

Article

Multi-Scenario Simulation and Restoration Strategy of Ecological Security Pattern in the Yellow River Delta

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Abstract

The Yellow River Delta is one of China's most ecologically fragile regions, experiencing prolonged pressures from rapid urbanization and ecological degradation. Existing research, however, has predominantly focused on constructing ecological security patterns under single scenarios, with limited systematic multi-scenario comparisons and insufficient statistical support. To address this gap, this study proposes an integrated framework of "land use simulation—multi-scenario ecological security pattern construction—statistical comparative analysis." Using the PLUS model, three scenarios were constructed—Business-as-Usual (BAU), Priority Urban Development (PUD), and Priority Ecological Protection (PEP)—to simulate land use changes by 2040. Habitat quality assessment, Multi-Scale Pattern Analysis (MSPA), landscape connectivity, and circuit theory were integrated to identify ecological source areas, corridors, and nodes, incorporating a novel hexagonal grid partitioning method. Statistical significance was evaluated using parametric tests (ANOVA, *t*-test) and non-parametric tests (permutation test, PERMANOVA). Analysis indicated significant differences in ecological security patterns across scenarios. Under the PEP scenario, ecological source areas reached 3580.42 km² (12.39% of the total Yellow River Delta), corresponding to a 14.85% increase relative to the BAU scenario and a 32.79% increase relative to the PUD scenario. These gains are primarily attributable to stringent wetland and forestland protection policies, which successfully limited the encroachment of construction land into ecological space. Habitat quality and connectivity markedly improved, resulting in the highest ecosystem stability. By contrast, the PUD scenario experienced an 851.46 km² expansion of construction land, resulting in the shrinkage of ecological source areas and intensified fragmentation, consequently increasing ecological security risks. The BAU scenario demonstrated moderate outcomes, with a moderately balanced spatial configuration. In conclusion, this study introduces an ecological restoration strategy of "five zones, one belt, one center, and multiple corridors" based on multi-scenario ecological security patterns. This provides a scientific foundation for ecological restoration and territorial spatial planning in the Yellow River Delta, while the proposed multi-scenario statistical comparison method provides a replicable methodological framework for ecological security pattern research in other delta regions.



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Keywords: PLUS model; ecological security pattern; ecological restoration; land use change; circuit theory

1. Introduction

Global land use and land cover change (LUCC) has intensified in recent decades due to accelerating industrialization, urbanization, and human activities, exerting profound effects on ecosystems. These effects include wetland loss, land degradation, increased frequency of extreme weather events, and declining biodiversity [1,2]. China, as one of the fastest-urbanizing developing countries, has experienced dramatic land use transformations over the past four decades, including rapid expansion of construction land, reductions in arable land and wetlands, and increased fragmentation of forests and grasslands. While these transformations have driven economic growth, they have also heightened ecosystem vulnerability and instability [3–5]. Consequently, balancing economic development with ecological functions to maintain ecosystem stability has become a central research focus in ecology and geography [6,7].

