify obstacle points (non-greenways) in the network, providing spatial-level action plans for policymakers to improve the integrity of greenways in BBUA. The results indicated that the average GVI in the study area is 10.78%, with significant spatial variability (Figure 7). Specifically, the central old city area features a mix of streets with varying GVI levels, highlighting the fragmentation of the greenway network. In contrast, connectivity of greenways is higher in peripheral areas, such as Haidian and Shijingshan districts. Notably, low-GVI streets are more prevalent in the southern regions, and main roads and ring roads in BBUA often exhibit poor GVI performance.

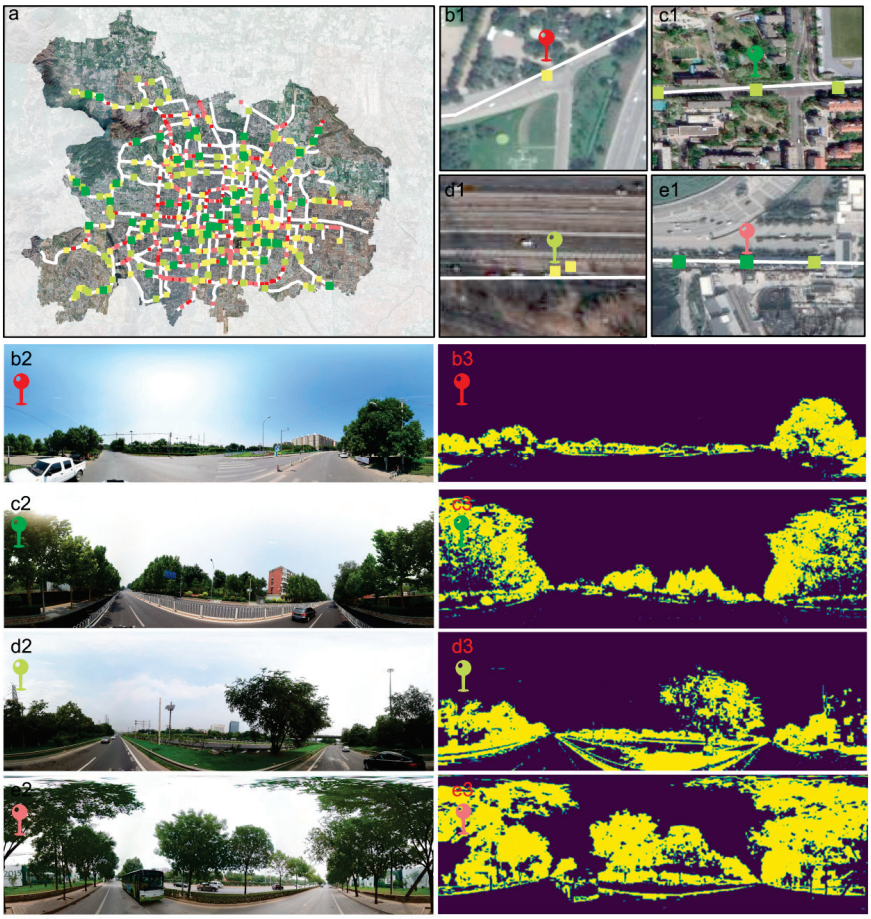


Figure 7. The performance and spatial distribution of the green view index (GVI) in relation to planned greenways are illustrated through panoramic images across four distinct cases. (**a**) Spatially explicit map regarding green view index in planning greenways; (**b1–b3**), (**c1–c3**), (**d1–d3**) and (**e1–e3**) present four different group of panoramic street images and their corresponding green visibility maps.).

4. Discussion

4.1. Implications of Our Study for Urban Greenway Identification

In this study, we employed a user mobility-based framework to identify greenway networks (Figure 2) networks within the BBUA, conceptualizing a comprehensive network blueprint that encompasses 93.88% of urban parks and spans a total of 1566.36 km (Figure 6 and Table 2). Our endeavor sought to interlink each green park in the urban area, forging an effective and accessible network pattern, which amplifies the bus passenger participation (Figure 6). This, in turn, increases the value of ecosystem services of urban greenery, such as stress relief, vision protection, and mental health [3,13]. The greenways engender a symbiotic relationship between ecosystems and well-being [57], fostering a harmonious coexistence between people and nature [58]. Furthermore, this study embraced the concept of versatile greenways, incorporating recreational, ecological, historical, and various other functions to cater to the diverse needs of stakeholders (Figure 6). Multi-functional greenways can energize and personalize cities. In addition, the revitalization and blueprinting of urban greenway are subject to a series of influences, including land valuation dynamics [59], resident preferences [60], and the delicate balance between environmental sustainability and socioeconomic imperatives [61].

We selected Beijing as a case study area because greenway planning is in full swing here. The Beijing government aims to create multi-level, multifaceted greenways that integrate human activities with the natural landscape in Beijing. The 2023–2035 Beijing Greenway System Special Plan proposes to build greenways that synergistically include elements of commerce, ingenuity, and art [62]. In addition, greenway policymakers have attempted to rely on greenway networks to mitigate inequities in human exposure to green space [1]. Greenway construction is also an integral part of an ecological and sustainable city [63]. The greenway network we planned can be considered to maximize passenger access to street greenery. The results showed that although the total length of the network is only 1566.36 km, it can be accessed by approximately 33.39–35.92% of bus passengers (Table A2). The on-street system provides a green and low-carbon mode of travel, and passengers are more likely to interact with the outside scenery [53]. In addition, Beijing's greenway system, planned to span more than 5000 km, aims to connect urban and rural areas. The extension of greenways in urban fringe zones augments connectivity [64] among wildlands, national reserves, and forested areas, thereby enhancing solutions for nature-based ecosystems [65], biodiversity [26], and human well-being [57]. This extensive network has also has the potential to alleviate the urban–rural divide and reduce inequalities in green space access [62]. Our results indicate that some greenways, such as the circular arterial, are included in Beijing greenway planning practices. However, greenways in central built-up areas are often overlooked by policymakers (Figure 7).

We described this framework as a multi-source big data-driven framework, which contains big data on transit trips and user reviews (Figure 2). User-based big data can capture stakeholders' intuitive experiences of greenways [27]. Here, we consider the recreational mobility patterns of more than ten million people from bus transportation datasets, and assesses the exposure level of park green spaces based on the integration of social media and geospatial data (Figure 2). In contrast to conventional methodologies, the utilization of big data in greenways planning offers a robust approach, underpinned by extensive samples of human behavioral patterns (Figure 3). Our framework endeavors to yield systematic outcomes while prioritizing the optimization of human well-being (Figure 6).

Street vegetation has been widely acknowledged to amplify leisure and verdant physical engagements, and augment the ecological integrity of urban surroundings [66]. As evident from our results, based on Baidu panoramic imagery, persisting issues such as greenway disruptions and congestion remain prevalent (Figure 7a). Beijing's urban blueprint laid out by the Beijing municipal authorities, emphasizes the imperative of factoring in greenway connectivity and coherence throughout the urban rejuvenation and shantytown reformation endeavors (https://www.beijing.gov.cn/). Serving as the vanguard city in the nation's drive for building reduction, Beijing has downsized urban and rural construction land by a stagger-

ing 110 km^2 as of June 2023 (https://yllhj.beijing.gov.cn), as part of its green development and carbon neutrality aspirations. In addition, we also emphasize that images of the city, such as street panoramas, surveillance cameras, and tourist-sharing images, will play an increasingly important role in urban greenway planning.

4.2. Limitations and Uncertainties

Here, we initially planned multifunctional greenways leveraging multi-source big data, including geographic information data, remote sensing data, and review data (Table 1). Although the ample sample size provides scientific and credible research results, this work still faces several challenges. The redundancy and representativeness of indicators within the green space exposure assessment framework need to be examined to ensure the reliability of the "3A" framework. In terms of data, our focus solely on greenway planning along bus routes limits the potential for greening non-bus routes, such as private and internet cars. We also did not include non-green parks in the scope of our study, such as car parks and commercial parks. We have given greenways a narrower definition that excludes walking and forest greenways. Filtering recreational travel patterns from traffic travel data remains challenging due to the unpredictable travel characteristics of some passengers caused by work. Additionally, studies have shown that GVI extraction based on deep learning algorithms and convolutional neural networks is more convincing [67]. However, this study only used a threshold model to consider time efficiency (Figure 7).

Spatially, our study area was solely focused on the urban area of Beijing, without considering the wildland–urban interface [68], due to the spatial constraints of geographic information data. Cross-regional metacoupling processes based on tourist mobility were not further considered in this study [69]. Furthermore, greenways under sustainable cities encompass various aspects including low-carbon, water permeability [70], stormwater management, and community adaptability [71]. The assessment of greenway performance still requires field surveys to obtain credible data based on stakeholder interests [39]. These challenges need to be addressed in future research; nonetheless, we offer a new perspective on planning greenways in urban areas.

5. Conclusions

Here, we introduced a greenway identification framework, which incorporates park green space exposure and user-based bus transportation flows. Our results showed that the greenways network planned in BBUA spans 1566.36 km, covering 93.88% of the parks and encompassing six functions. This network can serve 34.39% to 35.92% of bus recreation passengers, with this ratio tending to be higher on weekends. However, we found that the greenway network is unconnected, especially in the central built-up areas and the southern trunk road. These obstacle points should receive focused attention from urban planners to build robust and highly connected greenways. We presented an efficient user-based framework for greenway planning in urban areas, which provides a new perspective on potential urban greenway identification.

Author Contributions: T.L.: Conceptualization, Methodology, Software, Visualization, Writing—original draft. L.Y.: Conceptualization, Supervision, Funding acquisition, Writing—review and editing. X.C.: Funding acquisition, Methodology, Writing—review and editing. Y.C. (Yunmiao Chen): Data curation. X.L. (Xiaomeng Li): Data curation. X.L. (Xinyi Liu): Data curation. Y.C. (Yue Cao): Review and editing. F.Z.: Methodology. C.Z.: Review and editing. P.G.: Review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Key R&D Program of China (2022YFE0209400) and the Tsinghua University Initiative Scientific Research Programs (20223080017); China Postdoctoral Science Foundation (2022M711755).

Informed Consent Statement: All participants involved in this study provided their informed consent.

Data Availability Statement: The POI and AOI data related to Beijing's parks, the road network with topological relationships, street panoramic images involved in this study, and all Python codes are

available at 10.6084/m9.figshare.25358113. The bus traffic data for the week of February 13th to 19th, 2023 in Beijing and other data used in this paper are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that would have influenced the work reported in this paper.

Appendix A. Accessibility Analysis of BBUA

The accessibility of 331 parks in BBUA is an important data input for the "Availability–Accessibility–Adaptability" (3A) assessment framework. Park accessibility can reflect the frequency of human movement to green parks, thereby revealing the level of community exposure to park green spaces. We aim to reflect accessibility performance by studying the connectivity costs of multiple origins and destinations in the study area's transportation network. Therefore, this study adopts an origin–destination (OD) cost matrix model, which can be fully implemented in ArcMap (https://arcgis.com).

The workflow of this study began with the retrieval of 2023 road data for Beijing from the OpenStreetMap platform (https://openstreetmap.org/). This dataset encompasses roads of various grades, ranging from highways to sidewalks, with the vector road data existing in a non-topological state. To construct a multi-grade road network structure, we extracted three levels of road networks based on road width and driving speed criteria (https://www.mot.gov.cn/). The first-level road network comprises highways and national roads, the second-level road network includes expressways and main roads, while the third-level road network encompasses motor vehicle streets and similar thoroughfares. Subsequently, to establish the topological relationships of the road network (Figure A1), we conducted a series of network repair procedures, including road buffering (10 m), extension, linking, and segmentation, all of which are accessible within the ArcMap editor tools.

We established a multi-level road network for the study area with topological relationships (Figure A1), where each road node is connected and traversable. Following the creation of the feature dataset, we manually examined the usability of the road network once more and retained the topologically connected road network database as a backup (Figure A1). We assigned speed limits to the roads: first-level roads at 70 km/h, second-level roads at 50 km/h, and third-level roads at 30 km/h (https://www.mot.gov.cn/). Finally, we obtained the accessibility raster dataset based on the newly created origin–destination (OD) cost matrix, and this result was spatially visualized in Figure A1.

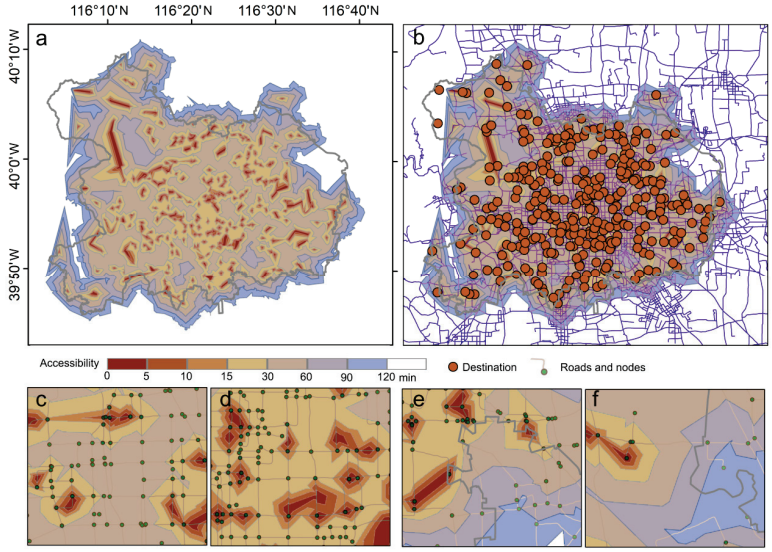


Figure A1. The accessibility and topological patterns of BBUA. (**a**) Spatial visualization of accessibility in BBUA. (**b**) Road network patterns and spatial distribution of parks. (**c**–**f**). are examples of road network topological relationships.)

Appendix B. Calculating Green View Index Based on Street Panoramic Images

The acquisition of street view panoramic images was conducted utilizing the street view imagery (SVI) from the Baidu Street View service. To ensure a comprehensive coverage while preventing data redundancy, sampling points were systematically generated along the road network at intervals of 50 m. These intervals were determined based on the road topology information provided by OpenStreetMap (OSM). For the extraction and retrieval of the images, a Python script was developed leveraging the Baidu Street Map API. The script systematically requested street view images corresponding to the predefined sampling points. Each request to the Baidu Street View service API followed the format: http://api.map.com/panorama/v2?ak=YOUR_KEY&width=WIDTH&height=HEIGHT&location=LON,LAT (accessed on 25 September 2024).

Where YOUR_KEY is the API key provided to authorized users, and WIDTH, HEIGHT, LON, and LAT were parameters set according to the requirements of our analysis. Through this automated process, we successfully acquired a total of xx street view images, which were subsequently utilized for detailed streetscape analysis. Here, we constructed a decision tree to evaluate the green view ratio indicators of street panoramas (Figure A2).