Ecological Security Patterns provide a foundation for regional ecological stability and a pathway toward sustainable development. Establishing ESPs mitigates habitat fragmentation, enhances connectivity among ecological patches, and promotes ecosystem resilience [8–10]. The mainstream ESP construction framework follows the sequence: “ecological source identification—resistance surface construction—corridor and key node extraction,” based on Yu’s (1996) theory. This approach integrates high-value ecological sources with landscape resistance and species dispersal mechanisms [11–13]. Identification of ecological sources typically combines habitat quality assessment, morphological spatial pattern analysis (MSPA), and landscape connectivity analysis [14,15]. Resistance surfaces incorporate natural, social, and economic factors to quantify potential barriers to species migration [16]. Recent advances include species-specific dispersal models to simulate migration pathways in heterogeneous landscapes, revealing the spatial dependency of ecological processes [17]. Graph-theory-based connectivity metrics, such as the probability of connectivity (PC) and the integrated index of connectivity (IIC), quantify functional links between source areas and evaluate corridor roles in network stability [18]. Circuit-theory-based corridor extraction simulates species random walks, thresholds, and key nodes, enabling multi-path connectivity assessment, corridor width estimation, and identification of ecological pinch points, thereby enhancing ESP accuracy [19–22]. LUCC is a key driver of ESP evolution, altering ecosystem structure and function and influencing ESP identification [10,23]. Spatial land use simulations employ models such as cellular automata (CA), CLUE, FLUS, and PLUS. CA models capture spatial adjacency and self-organization but rely on empirical rules with limited universality [24]. CLUE simulates multi-class transitions using probability matrices but is computationally intensive at high resolutions [25]. FLUS incorporates AI and adaptive inertia mechanisms to simulate land use competition, improving dynamic simulations but underrepresenting spatial heterogeneity and patch characteristics [26]. The PLUS model uses random seeding and multi-objective optimization to generate realistic spatial patterns, offering greater flexibility and precision. Accordingly, this study employs PLUS to simulate future land use change and its ecological effects [23,27]. Recent studies increasingly combine LUCC with ESP to construct and optimize ecological networks under multiple scenarios. For example, Nie et al. (2023) [28] integrated ESP as an ecological constraint within the PLUS model (ESP-MS-PLUS), establishing four scenarios—BAU, PUD, PEP, and BUE—in Anji County, Zhejiang Province. The ecological conservation and balanced development scenario effectively mitigated fragmentation and enhanced connectivity. Ma et al. (2024) applied a “multi-level ESP + risk warning” framework in the Guangdong–Hong Kong–Macao Greater Bay Area, showing reduced ecological risks under conservation scenarios while urban cores remained high risk [29]. Although multi-scenario ESP studies have progressed, statistical validation remains limited. To address this, the present study introduces hexagonal grid

statistics, integrating parametric (ANOVA, *t*-tests) and nonparametric (permutation tests, PERMANOVA) analyses to quantitatively compare ecological security patterns across scenarios, thereby providing stronger scientific support for regional conservation and territorial spatial planning.

The Yellow River Delta, one of China's most ecologically fragile and sensitive regions, has long been subjected to multiple pressures, such as coastal erosion, soil salinization, groundwater pollution, and rapid urbanization [5,30]. With a population density of 371.7 people per square kilometer, the area experienced an increase of 1623.49 km² in construction land between 2000 and 2020, and urban expansion has severely encroached upon ecological space. Concurrently, wetlands cover 43.77% of the area, representing the most intact temperate coastal wetland ecosystem in China. However, these wetlands are at risk of continuous shrinkage and functional degradation. As a vital national energy and agricultural base and a key distribution area for typical coastal wetlands, the Yellow River Delta is characterized by a marked conflict between ecological conservation and economic growth, making it an ideal region in which to test ESP construction and optimization strategies. In this study, ESP was employed as both a conceptual framework and a methodological tool, and an integrated approach of land use simulation, multi-scenario ESP construction, and statistical comparative analysis was proposed. Habitat quality assessment, MSPA, and circuit theory were applied to identify ecological sources, corridors, and key nodes, while hexagonal partitioning and significance testing were introduced to enable quantitative comparisons across multiple scenarios. The study has three objectives: (1) to simulate three land use scenarios (BAU, PUD, PEP) for 2040 using the PLUS model, comparing construction land expansion and ecological land evolution under different development orientations; (2) to integrate habitat quality, MSPA, and circuit theory for ecological source and corridor identification and subsequently perform statistical comparisons of ESP differences across scenarios; and (3) to propose an ecological restoration framework of "five zones, one belt, one center, and multiple corridors." This framework provides scientific support for balancing ecological protection with economic development in the YRD and offers transferable insights for sustainable development in other delta regions.

2. Materials and Methods

2.1. Study Area

The Yellow River Delta (YRD) lies in the northeastern part of Shandong Province, China, between latitudes 36°25'27"–38°16'17" N and longitudes 116°56'14"–120°18'15" E. It spans portions of Dongying, Binzhou, Yantai, and Qingdao, with a total watershed area of 26,500 km² (Figure 1). The region experiences an average annual temperature ranging from 12 °C to 15 °C and receives annual precipitation between 550 mm and 600 mm. The terrain is predominantly flat, as the Yellow River flows from southwest to northeast, with elevation gradually decreasing from south to north. According to 2020 land use statistics, arable land comprises 61.97% of the total area, thereby constituting the dominant land category. Construction land accounts for 20.99%, primarily concentrated around urban centers and major transportation corridors, which reflects the region's rapid urbanization. Water bodies cover 14.98%, including rivers, wetlands, and tidal flats, and provide essential ecological functions within the region. Forest and grassland areas are extremely limited, representing only 0.51% and 0.46%, respectively, indicating a lack of sufficient ecological vegetation coverage. The population density reaches 371.7 people per square kilometer, significantly higher than the national average, thereby exerting considerable pressure on ecosystem stability through human activities. The region is rich in oil, natural gas, sea salt, and geothermal resources and contains over one-third of Shandong Province's unused land, rendering it one of the eastern coastal regions with the most abundant