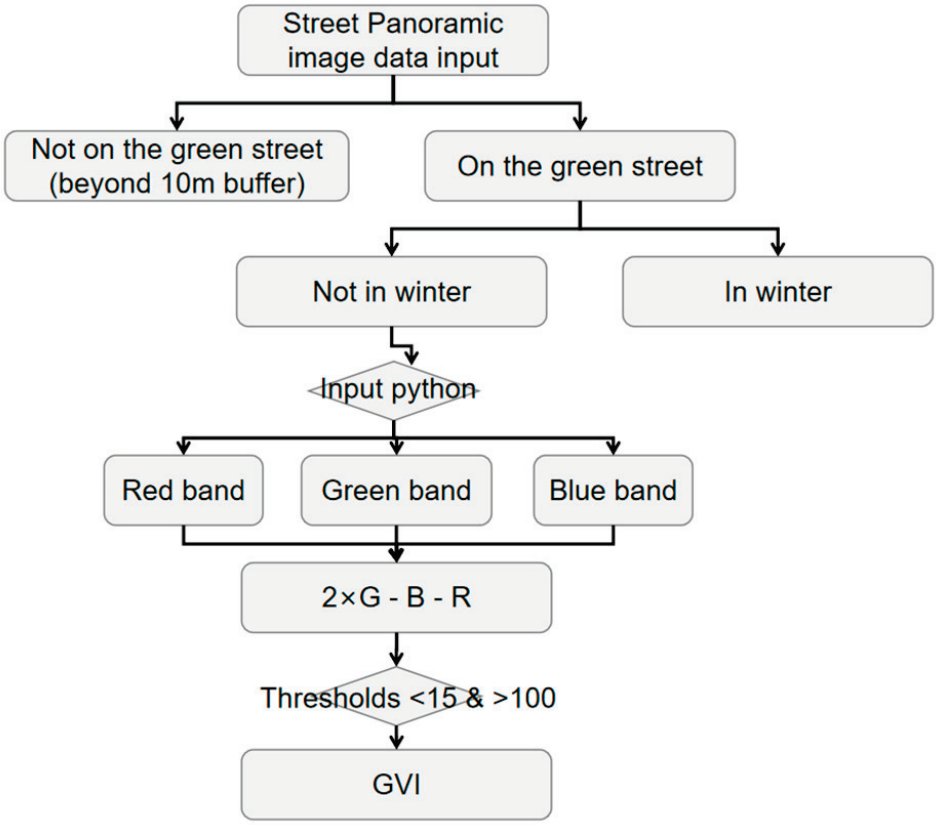


Figure A2. Decision tree for calculating GVI. (In this study, we employed an empirical model to assess the green area and its proportion in street panorama RGB images. Compared to image recognition-related deep learning algorithms, such as semantic segmentation and convolutional neural networks, the advantage of this algorithm lies in its ability to provide quick and efficient results. We calculated the GVI for each image and used a threshold to determine the green area on the photo. After multiple iterations, the optimal threshold for this model was determined to be between 15% and 100%).

Appendix C. Appendix Figures

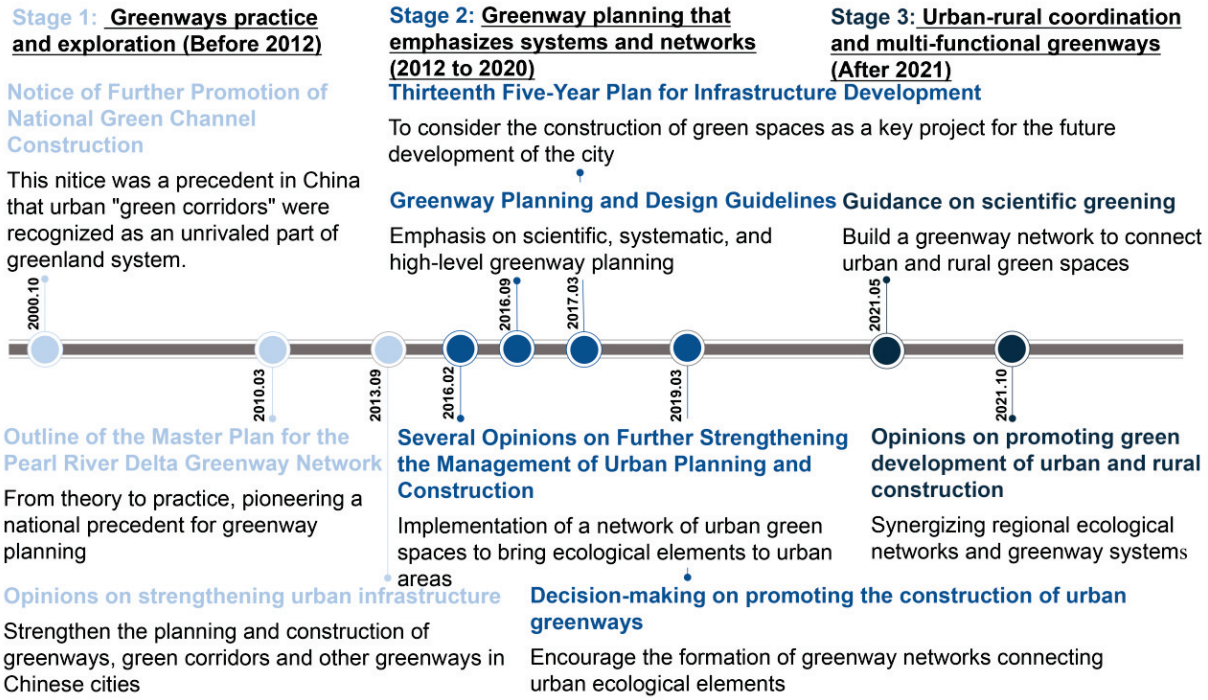


Figure A3. The timeline evolution of China's greenway planning policies: a three-stage development. (We reviewed the greenway planning policies issued by the Chinese government and classified them into three stages, each with unique greenway themes and objectives. As time passed, there was a growing emphasis on systemic, organizational, and integrated approaches.).

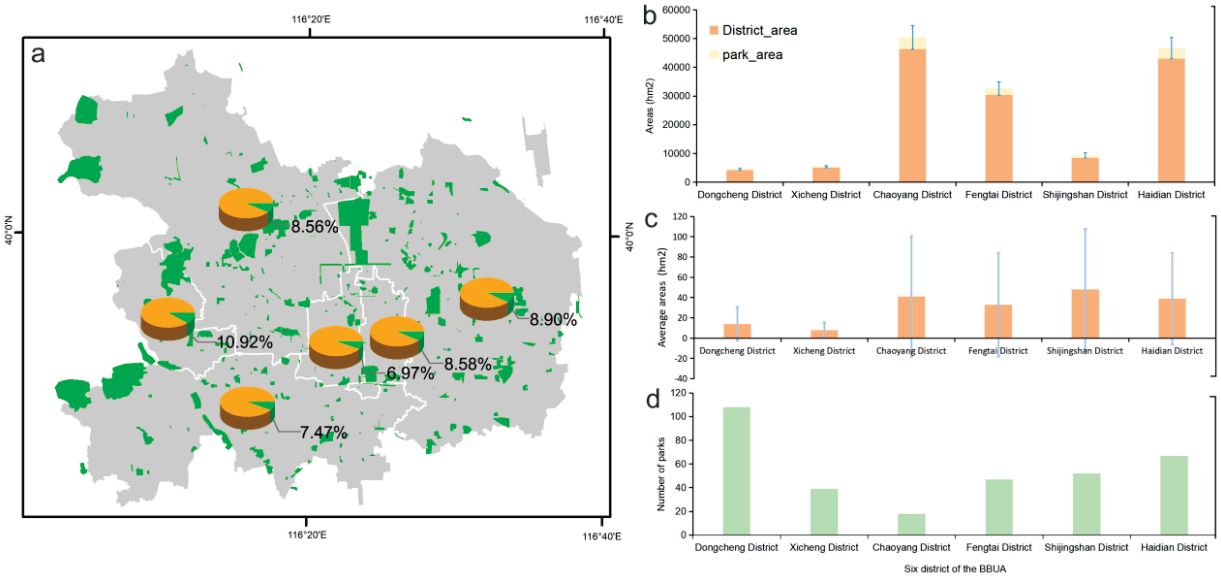


Figure A4. Essential quantitative green park information about sub-administrative in BBUA. (We calculated the green space area related to parks in each sub-administrative area of BBUA, which is crucial for implementing green space planning and construction projects based on green equity and accessibility. (**a**) The spatial pattern and percentage of park space in six districts. (**b**) Total area of the park. (**c**) Average areas of parks. (**d**) The number of parks in six districts.).

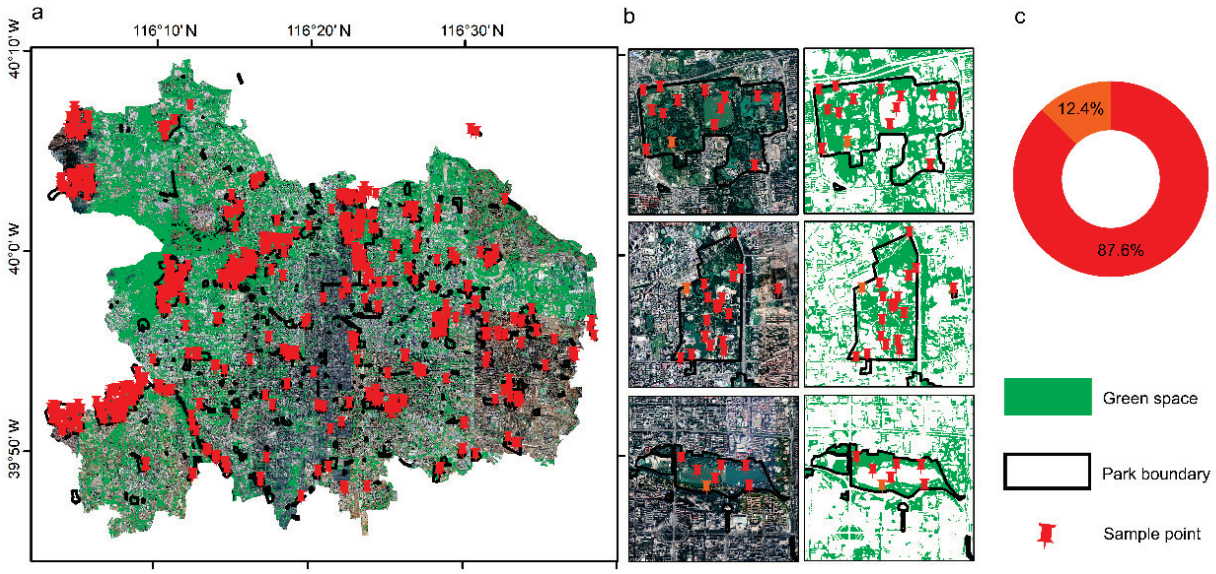


Figure A5. The spatial distribution pattern and three case studies of the accuracy assessment of park green lands in BBUA. (Here, we used a random sample point model to calculate the accuracy of park green spaces. We randomly generated 500 sample points within the parks and compared them with Google Earth images. The accuracy of manually marked park green lands was assigned a value of 1, resulting in a final accuracy of 87.6%. The reliability of the accuracy of our park green space data supports our next research.).

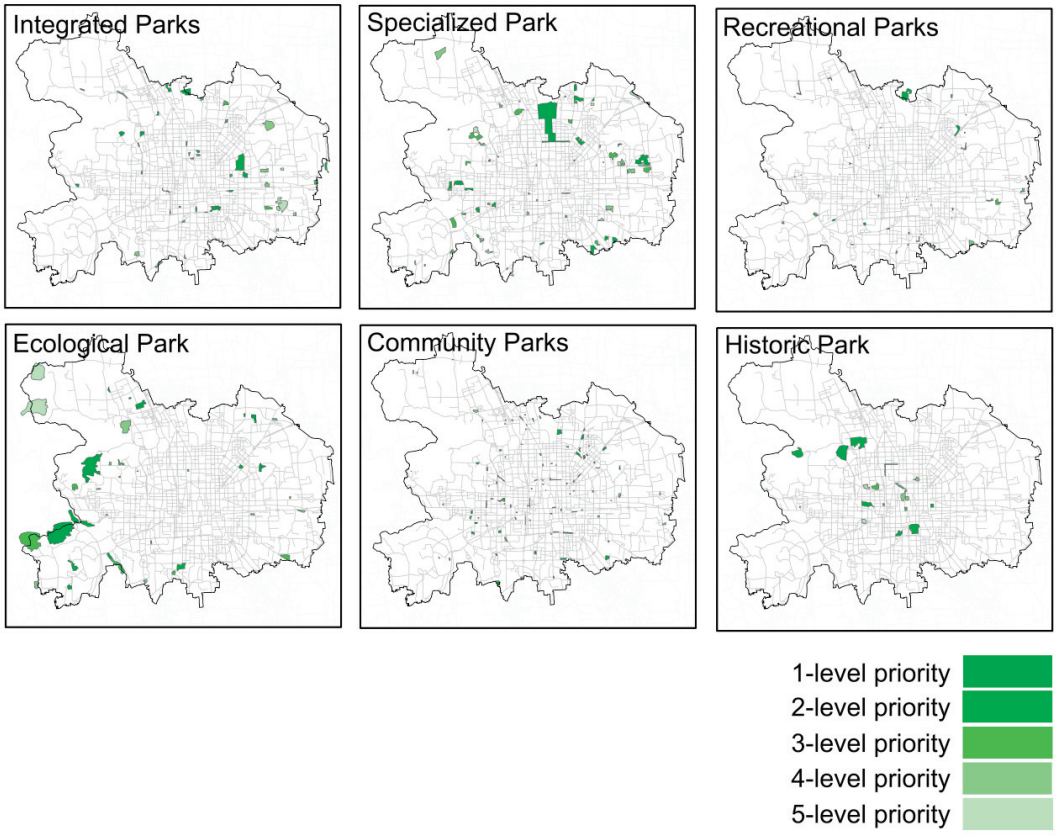


Figure A6. Planning the priority of greenway carrier. (In this study, we divided the exposure of park green spaces into five levels using a natural break point method. The first two levels are used as carriers for linking the greenway network.).