land reserves. Its unique natural conditions—where rivers meet the sea and terrestrial and marine ecosystems coexist—have fostered distinctive ecological systems, including extensive shallow tidal flats and diverse wetlands, which constitute China’s most complete and youngest temperate wetland ecosystem. With these outstanding resource advantages and ecological values, the Yellow River Delta High-Efficiency Ecological Economic Zone holds significant strategic importance. Nevertheless, rapid economic development and multiple overlapping disturbances in recent years have intensified ecological conservation pressures. Therefore, balancing ecological protection with regional economic growth has become an urgent scientific challenge, necessitating urgent scientific attention and strategic resolution.

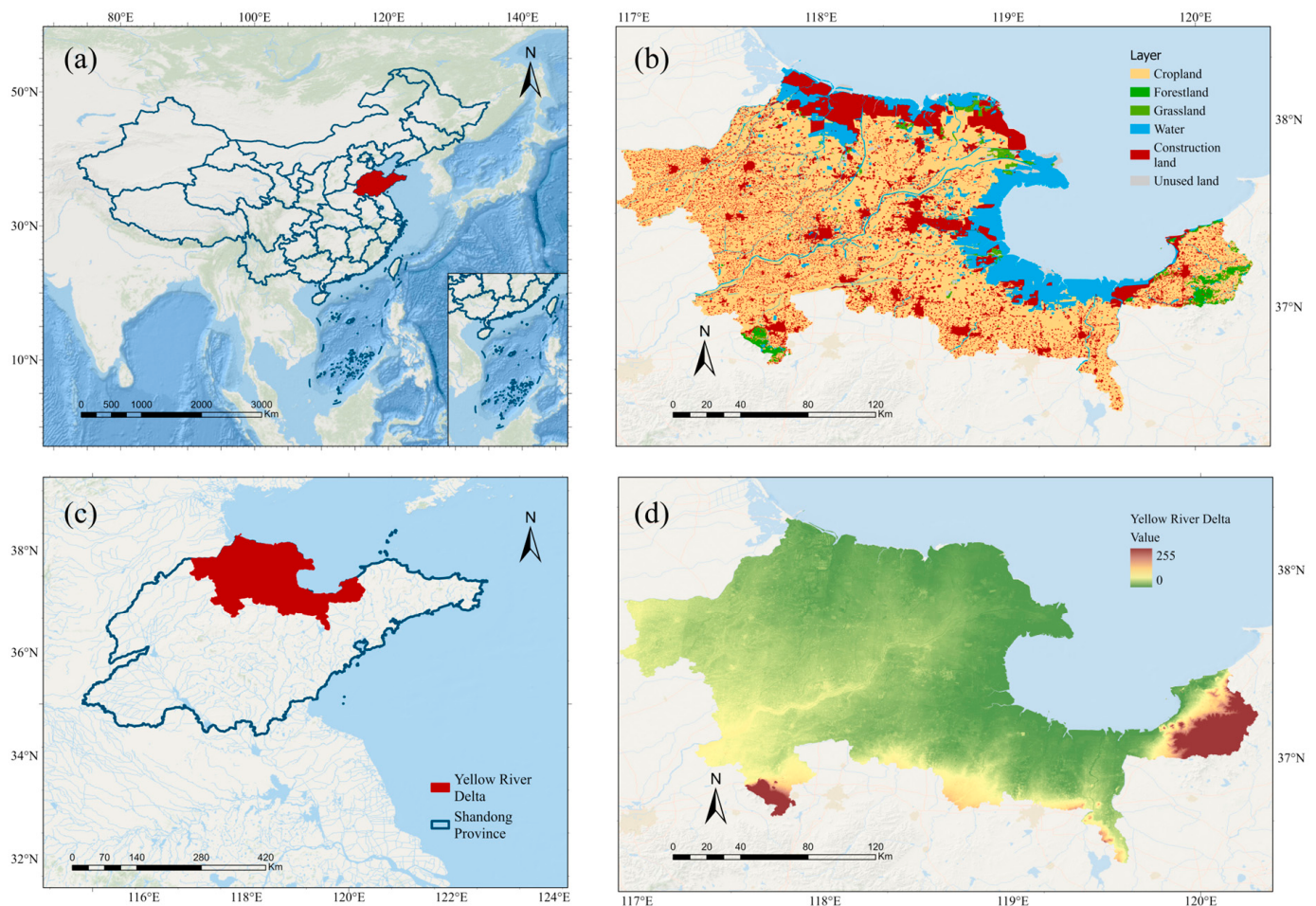


Figure 1. Overview map of the study area. (a) Map of China; (b) Land Use Distribution Map of the Yellow River Delta, 2020; (c) Administrative Boundaries of Shandong Province; (d) represents the DEM distribution map.

2.2. Data Sources and Preprocessing

This study constructs the ecological security pattern (ESP) of the Yellow River Delta under different scenarios and simulates its changes using land use data, as well as data on various socioeconomic and natural factors, as shown in Table 1.

Table 1. Table of data sources.

Data Type	Data Name	Original Resolution	Data Source
Land use data	Land use data (2000, 2010, 2020)	30 m	Resources and Environment Data Center, Chinese Academy of Sciences https://www.resdc.cn/ (accessed on 20 September 2024)
	DEM	30 m	Shuttle Radar Topography Mission (SRTM) DEM https://earthexplorer.usgs.gov/ (accessed on 13 June 2025)
	Slope	30 m	Geospatial Data Cloud https://www.gscloud.cn/ (accessed on 23 September 2024)
Natural factors data	Annual average temperature Annual average precipitation	1 km 1 km	Resources and Environment Data Center, Chinese Academy of Sciences https://www.resdc.cn/ (accessed on 2 November 2024)
	Soil type	1 km	Harmonized World Soil Database https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on 2 November 2024)