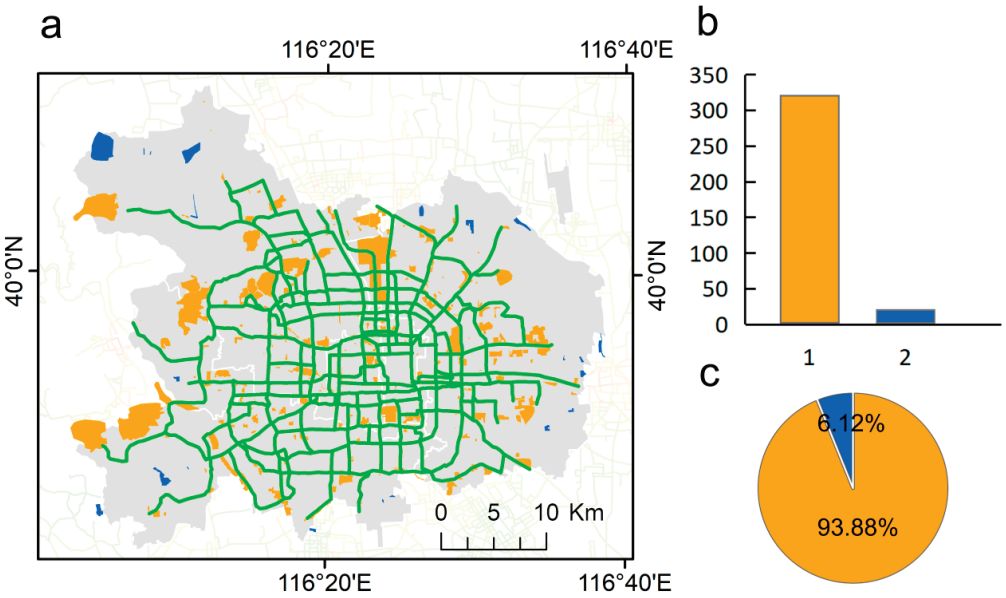


Figure A7. Planning the green streets system involving accessible and inaccessible parks. (Through overlay analysis and walk buffs based on a 15-min catchment area, we assessed the accessibility of green parks reached by planned greenways. (**a**). Spatially-explicit map concerning accessible and inaccessible parks. (**b**). Number of accessible and inaccessible parks. (**c**). Percentage of accessible and inaccessible parks).

Table A1. Service area corresponds to six different types of parks. (We reference the official national standard, namely the Basic Requirements of the Park Service (https://openstd.samr.gov.cn), to determine the areas of park service.).

Parks	Service Areas/m
Historic park	2000
Community parks	500
Ecological park	800
Recreational parks	300
Specialized park	1000
Integrated parks	1500

Table A2. Number and share of recreational passenger at bus stops corresponding to the green street network. (/per).

Parks	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Historic park (/per)	28,970	44,730	44,662	45,518	42,970	32,546	39,184
Community parks (/per)	69,391	108,474	108,168	111,152	105,762	78,040	94,156
Ecological park (/per)	58,958	94,880	94,952	96,324	92,978	69,532	78,088
Recreational parks (/per)	83,620	134,642	133,910	136,318	129,764	95,488	113,796
Specialized park (/per)	60,306	96,416	95,162	97,642	93,168	69,550	81,846
Integrated parks (/per)	75,428	118,498	119,712	121,824	117,430	85,334	101,098
Total (/per)	1,048,575	1,671,566	1,671,084	1,697,340	1,654,358	1,251,630	1,422,150
Historic park (%)	2.76%	2.68%	2.67%	2.68%	2.60%	2.60%	2.76%
Community parks (%)	6.62%	6.49%	6.47%	6.55%	6.39%	6.24%	6.62%
Ecological park (%)	5.62%	5.68%	5.68%	5.67%	5.62%	5.56%	5.49%
Recreational parks (%)	7.97%	8.05%	8.01%	8.03%	7.84%	7.63%	8.00%
Specialized park (%)	5.75%	5.77%	5.69%	5.75%	5.63%	5.56%	5.76%
Integrated parks (%)	7.19%	7.09%	7.16%	7.18%	7.10%	6.82%	7.11%
Total (%)	1	1	1	1	1	1	1

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Perspective

A National Vision for Land Use Planning in the United States

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Abstract: The time is nigh to organize the physical landscapes of the United States under a unified land use policy and planning framework. As human populations have steadily grown, so has the urgency for agencies to plan for land uses at broader scales to overcome continued jurisdictional fragmentation and achieve sustainable and environmentally just landscapes. This paper introduces a vision, conceptual approach, and implementation strategy that applies ecoregions and proposes a unified framework for land use planning and regulation in the United States. The Sustainable Ecoregion Program (SEP) is designed to enable local landowners; public stakeholders; other land users; and state, regional, tribal, and national natural resource professionals to set and achieve future desired conditions for sustainable land uses across landscapes. The objective is to outline a comprehensive and sustainably just solution to the recurring problem of managing conflicting land uses in the face of continued degradation and multiple land tenure systems. The SEP will determine how much of the physical landscape will go to developed, agricultural, and natural landcover types. The framework includes recognition of level III ecoregions as primary boundaries, proposed secondary boundaries and shapes to enhance connectivity and movement across landscapes, a proposed structure for the environmental governance and co-management of landscapes, and definitions of physical landscape types. The benefits and challenges of the SEP are discussed. The outcomes of the SEP include ecological integrity, sustainable land use management, deliberative democracy, just sustainability, and improved quality of life for residents of the United States.

Keywords: agriculture; connectivity; development; ecoregion; environmental governance; human well-being; land use; natural landscapes; sustainable ecoregion program

1. Introduction

> "The national government has not and does not practice what would constitute national land use planning as that term is commonly understood in the United States and abroad" [1] (p. 446)

> "Land use planning and regulation should be one of several mechanisms we can use as we struggle to learn and embrace what is good and right" [2] (p. 9)

Why is there no national, comprehensive land use policy or land use planning framework for the United States? There are many reasons why the United States lacks such a policy, including colonial, constitutional, historical, cultural, and economic traditions and factors [1,3]. Looking at the history of the nation and its progenitors before independence, we are reminded that the 13 colonies had governing institutions in place before there was a central government. There were many small and large farms in operation and production

before the United States' constitution was ratified. The colonial farmers and early frontier settlers had established land use practices and traditions that predated the national government. Before the arrival of settlers, the continent's indigenous peoples had done the same but in different ways. Land uses have shifted overtime as the continent moved from indigenous stewardship to settler colonial stewardship. For example, during indigenous land stewardship, fire was used as a management tool throughout the United States, and the harvesting and sharing of wild bison (*Bison bison*) were cultural practices necessary for food security. This land use regime later shifted to fire exclusion, timber management, and domestic cattle production under the management of the settlers. As they colonized, many forms of indigenous land uses were displaced, and the frequency of natural fires on the landscape was interrupted. There is no blank canvas on which to begin, although there is a rich and sorted history, both oral and written, of land use predating the United States' federal government. Natural history in the United States has a standpoint perhaps best described by ecoregions.

Today, there are substantial, and some will argue insurmountable, legal precedents, political lobbies, and value-driven barriers to developing and implementing a centralized national system of land use planning and management to include private lands and urban developments. Private land use rights in the United States are culturally and legally enshrined [4]. Approximately 60 percent of the land base of the United States is privately owned, and over 60 percent of those private lands are farms, ranches, and forests [1,5]. Private lands and American Indian reservations in the United States hold substantial amounts of economic, social, and ecological value and must be factored into all land use models and plans (both current and future) that are designed for sustainability and human well-being. On the other hand, private land tenure poses an obvious challenge to centralized land use planning and policy. Private property rights and tenure probably are one of the most important reasons why past efforts at regional, multi-state land use planning and regulations failed in the twentieth century.

The reasons for the lack of a national policy framework for land use include the nation's propensity toward private market and private land ideologies, preferences and values for local control over higher-level controls [6], and the geographical scope of the continental United States, not to mention the combined area of Alaska, Hawaii, and other dispersed U.S. territories. One rationale for having no national land use policy is the sheer size of the country; perhaps the nation is too large with too much variability to centralize land use planning within the federal government [1]. However, we suggest the nation's size and ecological and social diversity are assets, not hindrances, to improved land use management and societal well-being.

In the late 1930s and again in the early 1970s, there were efforts to establish national-level policies for land use planning and management. The first attempt grew out of President Roosevelt's New Deal-era Agricultural Adjustment Administration and was designed to alleviate rural poverty among the nation's farmers [3,7]. The Secretary of Agriculture reorganized the United States Department of Agriculture (USDA) in 1938 to bring order to Roosevelt's farming programs [7]. The new approach included county-level planning for agricultural land uses. Counties are local land-based governments within the states, and this agricultural planning initiative formed a vast network of thousands of community- and county-level planning committees throughout the rural United States, "designed to serve as conduits of data and policy-making from the grassroots to the USDA, and then back to the grassroots" [3] (p. 75).

Local farmers, working with extension agents and scientists from state and federal agencies and the land grant colleges, created countywide maps of agricultural land uses. The experts did not lead the process; however, the experts supported the process and

advised the local planning committees as they made decisions and maps based on local farming knowledge, experience, and needs [7]. As the process, discussions, and planning unfolded among the local committees, desired changes to land uses were incorporated into revised county maps, and the USDA checked all its proposed actions against the county maps. No federal funds were provided for any agricultural land uses that were not consistent with the county land use maps.

Despite imperfect representation on the local committees and disconnects between farmers' knowledge and technical and scientific expertise, this federal-county agricultural planning system mobilized thousands of rural peoples and government experts into a large-scale participatory and collaborative planning effort [7]. At one point during the program, 2200 counties had organized planning committees. The system was on track to harmonize local interests with national interests, achieve land use and economic benefits, and improve agricultural policies. Then, internal opposition and global geopolitics intervened [3,7]. After substantial political support for the new program, the American Farm Bureau Federation began to lobby congress against its continued funding in an attempt to reclaim local control from the community and county planning committees. The program ceased in 1942 with the onset of World War II. Farming in the United States became highly profitable during the war, without a need to plan for or change land management practices; the rural poverty crisis for the nation's farmers ended, and with it so did the drive to reform land use planning and policy in rural America [3].

In the early 1970s, the inspiration for national-level land use planning began in the legislative branch of the federal government, not with the president, as certain politicians and lawmakers joined the march of environmentalism sweeping the nation [3]. The context for national land use planning and policy had changed: "National planning in the 1930s . . . centered on farmlands and the experiences of farm people. National planning in the 1970s, however, was a response to rapid urban growth and the disappearance of open space; it centered on urban land and the experiences of urban people" [3] (p. 77). In 1970, Senator Henry Jackson proposed Senate Bill S. 3354, a largely procedural National Land Use Policy Bill, to establish order in responding to a multitude of environmental conflicts coming before his chairmanship of the Senate Interior Committee [3].

The proposed Senate Bill S. 3354 of 1970 largely focused on data collection and agency coordination, with federal funds going to the states to classify lands and write state land use plans designed to direct land use decisions by the states [8]. Federal allocations of funds for land management would have been determined according to the states' published plans, with little to no substantive protections prescribed for the environment. President Nixon and Senator Muskie, respectively, joined Jackson's proposal, adding requirements of environmental reviews; carefully planned land developments (Mr. Nixon); and more rigorous environmental protections for wetlands, flood plains, and important agricultural lands (Mr. Muskie). Congress was not convinced that adding teeth to what was once a procedural bill would have been politically viable; therefore, they failed to pass the bill and all of the iterations of the bill congress deliberated during 1971 to 1974. The revised bill never reached the president's desk for signature [3].

Land use planning and regulation in the United States remain generally decentralized and locally based, and continue to favor local, and sometimes state, jurisdictions while avoiding national land use regulations outside of publicly owned lands [1,3,6,9]. Despite its history, realistic challenges, and political inertia, the United States should seriously revisit a national land use policy and broad planning framework implemented through a mix of top-down national policy and bottom-up local planning and decision-making. Article I, Section 8 of the United States Constitution grants to the congress the power to regulate commerce among the states (i.e., the commerce clause). Kayden argued, "because the use of

land by one party inevitably affects others and because such others can reside across state lines from the initial user, the constitution axiomatically grants the national government the power to control local land use" [1] (p. 451) and [7].

For example, consider California's land use restrictions on the construction of new homes in sensitive coastal areas; new home construction and its environmental impacts, such as carbon emissions, were not eliminated by California's restrictive regulations but merely moved elsewhere to communities with a surplus of land, including Las Vegas, Nevada and Houston, Texas [10]. A completely local perspective and authority for land use policy and regulation is inadequate for producing benefits from lands for the wider society, economy, and ecology of the United States. Thus, the time is nigh to organize the physical landscapes of the United States under a unified land use policy and planning framework.

Environmental problems in the United States, resulting from managing a highly connected landscape as a bundle of independent fragments, are not going away [3,11]. Fragmentation and a lack of focus on connectivity are not the only sources of environmental and social problems. A lack of regional and national planning policies for land uses and an over reliance on local planning authority and city zoning laws have created and exacerbated these issues [1,6,12]. There are a number of pressing problems in the United States and elsewhere that justify reopening a dialog geared toward land use planning and policy at the national level. For example, planners, regulators, and land managers face ubiquitous non-point sources of water and air pollution, resource scarcity (e.g., water in western states) [3,13], urban sprawl and unaffordable housing [1,6,12], environmental injustices and social disparities in health related to the environment [14–16], social vulnerability to flood exposure [17], and the climate crisis (e.g., imminent human migration, displacement, and resettlement caused by changing environmental conditions, extreme weather events, and environmental disasters) [18–20].

The wisdom of landscape ecology; the principle of connectivity; and the push towards interdisciplinary, holistic, and landscape-scale planning each support the involvement of higher-level regional and national land use planning in which governmental experts, agency departments and bureaus, tribes, and community residents must participate [3,11,21,22]. These important concepts are brought together in ecoregional planning, which is organized around geographically and ecologically mapped areas of land called ecoregions [23,24]. We use ecoregions as the primary basis of our proposal for establishing a national land use policy and planning framework for the United States.

2. Background

2.1. Rationale

Outside federal and state lands, land use planning in the United States has primarily remained the purview of city, county, state, and tribal governments. These levels of organization are important and must retain a strong voice and hand in land use policy, although a wider perspective is also needed to account for the vast ecological and societal diversity of the nation. There is a need in the United States for an appropriate organizational and regulatory framework to determine how much of the nation's physical landscapes should go to intensive and moderate human settlement (i.e., urban and suburban), large- and small-scale farming (i.e., various agricultural areas), and natural areas (e.g., national and state parks, wildlife refuges, national forests, multiuse rangelands, urban forests).

A better and more carefully planned organization of the nation's physical landscapes holds high potential to enrich human experiences, improve well-being, achieve social equity, and ensure ecological integrity [25]. Different land uses do not always conflict and may be complementary. For example, some agricultural lands provide ecological services and are important for biodiversity conservation. Different landscapes and places are

connected through human cultures and technologies, belief systems, livelihoods, lifestyles, and relationships with the land and land managers, both public and private [25–28].

Managing large, connected landscapes as individual fragments and for single species and single economic pursuits has been problematic [11]. However, we do not wish to overemphasize, beyond what we described in the introduction, environmental problems, land use conflicts, and degradation as our primary motivation for proposing a national land use policy, nor do we propose a threat to private landownership. Healthy and trusting partnerships and collaborations with our nation's private landowners are essential to any form of landscape-scale planning and policy. Likewise, we do not propose a threat to tribal sovereignty and indigenous rights to lands and resources. Indigenous peoples' relationships with their territories are deep rooted and substantially older than land-based relationships of settler colonialists in the United States. The land use policy and planning framework proposed here includes tribal nations and recognizes the painful history of colonization and land dispossession for the indigenous peoples of the United States.

We emphasize and present a solution that should improve human well-being and reduce environmental injustices through better landscape organization and land use regulation grounded in an alternative, hybrid form of governance. Natural resource decision-makers and managers will continue to fail to set and achieve future desired conditions for sustainable land use without national support and funding that is tied to a unified land use planning and regulatory framework, including local and regional participatory planning with legal decision-making authority [29]. Hoŕelli defined participatory planning as "a social, ethical, and political practice in which individuals or groups, assisted by a set of tools, take part in varying degrees at the overlapping phases of the planning and decision-making cycle that may bring forth outcomes congruent with the participants' needs and interests" [30] (p. 611). In this paper, we add policy and regulations for land use to Hoŕelli's list of outcomes of participatory planning. Continued failure to plan for and regulate landscape uses, land use changes, and land management in a comprehensive and well-organized way will perpetuate a myriad of environmental impacts [31] and a waste of resources, time, and quality of life for all citizens of the United States.

2.2. Purpose and Method

The purpose of this perspective paper is to open a discussion on and provide a vision and implementation strategy for national land use planning and policy based in the co-governance and co-management of landscapes. Our vision includes (1) building a national framework for land use legislated and funded by the United States congress; (2) decision-making roles for local and regional landowners, tribes, residents, and other beneficiaries and stakeholders; (3) ecoregional comprehensive land use plans; and (4) advisory and support roles for all levels of government agencies, including tribes, scientists, land developers, and non-governmental organizations in the United States.

We outline a Sustainable Ecoregion Program (SEP) for natural resource professionals and local and regional planners to organize urban and other developed lands, agricultural lands, and lands with largely continuous, natural landcover types[1]. We apply the ecoregion concept as the central organizing feature of the proposed framework because ecoregions delineate patterns of terrestrial and freshwater biodiversity and the distinctive ways in which humans have used ecoregions through time [23,33].

We present the framework as an organizational tool to alleviate the pressures of development and agriculture while capitalizing on the strengths and benefits of these legitimate land uses. The SEP will enable planners, managers, tribes, citizens, and regulators to create formal partnerships and collaborate across jurisdictional boundaries and levels of government. To implement the proposed framework, we propose a representative co-management

system with regulatory and decision-making authority at local levels combined with national legal direction and substantial coordination among local, state, tribal, and federal participants.

Through this perspective, we showcase the historical and current developments in the field of land use planning specific to national-level planning and policy in the United States. An emphasis is placed on future directions in the field and the coauthors' personal and professional assessments of the topic area [34]. The method is used to present our vision, goals, objectives, and strategies for establishing the SEP in the United States, supported by and in the context of the existing literature.

We have included a targeted review and synthesis of the peer-reviewed published literature and other credible sources, without specific time bounds on the date of publication. The coauthors' points and arguments in the paper are supported by interdisciplinary but closely related citations of the pertinent literature. In a large-scale comprehensive framework such as the proposed SEP, it is important to cover topics that go beyond conservation ecology and land use planning and delve into the human dimensions and social sciences to cover key socioecological and sociocultural aspects of land use planning. Thus, we include references and information on just sustainability and environmental justice in the context of sustainable urban development and land uses in developed areas with sociocultural connections to natural and agricultural areas. The literature review was not exhaustive or systematic but targeted and geared toward supporting our vision and implementation strategies for the SEP.

We did make an effort to include the recent literature in addition to the older sources from our personal libraries and records from past work. The coauthors have been developing this paper and its foundational ideas since 2007, which has required us to continually review and update the relevant citations. To give coverage to more current sources, we conducted a targeted search in Google Scholar using a range of 2021–2025 for the publication dates. The searches used specific search terms arranged in strings:

- Sustainable ecoregion program;
- Environmental justice and landscape management;
- How to balance development agriculture conservation;
- Balanced landscape planning for development agriculture conservation in the United States.

2.3. Vision, Goals, and Objectives

Biodiversity, environmental justice, and sustainable land use depend on professionals working across large landscapes and diverse social and ecological scales. The SEP cannot be successful on a continental scale and across jurisdictional boundaries without congressional support and funding; leadership and coordination by local, tribal, state, and federal governments; effective partnerships; shared goals and objectives; the extensive sharing of resources; and genuine collaboration and delivery across multiple scales [21,22,35,36]. When these conditions merge into a unified coalition, collective action for large-scale land use planning is possible [37].

The SEP will openly and fairly establish and guide a land use planning and decision-making process and a regulatory framework to involve land managers at all levels of government, including tribal nations, private landowners, non-governmental organizations (NGOs), and legislators at all levels of government. Representatives from these groups will serve as the SEP co-managers and will be trained and supported by governmental and university experts and scientists to understand, plan for, and provide ecological integrity, social equity, and human well-being [25]. The proposed SEP is grounded in five vision statements that serve as high-level, strategic planning goals for the program:

1. Landscapes and their configuration, including developed, agricultural, and natural landscapes, are fundamental for shaping human experiences and quality of life [25];
2. Governmental, tribal, and non-profit agencies are empowered to provide comprehensive leadership and services, balanced programs, and land management planning that is sustainable, equitable, and just;
3. All states, tribes, and the federal government recognize the importance of broad-scale, participatory, community-based, and shared management authority to achieve and maintain fair governance, just sustainability, and adequate resources for current and future generations;
4. The environmental design, planning, and management professions advocate for the public good and social and environmental responsibility [38];
5. Working together, legislators, federal and state natural resource professionals, tribes, and private landowners can design and implement a national system of sustainable land use planning and regulation under private, public, tribal, and common property ownerships [26].

The specific objectives of the SEP include: (1) organize all terrestrial landscapes and land use settings in ways that guarantee current and future human families, communities, and societies will be able to make a living from the land and experience greater well-being from landscapes and legal land uses; (2) center land use planning and policy on people and their quality of life to sustain social, ecological, and economic integrity across ecoregions; (3) improve the conservation of abiotic and biotic resources; (4) ensure diverse and healthy communities of plants, animals, and humans (e.g., biodiversity, food security, well-being); (5) make sustainable land use fair and just for all segments of society; and (6) secure life support systems into the future (e.g., clean air and water).

Like any other properly crafted vision, the ideals and goals of the SEP are aspirational and future-oriented and will be expensive. Working towards these ideals is domestically necessary and can be achieved by implementing these specific objectives, future strategies, and future desired conditions for different landscapes as determined and described in comprehensive land use plans for ecoregions developed by the SEP co-managers.

2.4. Landscape-Scale Approaches

Natural resource professionals increasingly recognize and emphasize a landscape-scale approach rather than planning for and managing single resources [22,24,39–42]. The management of single resources usually does not benefit broader ecological connections and social processes [25,43]. Sayer et al. [42] argued that the integration of agricultural and conservation land uses requires a people-centered approach applied at the scale of landscapes and relationships. Human relationships with places in the landscape are equally as important as the relationships among residents, landowners, and governmental land managers [27,44].

The proposed SEP aligns with planning and regulatory frameworks outside the United States, with examples being Namibia and Nepal, whereby natural areas are located within each ecoregion and complemented by community conservation programs and regulations for which activities can be performed on lands outside natural landscapes [45]. Some SEP ideals and principles presented here are shared by partnerships in the United States that emphasize the management of specific resources or in specific regions across boundaries at the landscape level. A non-exhaustive list of these initiatives is shown in Appendix A. For example, the Landscape Conservation Cooperatives Network (LCC) was a federal program in the United States involved with landscape-scale planning at the continental level and across political boundaries.

The LCC network was the first federal program in the United States focused on the connectivity and persistence of wildlife at the national level [46]. However, the LCC framework primarily was, and may continue to be in some places, a platform for enabling collaborative research partnerships and data sharing; it served scientific and organizational purposes dedicated to landscape-scale conservation and administration of related collaborative research [35]. The LCC structure relied on existing governance, served a non-regulatory function, and had no authority to set rules, desired conditions, or regulations for what and how many activities and land uses can be allowed to occur on the landscape.

The other initiatives and joint ventures listed in Appendix A emphasize land acquisition, scientific research, management partnerships, working with private landowners, and sharing resources and knowledge but have no rule-making authority. Without regulatory authority, it is difficult to consistently achieve land use planning goals and desired conditions. The SEP will have a regulatory function that goes beyond the initiatives and partnerships shown in Appendix A.

The conservation programs listed in Appendix A use boundaries equivalent to level I or II ecoregions or coarser. As such, we argue that these programs do not allow for the detailed management of unique ecosystems found across the United States. For example, the Great Northern and Gulf Coastal Plains and Ozarks LCCs are each comprised of at least eight different level III ecoregions [47]. With a coarse focus, it is likely some ecosystems are not included in local land use management plans, because the emphasis is more likely to be placed on systems that are rare or harbor endangered species [48]. The conservation of rare ecosystems and endangered species is imperative, although it is also imperative to effectively plan for and manage non-endangered species and more common landscapes, including farms and cities [39,49,50]. The SEP will allow for this by using level III ecoregions as the primary boundaries, and the co-managers will consider and account for level IV ecoregions when establishing secondary boundaries as needed.

2.5. Just Sustainability

Urban land use planning and municipal zoning frequently emphasize politics and economics rather than what is sustainable and socially and environmentally just for all people [6,51–53]. The American Planning Association has established principles for urban planning that can be adapted and used as part of the proposed SEP, especially in the context of planning for developed landscapes. "Smart growth is not a single tool, but a set of cohesive urban and regional planning principles that can be blended together and melded with unique local and regional conditions to achieve a better development pattern" [54] (p. 3). The smart growth approaches and policies for urban planning and development initiated in the 1990s [54,55] may still hold promise for improving lives, creating sustainable cities, and reducing urban sprawl but there has been considerable opposition and adverse outcomes in many communities related to smart growth principles and policies, including decreased property values, decreased availability of affordable housing, restrictions on uses of private property, increased sprawl, and other disruptions [12]. Land use policy and ecological design are linked to social and environmental injustices, particularly in and near developed and urban landscapes where a high density and diversity of people live [2,38,51,52,56].

Land use planning must be socially equitable and environmentally just to be sustainable [25,57]. By just, we mean fair, inclusive, and beneficial for all groups of people; by sustainable, we mean the creation and maintenance of conditions in which humans and land can productively coexist and support present and future generations, socially, economically, and ecologically. Environmental justice involves the fair treatment and meaningful

involvement of all people in the development and enforcement of environmental laws, regulations, and policies, regardless of their race, national origin, or income [58,59].

There are important linkages and synergies between sustainability and environmental and social justice that can be leveraged by policy-makers in a national framework for land use planning and policy [60]. The environmental justice concept has multi-level dimensions, giving it the potential to link local, state, and national land use jurisdictions. Environmental justice is "Predominantly at the local and activist level, a vocabulary for political opportunity, mobilization, and action. At the same time, at the governmental level, it is a policy principle that no public action will disproportionately disadvantage any particular social group" [60] (p. 155). Up until recently, the United States Government had policy and guidance in place to address and integrate environmental justice and the advancement of equity across landscapes and social groups, including Executive Orders 12898, 14008, and 13985 [61–64].

We can expect to see continued conversions of natural landscapes to urban and agricultural areas as the number of people increases, if we do not establish desired future conditions and make rules and regulations that disallow or limit certain activities within specified boundaries at different scales. The loss of natural landscapes correlates with declines in biodiversity, diminished ecosystem function, and decreased ecosystem services on which humans rely [65–67]. However, the conversion of naturally vegetated areas to urban areas, suburbs, and large farms is often completed with little consideration of the externalities or costs to the environment and society [65,68,69]. In the United States, the current system of land use planning and management is neither fair, environmentally just, nor sustainable, as the burden of these costs are most often felt in the near term by lower socio-economic classes and in the future by younger generations and those not yet born, who will have to cope with an environment where we have lost landscape connectivity and depleted our natural resources [70,71].

Environmental justice issues have been addressed by urban planners to varying degrees across the country. For example, community planners in California are doing a relatively good job of accounting for environmental justice issues in community plans [16], whereas urban forest planners across the United States have devoted less attention and detail to environmental justice goals, objectives, and strategies [15]. The proposed SEP will acknowledge and integrate environmental and social justice into land use planning and regulation to address historical and current environmental injustices. To align with Agyeman and Evans' [60] (p. 157) argument for a balanced approach, the SEP will reframe and refocus environmental justice and sustainability in terms of "just sustainability"; just sustainability is a holistic model of land use planning that highlights quality of life, present and future generations, justice and equity in resource allocation for all people, and living within ecological limits. Without these factors, disadvantaged communities and underserved social groups in the United States will continue to experience entrenched disparities and other injustices.

The national examples of land use planning efforts from the 1930s and 1970s hold lessons for success and challenges to be overcome. The New Deal-era agricultural planning movement showed that the federal agencies and local land users can mobilize a substantial effort, align interests at disparate levels of jurisdiction, and perform participatory and collaborative planning from the bottom up. This effort was relatively inclusive given the state of racial and social class relations in the country in the 1930s and 1940s. The county committees included men and women; whites and blacks; and landowners, tenants, and sharecroppers, most of whom were low-income farmers; however, wealthier white male farmers were over-represented [7]. The 1970s example shows how the U.S. Congress can

craft and put forward legislation to direct land use planning and what can derail such attempts. The proposed SEP will capitalize on these lessons from history.

Today, we should strive to be more inclusive and allow all types of citizens in all income levels, races, and classes and living in all parts of the country to become genuinely involved and active in decision-making for land uses in places where those citizens live and make a living. The proposed SEP framework will directly address environmental justice and just sustainability issues by giving historically marginalized and excluded citizens a place on the co-management committees to plan and decide land use management and regulations in and near their homes.

3. Governance Structure

Similar to agricultural planning reforms of the late 1930s and early 1940s, a national land use planning framework requires a bottom-up coordinated approach, implementing the principles inherent to participatory planning, collaborative learning, and shared decision-making [7,30,37,72]. However, the New Deal experience with agricultural planning taught us that thousands of local county-level plans and maps do not necessarily add up, or translate, to an effective and meaningful land use planning framework or policy at the national level [7]. In the early 1970s, we learned that national legislation from Washington D.C. mandating a process of coordination and data collection by lower-level agencies (i.e., state governments) without local decision-making is not a politically viable solution either, with or without rigorous environmental safeguards [3].