	evaporation	1 km	National Earth System Science Data Sharing Service Platform https://nnu.geodata.cn/index.html (accessed on 2 November 2024)
	NDVI	1 km	MODIS/Terra Vegetation Indices https://search.earthdata.nasa.gov/ (accessed on 2 November 2024)
	Population	1 km	WorldPop https://hub.worldpop.org/ (accessed on 23 September 2024)
Socio-economic data	GDP	1 km	Resources and Environment Data Center, Chinese Academy of Sciences https://www.resdc.cn/ (accessed on 23 September 2024)
Accessibility data	Distance to residential point	30 m	OpenStreetMap https://www.openstreetmap.org/#map=11/1.3649/103.8229 (accessed on 24 September 2024), Calculating Euclidean Distances Using ArcGIS
	Distance to highway	30 m	
	Distance to national highway	30 m	
	Distance to provincial highway	30 m	
	Distance to railroad	30 m	
	Distance to water	30 m	

2.3. Technical Route

As illustrated in Figure 2, the first stage involved the acquisition of both natural and socioeconomic datasets, followed by their preprocessing to ensure consistency and accuracy. In the second stage, the PLUS model was applied to simulate land use zoning and spatial distribution for the year 2040 under three alternative scenarios, accompanied by an analysis of land expansion in each case. The third stage integrated habitat quality evaluation, morphological spatial pattern analysis (MSPA), and assessments of landscape connectivity to identify core habitat patches and potential ecological source areas. Based on the optimized resistance surface, ecological corridors and critical ecological pinch points were delineated using circuit theory. Finally, in the fourth stage, ecological security patterns (ESPs) of the Yellow River Delta were constructed and analyzed across the three 2040 scenarios. To enable comparative evaluation, hexagonal grid analysis was conducted for both univariate and multivariate statistics, which ultimately informed the design of a restoration framework characterized as “five zones, one belt, one center, and multiple corridors.”