We believe that a hybrid governance system is needed in which there is national direction and allocation of funds from the congress in the form of legislation (i.e., top-down) combined with local participatory planning, policy formation, and shared rulemaking authority at the regional and local levels (i.e., bottom-up). The legal national policy, congressional allocation of funds, and local deliberative democracy via participatory planning [12,30,37,73] should enable and produce a co-management system to organize and regulate the use of lands and resources at a landscape level. The SEP will be a national-level program implemented from the ground up, authorized by national law and policy, with shared decision-making authority among jurisdictions and the support of federal land managers, policy-makers, and university and governmental scientists and land management experts (Figure 1).

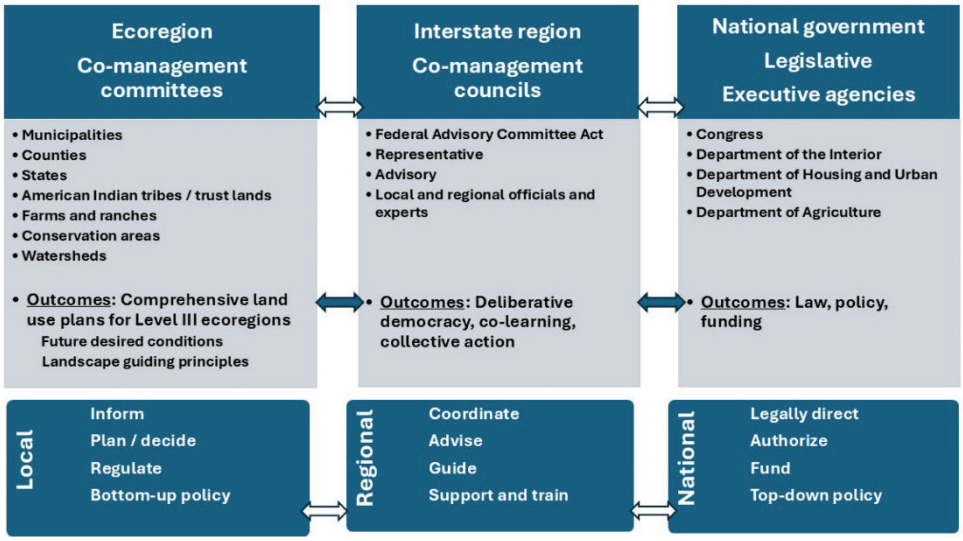


Figure 1. Governance structure for the Sustainable Ecoregion Program.

Adapting the approach used for the agricultural planning program of the New Deal era (1938–1942), we propose a program that develops and implements a deliberative democratic process among landowners, residents, and other land users, in which these stakeholders formulate land use policy through land use planning. The primary planning and policy decisions will be made by people living in communities, counties, and states within and across ecoregions, not by national government and university experts and scientists; these higher-level experts' roles in the proposed SEP will be to advise, support, educate, fund, and help coordinate the local-level land use planning committees [7].

The national, regional, and local environmental practitioners who organize the SEP (i.e., an interagency and interdisciplinary working group) will require representatives and supporters from communities, counties, states, and tribal governments. Setting up and implementing the SEP will require immense levels of cooperation between states; tribes; farmers, ranchers, and other private landowners; NGOs; and federal land management agencies. One of the first actions after the congress authorizes and funds the initial phases will be to establish a SEP working group to organize and form the co-management councils and committees (Figure 1). To cultivate support and trust, the diverse partners will be required to develop shared values and objectives and a common language for land use planning, regulation, and management [37]. Initially, they will be challenged to arrive at consensus and collective action on goals and objectives and will need to begin by setting easy-to-reach intermediate objectives to establish trust and a foundation for working together [42,74].

In the beginning of SEP formation, the partners will spend substantial time developing and implementing formal co-management agreements and arrangements, some of which may rely on existing authorities [75]. The program will require new legislation, amendments to existing laws, and funding from several sources, including large amounts of resources and coordination from the state and federal governments and new legislative appropriations. We envision one or more laws enacted by congress to implement the SEP on all lands in the United States, perhaps the Sustainable Ecoregions Lands Act (SELA), which authorizes the SEP as the national land use policy. The SELA could be partly modeled after portions of existing laws and bills and past programs, including the New Deal, Agricultural Adjustment Administration; Senate Bill S. 3354, National Land Use Policy Act (proposed bill); Coastal Zone Management Act; Outer Continental Shelf Lands Act; Alaska National Interest Lands Conservation Act; Federal Advisory Committee Act [76]; and other environmental laws and programs [1,3].

The guiding framework for administration and coordination will come from the national level, although the SEP will be implemented at multiple levels of decentralized governance through co-management councils that consist of regional, state, and tribal representatives and their designated planning and decision-making committees (Figure 1; Section 4.2). Citizens and governmental authorities from all regions of the United States will be represented and will work through their respective co-management bodies to set and enforce SEP policies and regulations.

Like municipal zoning, SEP land use regulations and interventions will be guided by comprehensive land use plans developed with meaningful and genuine tribal consultation and public involvement as appropriate. Brooks [77] explained that sovereign tribal nations have a unique relationship with the United States federal government based in the federal trust responsibility, and tribes are not to be simply involved as members of the public due to the legal relationship tribes have with the federal government. The federal agencies that support and participate in the SEP will invite tribal nations to formal government-to-government consultations regarding the work of the SEP and the ecoregional comprehensive plans. Committee members will include private landowners such as

farmers and ranchers, tribal leaders and indigenous land managers, and other stakeholders, and they will have decision-making authority, not merely serve an advisory role under the Federal Advisory Committee Act (FACA).

This governance structure and process will result in well-informed and well-supported legal decisions and consistent management guidance across jurisdictional boundaries. Comprehensive land use plans will be developed for each level III ecoregion. These ecoregional plans will contain goals, objectives, and future desired conditions, including the intensity of landscape uses such as large- and small-scale agriculture, outdoor recreation, and housing developments. Land use designations, management interventions, and continued program funding will be guided and directed by the comprehensive land use plans developed by the co-managers.

4. Discussion and Program Implementation

The implementation of the SEP involves several steps:

1. Recognition of level III ecoregions as primary boundaries (Appendix B);
2. Creation and provisioning of SEP co-management councils and committees;
3. Definition of physical landscape types and settings;
4. Definition of secondary planning boundaries;
5. Determination of future desired conditions;
6. Establishment of guiding principles for the management of each landscape type.

4.1. Ecoregions as Primary Boundaries

Ecoregion designations already exist, and experts have demonstrated that ecoregions are a suitable approach to land use planning and ecosystem management [24,33,45,78–81]. Ecoregions were designed in response to governmental recognition of the need to manage systems across political boundaries [79]. Ecoregions are unique functional areas that share similar ecosystems, landcover types, biotic communities, environmental resources, and sociocultural and socioecological systems [24,82]. Ecoregions have natural boundaries similar to watersheds. Interactions between climatic conditions, geographies, abiotic elements, and endemic plant and wildlife communities have created distinctive ecoregions.

Human populations and their settlements rely on ecosystem services and environmental resources provided by and within ecoregions. Over time, people have modified ecoregions and adapted to their different and changing conditions. Thus, there are somewhat distinct socioecological systems within each ecoregion, and ecoregions are distinctive in the ways that humans have used these regions [23]. The SEP framework will be designed to account for people and their cultural and ecological relationships to ecoregions. The main goal of sustainable ecoregional planning is maintaining "the balance between the ecosystem, economy, and society, where the combination of local and human needs is highlighted with environmental conservation and biodiversity perspectives" [24] (p. 685). The concept is ideal for landscape-level plans because "ecoregions provide a way to integrate different ideas, and social and physical processes, across scales" [23] (p. S5).

Appendix B shows that the level III ecoregions are large, with many crossing multiple state lines of jurisdiction. Ecoregions encompass landscape and sociocultural diversity and provide the primary boundaries co-managers of the SEP can use to organize and maintain landscape diversity and preserve the unique flora and fauna, ecosystems services, and human cultures and relationships with the land in these ecoregions. For example, ranching cultures and families in the western states are included in the SEP process in both AL and NL, and representatives from the ranching communities will be part of the local and regional SEP planning committees; these private landowners are key stakeholders and decision-makers in the proposed SEP.

The same is true for indigenous peoples, as they have ancient and complex relationships with landscapes and sacred sites in North America [28,83]. These connections can be thought of as tribal cultural landscapes [84]. The ancestral and traditional lands of American Indian tribes and Alaska Native Peoples still exist as part of the present-day cities, counties, states, and ecoregions. Some indigenous peoples have been removed or displaced from their ancestral lands, but they still have interests, cares, and concerns for these ancestral lands. The nation's indigenous peoples have deep cultural and spiritual connections to their homelands. Their ancestral lands are now composed of developed urban places, agricultural lands, and natural protected areas. The SEP committees will include tribal representation, and these co-managers will include tribal cultural landscapes, when and where appropriate; Native American Indian reservations and other trust lands; and local and regional scared sites, viewsheds, and landscapes where appropriate.

Ecoregions have been defined at broad (level I) to fine (level IV) scales [47,85]. We propose that level III ecoregions provide the most suitable delineation for primary boundaries for the SEP (Appendix B) [82]. Although level IV ecoregions would be optimal, there are 967 level IV ecoregions compared to 105 level III ecoregions for the contiguous United States and Alaska. It would be difficult to maintain the organizational framework required if level IV ecoregions were used as primary boundaries.

Level IV ecoregions (or watershed boundaries that lie within level III ecoregions) will need to be considered, and possibly adapted to the SEP, to capture and represent the social and ecological diversity of landscapes nested within some level III ecoregions at smaller scales. Once the SEP is established and operating satisfactorily, the co-managers of the largest ecoregions may wish to include level IV categories or watershed boundaries to capture local issues and provide finer-scale regulations and management interventions if, when, and where appropriate. The SEP will allow for this type of flexibility, especially in the case of watersheds, given their established importance to conservation ecology and human and ecosystem health. Such nuances and allowances for flexibility in planning will be captured, described, and accounted for in each ecoregional land use plan.

4.2. Co-Management Councils and Committees

An initial working group of SEP organizers (i.e., the SEP working group) will set up and establish two types of groups that will ultimately implement the program: interstate, regional co-management councils and ecoregional co-management committees (Figure 1). The initial organizers on the working group will be a combination of officials and experts from the state and tribal governments, universities, NGOs, and representatives from federal regional offices, including the U.S. Forest Service, National Park Service, Bureau of Land Management, Bureau of Indian Affairs, U.S. Fish and Wildlife Service, and Department of Housing and Urban Development. In consultation with attorneys specialized in establishing FACA advisory groups, the SEP working group, coordinating and talking with legislators at the national level and experts at the regional and local levels, will establish approximately nine regional co-management councils to shepherd the SEP, one each in the Northeast, Mid-Atlantic, Southeast, Great Lakes, Midwest, Southwest, Hawaii, Pacific Northwest, and Alaska regions of the country. Membership of the regional co-management councils will primarily consist of natural resource, land use, and urban planning professionals in city, county, state, and tribal governments; NGOs; and community representatives, including private landowners. Many of the SEP working group members will most likely stay involved as members of the SEP co-management councils.

Initially, the SEP regional councils' primary functions will be to advise, liaison, and coordinate with the regional and national federal government agencies, most likely land managers at the Departments of the Interior and Agriculture and representatives from

the state governors' offices. There will also be a need to include experts from the U.S. Department of Housing and Urban Development. Another main function of the SEP regional councils will be to set up and support the decision-making and planning work for each co-management committee (i.e., one committee per level III ecoregion) as they develop comprehensive land use plans for their respective level III ecoregions.

The SEP co-management committees will primarily be comprised of natural resource and land use professionals in state, county, tribal, and community agencies and organizations. Tribal council presidents, municipal mayors, city managers, county planners, and private landowners and farmers will be included on the committees to represent communities and local governments. The committee members will be from each state either in or encompassing each level III ecoregion and will include one representative from a state outside the ecoregion to act as a neutral observer. The number of members from each state and stakeholder group to serve on each ecoregional committee will be determined by its regional SEP co-management council. The regional councils will provide technical support and logistics for the process and coordinate, guide, and train the committees' work and membership.

All members of the ecoregional committees will receive training on incorporating the principles of transparency, information management, just sustainability, and citizen participation for the planning and implementation of the SEP [29]. The program will also provide nominal compensation in the form of honoraria for the time commitments of the co-managers and cover most travel expenses when travel is required. The principles of deliberative democracy will be taught while training the committee members [12,73,86]. Frameworks of environmental governance highlight how to apply and evaluate the process against criteria such as accountability, direction, and capacity that the SEP councils may use when guiding and instructing the work and decision-making of the planning committees [87,88]. A framework developed by Campellone et al. [21], the iCASS Platform, should be used by the SEP councils and committees to ensure principles of landscape planning, design, and collaborative science are incorporated into decisions made by the co-management bodies. The co-managers will focus on mutual respect, equity and equality, inclusivity, trust, transparent communication, the interdisciplinary establishment of desired future conditions, and participatory planning [12,21,30].

4.3. Physical Landscape Types

The surface area of the United States will be classified into three physical landscape types: developed landscapes (DL), agricultural landscapes (AL), and natural landscapes (NL) (Figure 2). Each physical landscape type will be managed at a low, moderate, or high level of use intensity based on prescriptions from the SEP co-management committees and directed by the comprehensive land use management plan for each ecoregion. The result will be a 3×3 matrix of combinations for a total of nine physical landscape settings (Table 1). The SEP co-management councils and committees will work together to define the composition of the intensity levels in the early stages of development of the ecoregional land use management plans.

Table 1. Nine landscape settings for the SEP arranged in a 3×3 matrix of landscape type by intensity of human use.

Landscape	Low-Use (LU)	Moderate-Use (MU)	High-Use (HU)
Developed (DL)	LU-DL	MU-DL	HU-DL
Agricultural (AL)	LU-AL	MU-AL	HU-AL
Natural (NL)	LU-NL	MU-NL	HU-NL

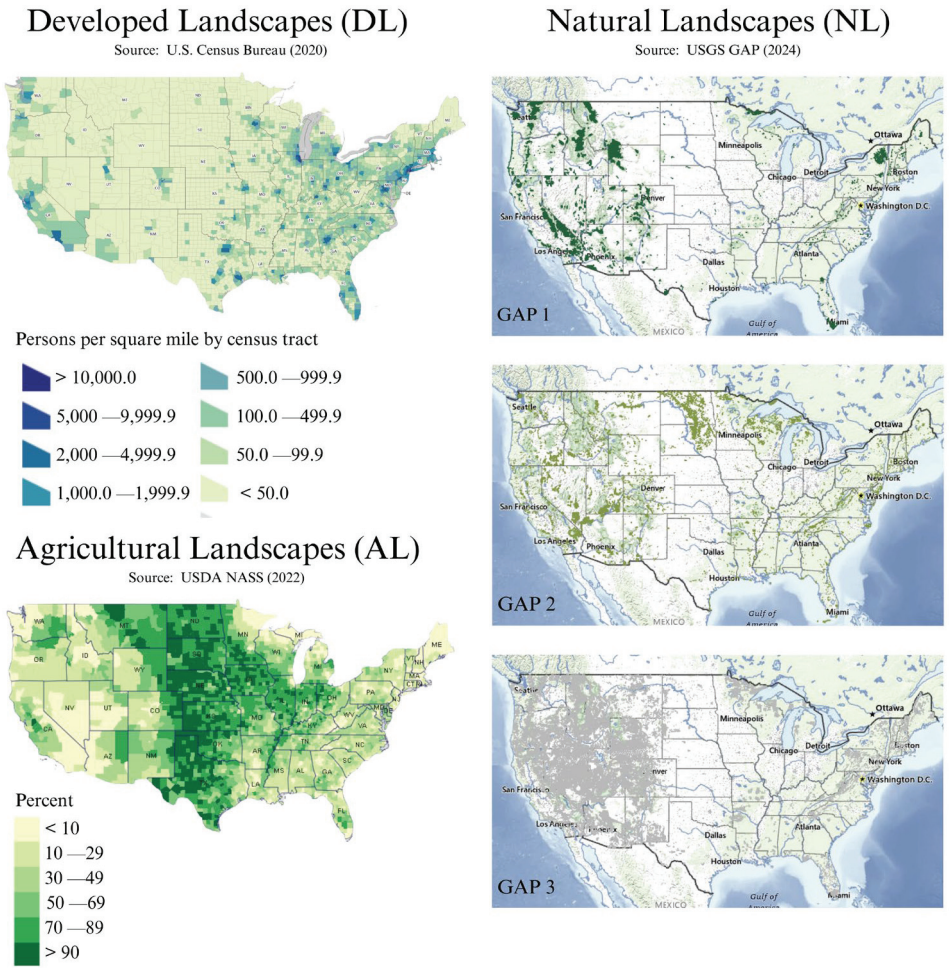


Figure 2. Maps of the 2020 U.S. population based on U.S. Census [89] data representing developed landscapes (DL), percentage of land in farms representing agricultural landscapes (AL) from the USDA [90] Census of Agriculture, and protected areas classified into three GAP categories representing natural landscapes (NL). The GAP categories vary in their level of conservation protection, from GAP 1 being the most protected to GAP 3 being the least protected, implying increased land use intensity as one moves from gap 1 to gap 3 [91].

Published maps and descriptions define some NL, particularly for public lands, otherwise known as protected areas with well-demarcated boundaries (Figure 2). Private landowners would be engaged on the councils and committees to define areas of NL on private lands. The current extant DL and AL are relatively well defined (Figure 2) but are in a continual state of change because these fluctuate throughout landscapes over time. The primary function of DL is to provide an area for humans to live a healthy and comfortable life and for industries to sustain production, jobs, housing, and economies within ecological limits.

The AL will often have fewer humans present than the DL and will be carefully managed for food and fiber production while maintaining populations of native flora and fauna. The primary function of NL will be to provide ecosystem services and sustain communities of indigenous and endemic plants and wildlife populations. NL will provide places for carefully managed visitation by humans for outdoor recreation, tourism geared toward culture and ecology, fishing, subsistence harvest and gathering, sport hunting, the enjoyment of solitude, visitation and ceremony by indigenous peoples at sacred sites, and other beneficial but limited land uses as determined by the SEP and published in the comprehensive land use plans for each level III ecoregion.

The NL primarily consists of publicly protected areas and privately owned natural areas and landcover types managed for ecological integrity and human uses and enjoyment. Where appropriate, many land uses on private lands could be managed as part of the SEP by the landowners, using conservation easements, land trusts, and other mechanisms devised by the landowners or the SEP co-management committees on which they serve or are represented by their peers. Private landowners will be decision-makers in the governance structure. The SEP co-managers will establish norms and procedures for deferring to the legal rights and practical and livelihood needs of farmers and ranchers in all but extraordinary decision-making and regulatory situations.

Conflicts between private and public property cultures in the United States should not be overemphasized when it comes to sustainable landscape planning, as the inclusion of private lands is necessary to allow connectivity; alternatives to exclusive public or private land tenure exist and may be developed for communities, regions, and ecosystems [26] (p. 57). For some landscape settings, the SEP councils and committees may have to set in place a common property system of land tenure.

Common property is a form of shared private property where individuals jointly own rights to a resource system or have shared rights to use a resource for grazing livestock or gathering firewood, for example [92]; common property tenure offers efficiencies in the management of common pool resources ([68] (p. 227) and [93]). In densely populated urban and suburban areas and where resource uses are intense, the SEP co-managers may find a common property model desirable to control economic externalities [68]. Common property arrangements do not allow unregulated uses and non-members may be excluded. "Commons limit use because only community members have a right to use them. Many commons have rules limiting use (limiting the season for grazing, limiting types of livestock, etc.) . . . common property refers to a situation where there are controls over the use of the resource" [92] (p. 3).

4.4. Secondary Boundaries

The SEP committees will be allowed flexibility when planning secondary land use planning boundaries within each level III ecoregion. The national SEP direction will provide guidelines and broad rules for setting secondary boundaries; there could be a set of options or alternatives in terms of shapes, sizes, and corridor types for this land use planning layer. The local SEP committees will have decision-making authority to determine specific details and spatial arrangements. Since some ecoregions run east-to-west and some north-to-south, there may be a need to be flexible in determining the secondary boundaries' shapes, extent, and direction (Appendix B).

For demonstration purposes, we recommend that the SEP committees and counsels explore how to connect ecoregions with a type of side-by-side and end-to-end hourglass-shaped grid or overlay with alternating areas of DL, AL, and NL to encompass all level III ecoregions (Figure 3). The hourglass grid is conceptualized as a land use planning layer, overlaid atop the core ecoregions layer. This layer of secondary boundaries will allow portions of all ecoregions to remain conserved as NL and have permanent connectivity to all other ecoregions. We recommend maintaining a classical, medium bulbous-shaped hourglass throughout each ecoregion and across adjacent ecoregions versus long, flattish grid shapes or near round ones. With a medium shape, an eye looking at a map of planning layers should be able to pick up on the same hourglass shapes or patterns running as both east-to-west and north-to-south.

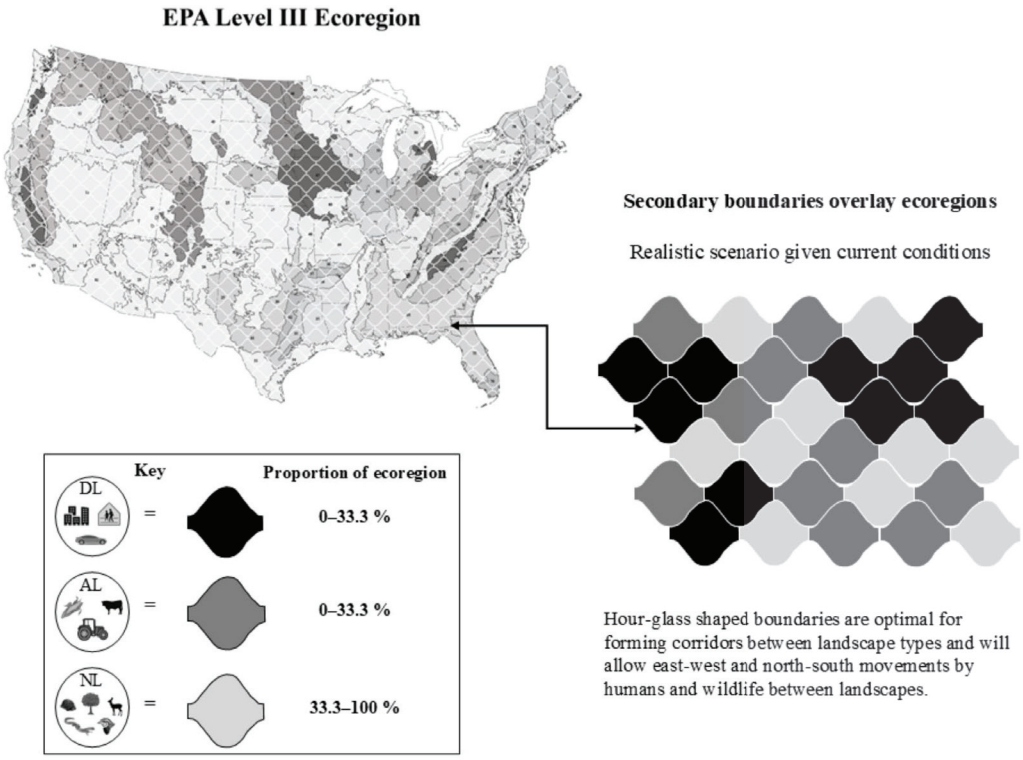


Figure 3. A map of the Environmental Protection Agency's level III ecoregions [82] and proposed placement of hourglass-shaped (i.e., corridors and patches) secondary boundaries to define developed landscapes (DL), agricultural landscapes (AL), and natural landscapes (NL) within each level III ecoregion. The size and direction of the secondary boundaries could vary from those displayed on the map and will be decided by the Sustainable Ecoregion Program co-managers. Note: The ecoregions are numbered and correspond to the labels shown in Appendix B.

Figure 3 depicts a hypothetical grid overlay that roughly matches the realities on the landscape today in which DL, AL, and NL are dispersed in patches or clusters. Ideally, each landscape type would occupy a complete latitudinal row of hourglasses and alternate in the DL–AL–NL order to maintain connectivity. For example, if DL were organized in east–west rows, existing U.S. highways with even numbers (running east–west) could run through the centers of the DL hourglass rows. The idea is to enhance their connectivity while fully organizing the three landscape types to address issues of environmental management, including the carbon footprint related to transportation, aesthetics, the simplified control of nuisance wildlife or feral animals, and the control of the threat of invasive species. Figure 3 depicts a scenario example that is less desirable but still provides improved outcomes for many already populated areas and matches current conditions. However, when DL, AL, and NL are not arranged in rows, travel distances to the same area types are longer. The SEP co-managers will strive for the ideal placement pattern of secondary boundaries within each level III ecoregion to the extent practicable.

This proposed spatial arrangement is based on approaches developed in landscape ecology, sustainable development, and ecoregional planning [24]. The main spatial and physical elements of a landscape are the substrate, patch, and corridor, and the landscape planner's objective, among others, is to maintain connectivity for the movement of species and people [24,94]. Figure 3 shows the proposed hour-glass shape of the boundaries, which is optimal for forming corridors between the 3 landscape types and will allow movement between each by humans and wildlife. The design of corridors in SEP comprehensive management plans for each ecoregion will account for the specific needs of plants and animals, including humans, within each level III ecoregion [95,96]. The hourglass shape,

concurrent with a carefully planned spatial configuration, will allow humans to experience each landscape type nearby their homes. This will more closely tie people to their food and local environments, preventing disconnects associated with the separation of past generations from food and fiber production and the stewardship and enjoyment of environmental resources [97]. The hourglass-shaped corridors should allow for a balance of interior and edge areas to accommodate species' needs [98–101].

The shape of the secondary boundary overlays becomes especially important in forested environments where areas could receive very different sunlight-hours per day due to shading or not and depending on the orientation of the hourglass shape (i.e., east–west orientation, north–south orientation, or an orientation at an angle between the perpendiculars). In forested environments, the orientation of secondary boundaries could have implications for more or less shade per day for the suburban lives of people, forest regeneration, and productivity for timber products and growth hours for crops, which could be controversial and politically charged. The proposed governance structure and deliberative and participatory processes used by the SEP committees are designed to mitigate and resolve these types of conflicts and controversies at the ecoregional level.

Maintaining the hourglass shape (Figure 3) would protect ecoregions long term even as ecoregion classifications change in the future. That is largely why maintaining a perfect medium hourglass shape is important throughout. Climate change already has plant and animal communities shifting, mostly north and south. From a wildlife management perspective alone, there may be reasons to argue for a different shape of hourglass. Concepts such as the patch size and edge effect would be impacted. The SEP co-managers will address these nuances and options for spatial arrangements on an ecoregion-by-ecoregion basis in the comprehensive land use plans.

For example, wherever natural corridors or passes are absent, SEP co-managers could interweave and link the areas of DL, AL, and NL with overpasses and underpasses at the narrowest junctions in the hourglass grid layer to act as corridors between landscapes. The SEP committees and councils will determine the size of the overpasses and underpasses and direction as appropriate. The DL and AL are currently connected in a suitable way to allow for the movement of humans and commodities via existing infrastructure and roads. The SEP co-managers will establish and organize corridors to connect NL across the secondary boundaries where necessary and accommodate already established private property, human structures, and existing rights of way.

Again, flexibility will be allowed for the SEP committees to establish the specific dimensions and exact shapes of the secondary boundaries based on the ecological needs of populations of endemic species and the sociocultural makeup of human populations and their needs, such as food security and outdoor recreation. The SEP committees will consult with the councils' experts and other botanists, biologists, and ecologists for expertise and supportive guidance to identify locations, home ranges, and space requirements for the long-term viability of species in each ecoregion.

Economists, anthropologists, and other social scientists will provide guidance for accounting for the sociocultural factors and needs of the people living in the ecoregions. For example, tribal cultural landscapes and sacred sites will require the desired conditions and land use intensities prescribed in the ecoregional plans. In terms of wildlife, the bobwhite quail requires large areas (i.e., 800–9600 ha) to maintain viable populations [102], and the pronghorn antelope relies on specific migratory pathways [103], for example. The committees will need to account for species' space requirements when setting the size of secondary boundaries and establish corridors along the edges of or across secondary boundary zones for some DL and AL. The SEP co-managers will use existing maps to

identify naturally occurring secondary boundaries within ecoregions and determine which landscape type will be associated with each secondary boundary [46].

A high percentage of some ecoregions currently are in agricultural development or private rangelands, and the SEP co-managers may consider restoring a portion of AL to NL to achieve desired future conditions. The aim is not for each of these boundaries to exclude the other types of lands but to allow for setting regulations for what and how much future development and intensity of land uses can occur and where to focus restoration when needed. Human life, health, and welfare are linked to ecological services and natural resources [104–106], and some species of wildlife and plants have become common residents of DL [107,108]. Some NL is present within the DL secondary boundaries to benefit human health and enjoyment and maintain flora and fauna in urban and suburban environments and green spaces. Conversely, some NL contain amounts of DL and AL.

Once the spatial arrangements of secondary boundaries are determined for NL, no further conversion to DL or AL should occur, and the SEP planners and co-managers should focus restoration efforts within those boundaries to reestablish or maintain healthy ecosystems.