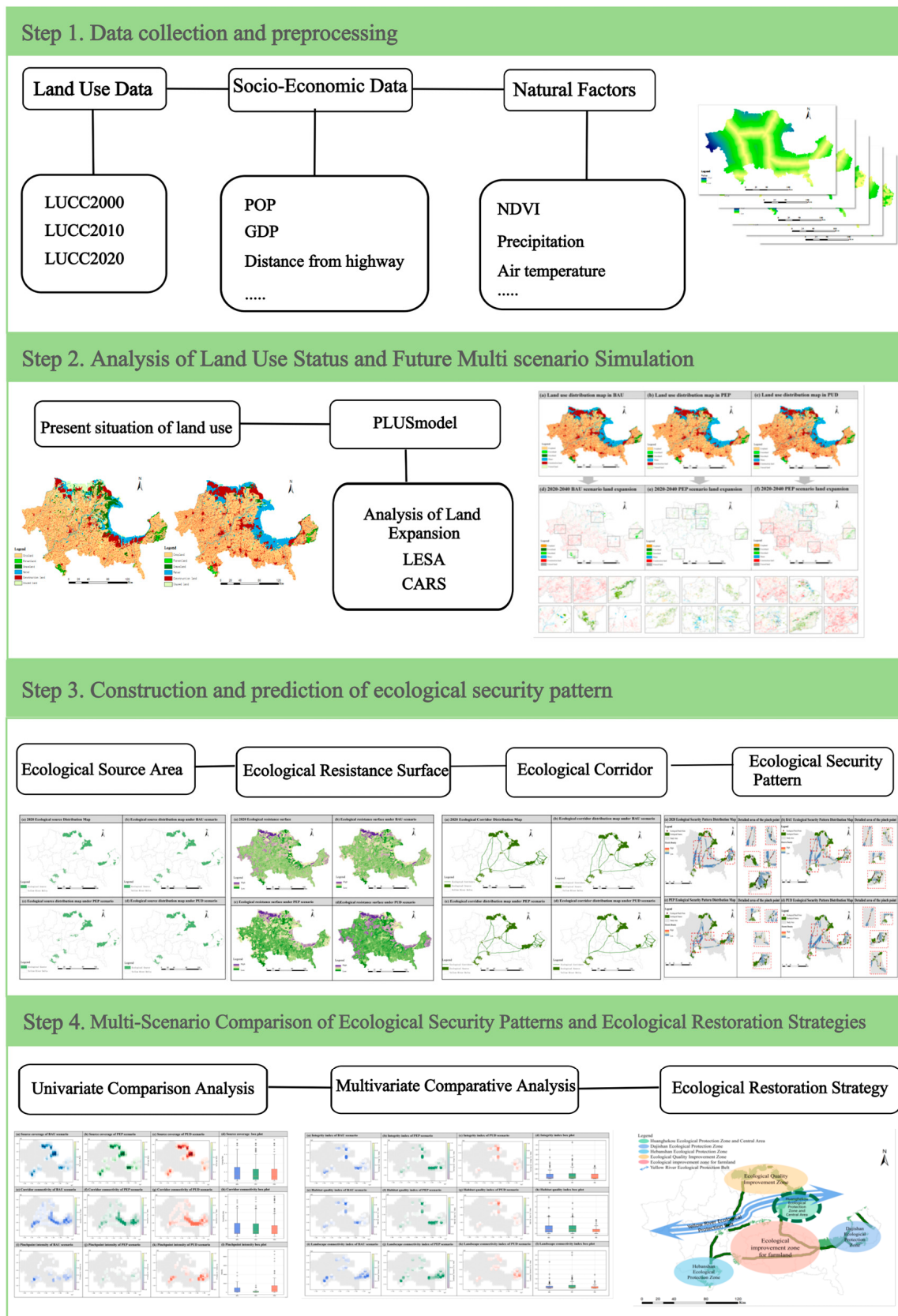


Figure 2. Technology roadmap.

2.4. Spatio-Temporal Simulation of LUCC in the Yellow River Delta Region in 2040

(1) Spatio-temporal simulation of land use change

This study employs the PLUS v6.5 (Patch-generating Land Use Simulation) model to conduct multi-scenario simulations projecting the 2040 land use pattern in the Yellow River Delta. The model consists of two core modules: the Land Use Expansion Analysis Strategy (LEAS) and the Randomized Patch Generation Mechanism (CARS). The LEAS module employs machine learning techniques, including random forests, to characterize the spatial relationships between land use changes and their driving factors, producing probability distribution maps for different land categories. Drawing on relevant literature, 15 natural and socioeconomic factors—including topography, climate, soil, transportation accessibility, and population density—were identified as key driving variables (Table 2). The CARS module simulates land use transitions by generating random patches of multiple types, varying scales, and diverse shapes, thereby effectively overcoming the limitations of traditional cellular automata models in capturing fine-scale land use changes [23]. While this mechanism significantly enhances the accuracy of local landscape dynamics simulations, it may introduce local biases due to excessive randomness. To mitigate these biases, parameter calibration and multi-year data validation were conducted, ensuring the stability and reliability of the results.