4.5. Desired Future Conditions

The three physical landscape types serve as the basis for establishing the desired future conditions. The desired future conditions will be defined early in the implementation of the SEP and planning process used to develop the ecoregional plans. Discussing and determining the desired conditions will require coordination among the co-management councils and ecoregional committees and substantial input from stakeholders to reach consensus on what use limits are acceptable. The desired conditions will appear in each comprehensive plan as a series of statements. Desired condition statements are aspirations that describe the desired conditions within the three landscape types. The desired conditions address conditions, not management actions; these statements indicate what is desired, not how it will be achieved [109]. However, statements of desired conditions should be written clearly enough and with proper detail to guide management actions.

We recognize that different desired conditions may be applicable to different scales within ecoregions and landscape types. For example, the desired conditions will vary depending on whether the planners are addressing patches of habitat, watersheds, or ecosystems. Not all scales of land and land use will be included in every ecoregional comprehensive plan, as the physical spaces of ecoregions vary across the country. For example, a small ecoregion may not encompass an entire watershed but may contain all of the habitat of an endemic species that has a small home range.

The first step is to determine spatial arrangements for all physical landscape types, using already established level III ecoregions as primary boundaries. Spatial arrangements include landscape components such as corridors for species migrations and movements, secondary boundaries within level III ecoregions, patch sizes, and rights of way to accommodate varying types and intensities of land use, land access, and overland travel. The desired future conditions will include the intensity of management, quantities and qualities of endemic plants and wildlife, and allowable levels of human interactions with the land. Other desired conditions are possible and should vary across ecoregions, including land use activities, resource conditions, habitat functions, human experiences and opportunities for visitors, the size and type of agricultural production, and ecosystem services.

The committees will design planning layers to overlay onto the ecoregion boundaries and serve as secondary boundaries and corridors and choose desired future conditions that will endure time and societal pressures. The desired conditions will vary spatially but not necessarily temporally, especially not in the short term. “Desired condition statements

provide long-term vision for an area. They describe future conditions, not necessarily what exists today; and they are not necessarily time-bound nor do they include completion dates. Desired condition statements consider potential changes due to climate change" [109] (p. 25). The desired conditions will be reviewed and may be revised if appropriate when the comprehensive plans are reviewed and revised.

The DL and AL each ideally could occupy up to one-third of each ecoregion, and the NL should occupy a minimum of one-third of each ecoregion (Figure 3). The 33% target for NL is lower than the scientifically recommended target of 50% suggested in the Nature Needs Half agenda [45,110]. Our minimum target for NL recognizes there are areas nested within the AL and DL that are relatively healthy and functioning ecologically as NL. For example, timber companies and many non-industrial forest landowners in the southeastern United States often plant loblolly and slash pines in areas that were once longleaf pine savannahs [111]. Although the overstory tree composition is not native, many of these companies manage for a relatively continuous understory indicative of longleaf pine wiregrass ecosystems that benefit wildlife [112]. Indigenous wildlife managers practice land stewardship and habitat restoration on American Indian reservations. Ranchers in the western United States practice land stewardship and environmental conservation on private rangelands and federal grazing allotments [113]. Parts of private and tribal lands will most likely contain areas of NL.

Additionally, NL will include small urban parks, small urban forestlands, and some relatively larger green spaces (e.g., Central Park in New York) for outdoor recreation, scenic beauty, spiritual connection, limited and regulated resource harvests in some places, the preservation of flora and fauna, and other benefits and services. These types of NL may be encompassed by DL or located in and near AL. The SEP could ideally achieve a target of at least 50% of each ecoregion being NL and will strive to exceed this target wherever possible. The conservation of 50% of NL may not be possible in some imperiled, threatened, or recovering ecoregions [45]. In many contexts, AL serve similar functions to NL due to the stewardship and conservation values and practices of farmers, ranchers, and tribal land managers who understand the importance of respectfully caring for and efficiently utilizing the lands that support their livelihoods and families [113,114].

One-third of each physical landscape type will be managed at low-, medium-, and high-use intensities, and the committees will aim for 33% or more of each NL at each level of intensity to be publicly or communally owned. The decision-making for each area must match the definition and intent for each of the three physical landscape types and nine settings shown in Table 1. The SEP co-management committees will design all interventions to restore and maintain the quality and quantity of future desired conditions for each of the physical landscape types and settings based on a foundation of guiding principles published in the comprehensive land use plans and designed to promote ecological integrity, social equity, and human well-being.

4.6. Guiding Principles

The SEP councils and committees will develop and recommend, and in some cases prescribe, specific guiding principles for management and define low-, medium-, and high-intensity uses (Table 1). The local and regional SEP co-managers will solicit input from the governmental agencies and all partners involved in the SEP to develop and publish four sets of tools called landscape guiding principles (LGPs) for managing physical landscapes (3 within-LGPs and 1 complete-LGP). The three within-LGPs (i.e., developed, agricultural, and natural) will provide unique principles for high, moderate, and low management intensities for each landscape type. The result will be three published sets of principles having nine sections each. The fourth set of LGPs will be called the complete-LGP and will

be applicable to all physical landscape types. The complete-LGP will describe and map future desired conditions designed to:

1. Describe the core values of ecological integrity, social equity, environmental justice, and the underlying principles the co-managers will apply to ensure these values are upheld. The SEP could use the iCASS Platform as a model to design stakeholder engagement and build trust [21].
2. Provide a description of how the SEP was founded and how it is protected and maintained by LGPs and the agencies and participants of the SEP that developed them.
3. Describe the nine physical landscape settings that should each occupy roughly 11% of the total United States land area.
4. Provide landscape diversity ranging from urban to rural backcountry wildlands.
5. Emphasize the need for secondary boundaries to be carefully arranged and interwoven to ensure relatively easy but regulated movement and access for everyone.
6. Document how the SEP co-managers and the comprehensive plans considered and incorporated appropriate scientific and indigenous knowledge and relevant data into decisions. The co-managers could apply science capacity and data sharing practices developed by the Landscape Conservation Cooperatives Network [35].

The LGPs will be maintained through an officially recognized website and other media forums available to agencies, tribes, NGOs, and the public. The LGPs will be published in the comprehensive land use plans for each ecoregion, allowing the principles to be revised and updated as necessary when plans are periodically updated.

5. Benefits, Outcomes, and Challenges

The proposed SEP approach to landscape planning, designation, and co-management will increase the quality of life for people, reduce economic waste, improve ecosystem services for people, and maintain populations of native flora and fauna for generations to come. The time has come to plan for and organize our land uses to improve our quality of life and well-being in the United States. Our natural resources have suffered tremendously from ambivalence, lack of vision, and an overwhelming societal focus on single-resources such as air and water quality alone, endangered species alone, or soil erosion alone, as well as other single-issue initiatives such as zoning for detached, single-family housing.

5.1. Benefits for Developed Landscapes

Urban planning under the SEP will provide a forum for better and more inclusive communication and cooperation in urban development, giving attention to long-lasting functionality, durability, aesthetics, and appeal. The SEP will use deliberative democracy and participatory planning when addressing contentious issues such as urban sprawl, the pros and cons of smart growth, affordable housing, housing availability, and city zoning laws [12]. The SEP will emphasize public deliberation to work through these controversial issues to create political legitimacy and willingness to abide by decisions reached through inclusiveness, mutual respect, and meaningful dialogue. All parties to these discussions will have equal standing to defend and critique arguments during urban planning. This approach will account for past and present issues of inequity and environmental injustices and lessen the reliance on decisions made by voting on heated political referenda, the manipulation of voter districts, and city zoning strategies that exclude certain groups of people and drive up housing costs and displace residents.

The SEP will offer city officials opportunities to set boundaries for the designated land uses of cities, towns, and suburban areas. The SEP will focus on the benefits for people who live in developed urban areas. Citizens should be more able and pressed to focus on careful planning for building concepts and the design and construction of housing and commercial

areas for increased quality of life. Ideally, the SEP co-managers, working closely with city and county officials, will be able to plan for DL and settings to reconcile the benefits and disbenefits of smart growth approaches such as limiting the impacts of urban sprawl, not exacerbating its impacts [12]. The SEP will accentuate the benefits of smart growth while mitigating or eliminating its adverse impacts. This will also lead to less economic waste in the long term if population densities and related transportation issues can be reconciled by improved urban planning and management.

People will have improved quality of life via reduced commute distances and travel times from home for work, food security, and pleasure visits with each other. The SEP will provide new access and improve existing access to natural places for pleasure, outdoor recreation, socializing or solitude, and tourism closer to home. People will have increased opportunities for improved human health directly with more walkable communities and indirectly with less environmental costs of transportation. The SEP is designed to achieve better connectivity within and across landscapes, which will provide more people with access to AL and NL. People will have direct views of scenic agricultural areas and taller-statured or elevated natural landscapes from home and work and while commuting. People will be more familiar with agricultural and natural landscapes without crowding them and will have designated areas for manageable access to them.

5.2. Benefits for Agricultural Landscapes

With area boundaries set for the designated land use of agricultural landscapes and production, citizen farmers and producers should be more able and pressed to focus carefully on agricultural practices for better product yields, long-term investments in erosion control, and conservation practices in farming that will be more visible to citizen customers than before. Farmers and producers will have closer proximity to customers, which will reduce the transportation costs for products and increase economic opportunities through entrepreneurial hands-on initiatives, such as you-pick farms, which could directly involve the adjacent citizen populous. Visits to city farmers' markets will cost less in fuel costs, as the connectivity between the AL and DL will allow for the more efficient transportation of produce and other food products between production sites and city markets.

With less periphery around natural areas, farmers should incur less agricultural damage from nuisance wildlife and be able to manage occurrences more efficiently along the boundary interfaces. These designated agricultural areas will allow for the more efficient use of farm machinery and equipment and lessen the spread of costly invasive plant species. This will reduce the costs for producers and lower the costs for customers.

The SEP will directly include farmers, ranchers, and other people who make a living from lands they own or lease in the planning and decision-making for land uses and regulations that affect their lands and livelihoods and those of their neighbors.

5.3. Benefits for Natural Landscapes

With area boundaries set for the designated land use of NL in each level III ecoregion, natural resource managers should be more able and pressed to manage these areas to provide ecosystem services for people and sustain NL for native and endemic plant and animal populations.

Increased ecosystem services of large natural areas combined with seamless connectivity among each NL via the hourglass end corridors will reduce the negative impacts from varied and fluctuating land uses and land fragmentation, which adversely impact many populations of wildlife species. Efforts to eradicate and control invasive plants and animals will be more achievable with these focus areas.

Larger, more continuous and ecologically healthy natural areas coupled with adjacent agricultural areas will create protective spatial buffers from many human-caused disturbances, such as unnecessary mechanical disturbances, the influx of invasive species, and wildlife depredation by stray pets. This will help restore and maintain the natural conditions necessary for wildlife recruitment, wildlife populations, and the long-term stability of populations of the species native to each ecoregion.

These adequate NL area sizes will allow for the safer practice of ecologically necessary prescribe fires (e.g., smoke mitigation) that mimic the natural fire patterns of each ecoregion to maintain native populations of wild plant communities that native wild animals need. Maintaining the ideal hourglass shape and an evenly spaced pattern of natural areas would protect ecoregions long term, even as ecoregion classifications may change in the future. Climate change already has plant and animal communities spatially shifting, mostly north or south, and humans will increasingly move inland from the coasts as the effects of climate change raise the sea level and perpetuate natural disasters related to extreme weather events.

5.4. Challenges of Implementing the SEP

Similar to most other large-scale societal initiatives, the biggest challenges to establishing and implementing the SEP as proposed here would be passing the proper legislation and congressional allocation of adequate and long-term funding (e.g., SELA). There will be a need to establish like-minded, bipartisan congressional committees in land and natural resource use, management, and policy to craft a bill to authorize the SEP. There will be large expenses of time and monies involved with the SEP.

Another foreseeable and substantial challenge will be determining how to include and garner the support and collaboration of private landowners across the landscape. Private lands will need to be part of the SEP, as they currently comprise over half the land mass of the United States. Private landowners are good stewards of their lands and already have substantial amounts of rights and authority to plan and regulate many uses and activities on those private lands. They frequently talk and work with their neighboring landowners, and they are not new to collaborative processes, ecological conservation, and larger landscape goals [113]. These are the strengths of private landowners on which the SEP working group and future co-managers must capitalize as they reach out to include farmers, ranchers, allotment holders, and other private land stewards to participate in the ecoregional planning committees and sit on the co-management councils.

Including DL, urban residents, city officials, and urban planning experts in ways that alleviate historical environmental injustices presents a challenge to the SEP. Incorporating the advantages of smart growth while avoiding its disadvantages will be necessary [12]. The SEP will be challenged to integrate with already well-established zoning and property tax systems and traditions. Adhering to the principles of deliberative democracy, spatial organization, and connectivity inherent to the SEP will help to meet these challenges and produce just sustainability for urban residents.

The national, regional, and local components of the SEP shown in Figure 1 must effectively coordinate and work together across jurisdictions and scales while maintaining two-way flows of communication, information, and decision-making. The SEP co-managers will be challenged to maintain the levels of coordination and collaboration needed to develop and adopt comprehensive land use plans that guide policy and regulations for each ecoregion and landscape type. Group dynamics and high social complexity in this arrangement will need to be overcome or effectively managed in order to implement the full SEP. However, because of the SEP's potential for complete multi-resource land use

considerations and improved long-term quality of human life, the time, money, and work required to implement the program would be justified.

6. Conclusions

The United States government does not have a unique land use planning law or clearly expressed and commonly accepted national land use policy [1]. Attempts during the twentieth century to establish a national land use policy failed for multiple reasons [1,3,7]. We have proposed that organizing and regulating the landscape according to predominant land uses at the ecoregion level will improve our ability to manage natural resources in a sustainable manner and decrease land use conflicts, resource degradation, and fragmentation in the United States.

The proposed SEP will require the allocation of funds by congress, probable amendments to current laws, and new legislation to support and formally authorize the local and regional deliberative processes envisioned for the SEP. The adoption of the SEP as a national policy and legal management standard would alleviate conflict, fragmentation, and degradation in land use management by directing future development and agricultural practices to occur within defined spaces and according to future desired conditions. SEP regulations will be set in place by groups of people working together who live in the ecoregions and have well-established understandings of and relationships with the land.

Implementing the SEP would increase the quantity and quality of NL and the quality of AL and DL for the diverse range of people who live and work in these settings. A properly implemented SEP would empower communities, states, indigenous peoples, private landowners, and public land managers via their inclusion in the decision-making process. We propose that the SEP model will achieve the spatial conservation of biodiversity and natural resources by both separating and integrating physical landscape types as simply as possible and in a way that is environmentally just, without compromising socioeconomic progress, biodiversity, or sustainable land tenure, including private land ownership.

Like any other properly crafted vision, the ideals and goals of the SEP are aspirational and would be expensive to fully implement, although these ideals are domestically necessary and achievable. The SEP co-management committees will develop and adopt specific objectives and strategies in comprehensive land use plans for each level III ecoregion. It is time for responsible citizens and governments to openly recognize and agree that managing for sustainable landscapes requires that we carefully define future desired conditions and set regulations to achieve those conditions. Substantial inclusivity, shared authority, and at times common-property land tenure will be necessary to control externalities and fragmentation caused by the parcellation of private lands [68].

We focused the framework on the United States but land managers could implement similar frameworks in other nations and globally [33,45,80,81]. The SEP promises high quality of life and adequate amounts of food, water, and plant cover to support human societies and biodiversity in ways that are sustainable and environmentally and socially just.

7. Future Direction

There are several next steps and future directions for the proposed SEP. First, land use planners and environmental professionals across the United States (national, tribal, regional, and local) should start talking amongst themselves and garner support and leverage resources from their leaders and other professional supporters and legislative representatives to organize, fund, and hold a national SEP kickoff workshop or host one as part of a larger professional meeting (e.g., the American Planning Association). The kickoff gathering will be dedicated to setting an agenda and publishing resolutions to establish

and advance the SEP, using this foundational document and other notable directives to guide its establishment.

Second, at the kickoff meeting or shortly thereafter, this group of professionals should charter the SEP working group to move the program forward. One of its first directives will be to identify and connect with the proper congressional committees, other federal and state lawmakers, and agency representatives in the federal executive branch and the offices of state governors. The SEP working group should focus these early efforts with congressional committees and other law-makers to draft new legislation and amend current laws as necessary to authorize the SEP.

Third, the working group will establish the SEP in two ecoregions in the respective multistate regions as demonstration projects to pilot test the SEP concept and its implementation strategies described here. Two carefully crafted pilot tests in different regions will create comparable case studies with administrative records and lessons learned to be used in the future to move the SEP into all level III ecoregions in the nine multistate regions. Indigenous Peoples should be meaningfully included at every step, including within the demonstration projects. Therefore, tribal leaders and other indigenous land use experts must be adequately represented on the SEP working group.

Fourth, the SEP working group will form two co-management councils and two co-management committees to begin implementing the SEP case studies. The participants will use planning techniques and related land use and land management tools to test and demonstrate different methods in the context of the SEP. These will include GIS mapping, participatory mapping, natural resources mapping, resource benefit analyses, quantitative modeling, scenario planning, and landscape planning and design [21,115]. They will pilot test the proposed governance structure and adapt ideas and successful methods from existing planning groups and projects that use deliberative democracy and participatory planning [73,116].

Fifth, the participants in the demonstration projects, including indigenous experts, should determine how to effectively coordinate and include tribal nations and American Indian trust lands in the context of the SEP to account for planning and policy-making with tribes and for the benefit of their lands, including tribal cultural landscapes and sacred sites and for larger ancestral homelands and traditional territories [83,84]. Including tribes without a present-day land base will also be necessary in some ecoregions. The SEP must devise effective approaches to work with tribal partners and bring them into the co-management councils and committees where appropriate. When planning land uses on tribal lands and American Indian reservations, appropriate indigenous leaders and experts from those places should propose and decide on the governance and deliberation processes that best suit their peoples' needs and lands.

American Indian and Alaska Native governance structures and understandings of authority vary a great deal across the country, so the case study designers and implementers should not quickly generalize an approach such as deliberative democracy, as it may not be a ubiquitous component of tribal governance [86]. Reedy et al. [86] found some important areas of synergy between the ideals of deliberative democracy and indigenous methods of political discussion used in the United States, and there may be some benefits to deliberation when working with tribal leaders to develop engagement techniques for contemporary American Indians and Alaska Native Peoples. We recommend identifying and talking with the appropriate tribal leaders regarding whom to include in the SEP process and when and how it may be best to do so. Comparing the SEP case studies on how each addressed tribal inclusion and engagement will most likely reveal differences and similarities, highlighting the need for flexibility and bottom-up planning when devising opportunities for the participation and inclusion of tribal nations.

Sixth, the same is true for including urban lands, urban forests, and residents of developed landscapes. Developed lands will be a large part of the SEP, and these lands are where the majority of citizens now reside and make a living. The SEP must devise ways and means to best include urban planners and developers, city mayors and managers, and state and federal representatives from housing and urban development agencies and organizations such as the U.S. Department of Housing and Urban Development. This will help to balance ecoregional planning focused on conservation with planning for environmental justice and just sustainability in urban settings.

The SEP demonstration projects and resulting case studies must determine how to best work with, adapt, modify, or replace existing city master plans and zoning regulations. The SEP will need to work with and include real estate developers and their organizations. The SEP has to figure out how to best include and account for existing patterns of urban spatial organization, planning traditions, building codes, property taxation systems, and planning and zoning approaches such as smart growth to account for housing and transportation conditions and needs. Some of the principles and strategies of smart growth may be adapted by the SEP to help protect the health and productivity of developed landscapes and make communities more attractive, economically stronger, and resilient to climate change [55].

Environmental justice should be included in urban and suburban planning goals to provide just sustainability and reduce injustices [16]. The link between the SEP co-managers, ecoregional plans, and urban areas has to be clearly understood and articulated in the SEP and the comprehensive plans. The initial work of the SEP working group and case study participants should establish clear connections between ecoregional land use planning and the inclusion and participation of all socioeconomic classes and races of urban citizens with diverse incomes and educations.

Seventh, the same is true for including private landowners in the SEP case studies. The SEP co-management councils will include private lands in the program, and private landowners will be invited to sit on the SEP ecoregional planning committees and councils to represent themselves and other private landowners such as farmers and ranchers. The SEP working group will learn about how to best reach out to and invite private landowners during the demonstration projects and case study analyses. The SEP working group, and the co-management bodies they establish, will have representation from groups of private property owners who are also land use experts and resource managers. Private property owners who participate in the case studies will be able to describe and help establish ways to best include private lands and property owners' rights in the SEP. They will teach the SEP co-managers about the issues they face while stewarding their lands as a part of the surrounding landscape. It will be crucially important for the SEP co-managers to include and incorporate a clear understanding of land property rights in the proposed SEP. The SEP should safeguard property rights in the United States because secure property rights have been shown to correlate positively with higher levels of land use efficiency and productivity and conditions that promote sustainable land management practices [114].

Author Contributions: Conceptualization, E.G.D. and J.J.B.; literature review, J.J.B. and A.K.D.; investigation and synthesis, E.G.D., J.J.B. and A.K.D.; resources, J.J.B., E.G.D. and A.K.D.; writing—original draft preparation, E.G.D., J.J.B. and A.K.D.; writing—review and editing, J.J.B., E.G.D. and A.K.D.; visualization, E.G.D., J.J.B. and A.K.D.; supervision, not applicable; project administration, E.G.D. and J.J.B.; funding acquisition, A.K.D., E.G.D. and J.J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding outside of Open Access and article processing charges.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. government, including the U.S. Department of the Interior or its bureaus; U.S. Department of Agriculture; U.S. Forest Service; U.S. Department of Housing and Urban Development; state, tribal, or other governments; the Wildlife Society; or Murray State University. The mention of trade names or commercial products does not constitute endorsement by the U.S. Government. Eric G. Darracq is credited with the initial conceptualization of the SEP and original manuscript in 2007. The authors claim sole responsibility for errors, omissions, and inaccuracies. The authors thank a number of anonymous reviewers and technical supporters for their valuable assistance with developing graphics, improving the text, providing constructive comments, organizing the structure of earlier drafts, and assisting with the payment of article processing charges for Open Access publication.

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

Abbreviations

The following abbreviations are used in this manuscript:

AL	Agricultural landscapes
DL	Developed landscapes
EPA	Environmental Protection Agency (Federal)
FACA	Federal Advisory Committee Act
iCASS	Innovation, inclusiveness: convene stakeholders, interdisciplinary assessment of future conditions, interactive spatial design, informative strategy design
IVUMC	Interagency Visitor Use Management Council
LCC	Landscape Conservation Cooperative
LGP	Landscape Guiding Principle
NGO	Nongovernmental organization
NL	Natural landscapes
SELA	Sustainable Ecoregion Lands Act
SEP	Sustainable Ecoregion Program
U.S.	United States
USDA	United States Department of Agriculture

Appendix A

Table A1. Select examples of partnerships designed to plan and manage across political boundaries at the landscape level. The SEP is highlighted in boldface type.

Program	Structure	Focus	Regulatory	Location	Lowest Level Management Unit	Website
American Tree Farm System	NGO	Forest management on private lands	Partially (certification requirements)	United States National	States	https://www.treefarmsystem.org/state-tree-farm-programs (accessed on 11 September 2020)
Crucial Habitat Assessment Tool	NGO	Wildlife and land use planning	No	United States Regional	States	https://wafwa.org/legacy/ (accessed on 7 June 202)
Forest Stewardship Council	NGO	Forest management and industrial timber companies	Partially (certification requirements)	International	Country	https://www.fsc.org/ (accessed on 7 June 2020)
Forest Stewardship Program	Federal	Forest management on private lands	No	United States National	States	https://www.fs.usda.gov/managing-land/forest-stewardship/program (accessed on 11 September 2020)
Landscape Conservation Cooperatives	Federal	Science partnerships, conservation, and climate change	No	United States National	Slightly coarser than level II	https://www.landscapepartnership.org/cooperative/the-network (accessed on 15 October 2021)

Table A1. *Cont.*

Program	Structure	Focus	Regulatory	Location	Lowest Level Management Unit	Website
Mid-America Monarch Strategy	NGO	Monarch butterfly conservation	No	United States National	Levels I and II (in some cases coarser than level I)	http://www.mafwa.org/?page_id=2347 (accessed on 7 June 2020)
Migratory Bird Joint Ventures	Federal NGO	Bird conservation	No	North America	Levels I and II (in some cases coarser than level I)	https://mbjv.org/joint-venture-map/ (accessed on 7 June 2020)
National Fish Habitat Partnership	NGO	Fish conservation	No	United States National	Levels I and II (in some cases coarser than level I)	http://www.fishhabitat.org/the-partnerships/ (accessed on 7 June 2020)
North American Bird Conservation Initiative	NGO	Bird conservation	No	United States National	Levels II and III	http://nabci-us.org/resources/bird-conservation-regions-map/ (accessed on 7 june 2020)
Northern Bobwhite Conservation Initiative	NGO	Bobwhite quail	No	United States Regional	State	https://nbgi.org/about-us/nbci/ (accessed on 15 October 2021)
Northeast Regional Conservation Needs	NGO	Regional landscape conservation projects	No	United States Regional	Regional or sub-regional	https://rcngrants.org/content/northeast-regional-conservation-needs-grant-program (accessed on 7 June 2020)
Southeast Conservation Adaptation Strategy	NGO	Connection of lands and waters for the benefit of wildlife, fish, and people	No	United States Regional	Regional with state involvement	http://secassoutheast.org/about (accessed on 7 June 2020)
Sustainable Ecoregion Program	**Co-managed**	**Land-use planning and regulation, sustainability includes social equity and environmental justice**	**Yes**	**United States national, state, local**	**Level III**	**Proposed; to be developed**
Sustainable Forestry Initiative	NGO	Forest management and industrial timber companies	Partially (certification requirements)	North America	State, provincial, or regional	https://www.sfiprogram.org/sic/ (accessed on 7 June 2020)
Yellowstone to Yukon	NGO	Connection and protection of landscapes	No	Canada and United States Regional	Priority areas by sections of region	https://y2y.net/work/where-by-region (accessed on 23 March 2025)

Appendix B

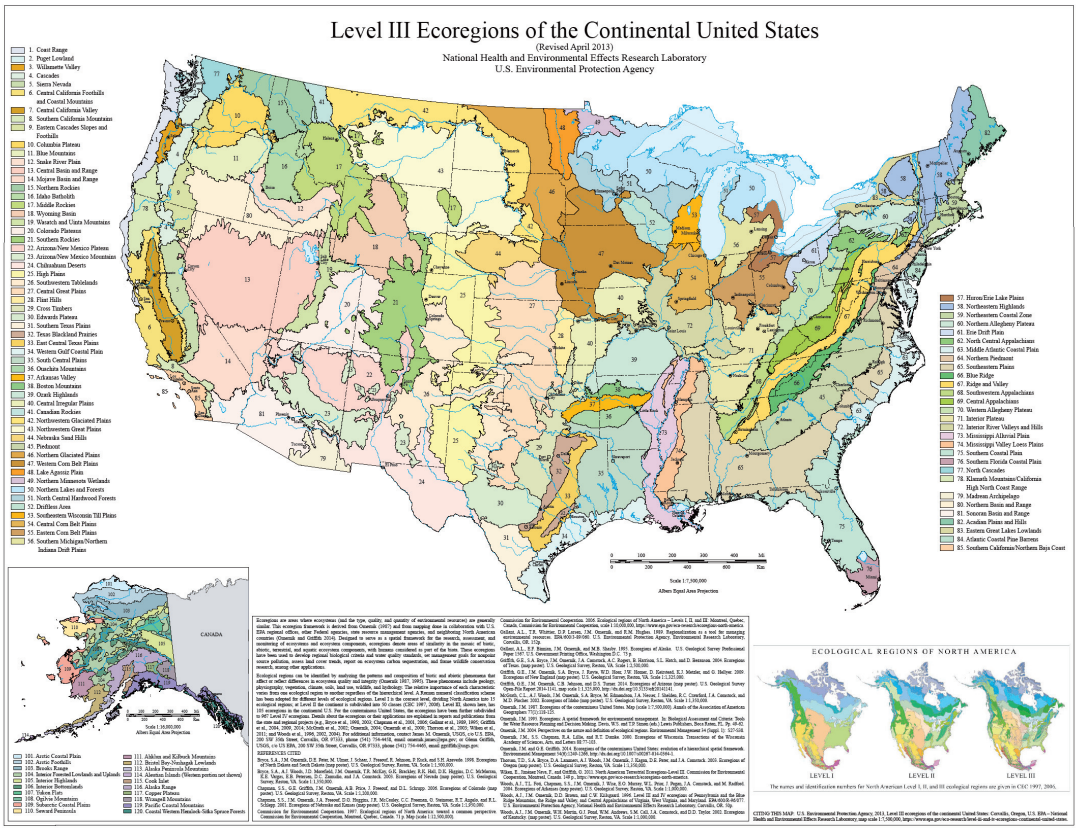


Figure A1. Level III Ecoregions [47,82,114,117–137].

Notes

[1] "EnviroAtlas defines natural land cover as forest, shrubland, grassland, barren land, and wetland cover classes, while it excludes agriculture and developed land. For Alaska, natural land cover also includes perennial ice and snow, lichens, moss, and sedges and forbs. The term natural in natural land cover does not imply good quality or a lack of human disturbance but rather vegetative cover that is not typically intensively managed. For example, natural land cover includes range but not pasture land, which is included under agriculture" [32] (p. 1).

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ISBN 978-3-7258-6307-5