Table 2. PLUS model Driving factors.

Type	Driving Factors
Natural factors	DEM
	Slope
	Soil
	Annual average temperature Annual average precipitation
Socio-economic data	GDP
	POP
Accessibility data	Distance to water
	Distance to residential point
	Distance to highway
	Distance to railroad
	Distance to national highway Distance to provincial highway

(2) PLUS model parameter setting

The cost matrix represents the potential for mutual conversion among landscape types. Accordingly, the land use conversion matrix defines the feasibility of transformations between land use types, where a value of 1 denotes convertibility and 0 denotes non-convertibility. In this study, water bodies were treated as restricted conversion zones. This matrix incorporates expert knowledge and published research findings [31] to provide a comprehensive definition of conversion conditions for various land use types (Figure 3). Neighborhood weight parameters are used to reflect the relative difficulty of conversion between landscape types [32,33], ranging from 0 to 1, with higher values indicating greater expansion potential (Table 3).

Table 3. Neighborhood Weighting.

	Cropland	Forestland	Grassland	Water	Construction Land	Unused Land
Neighborhood Weight	0.10	0.38	0.24	1	0.74	0.31

2020							BAU						
	a	b	c	d	e	f		a	b	c	d	e	f
a	1	1	1	0	1	1	a	1	1	1	0	1	0
b	1	1	1	0	1	1	b	1	1	1	0	1	1
c	1	1	1	0	1	1	c	1	1	1	0	1	1
d	1	1	1	1	1	1	d	1	1	1	1	1	1
e	0	0	0	0	1	1	e	1	1	1	0	1	1
f	0	0	0	0	0	1	f	1	1	1	0	1	1
PEP							PUD						
	a	b	c	d	e	f		a	b	c	d	e	f
a	1	1	1	0	1	1	a	1	1	1	0	0	1
b	1	1	1	0	1	1	b	1	1	1	0	0	1
c	1	1	1	0	1	1	c	1	1	1	0	0	1
d	1	1	1	1	1	1	d	1	1	1	1	1	1
e	0	0	0	0	1	1	e	1	1	1	0	1	1
f	0	0	0	0	0	1	f	1	1	1	0	0	1

Figure 3. Land Use Transition Matrix. **a** represents arable land, **b** represents forested land, **c** represents grassland, **d** represents water bodies, **e** represents construction land, **f** represents unutilized land.

(3) LUCC Simulation Results Verification

Before predicting land use changes under future scenarios, it is essential to validate the effectiveness of the PLUS model parameter settings. Accuracy was assessed using Overall Accuracy (OA) and the Kappa coefficient. OA represents the proportion of correctly classified pixels, whereas the Kappa coefficient measures the consistency between simulated results and actual conditions by accounting for random agreement [34]. The Kappa coefficient is calculated as follows:

$$Kappa = (P_o - P_e) / (1 - P_e) \quad (1)$$

where P_o represents observed agreement and P_e denotes expected agreement. According to Landis and Koch's (1977) criteria, Kappa values greater than 0.80 indicate excellent agreement, values between 0.60 and 0.80 represent good agreement, and values between 0.40 and 0.60 indicate moderate agreement. In land use simulation studies, OA is typically required to exceed 75%, with Kappa values ranging from 0.70 to 0.85 [23,34,35]. In this study, land use data from 2000 and 2010 were used as inputs to simulate the 2020 land use pattern. Comparison with actual 2020 data yielded a Kappa coefficient of 0.85 and an OA of 0.92.

2.5. Design of Three Regional Development Scenarios

To reflect the current development status of the Yellow River Delta, three scenarios—Business-As-Usual (BAU), Priority Urban Development (PUD), and Priority Ecological Protection (PEP)—were developed to simulate future land use changes. The area of each land use category under different scenarios was adjusted according to the probability of land use transitions in the Markov chain. To ensure both scientific validity and operational feasibility, conversion probabilities were established based on historical land use change rates, national and regional planning documents, and empirical values from the literature [28,29,36,37]. Adjustment probabilities were set between 10% and 30% to ensure consistent land use changes across scenarios. The specific designs of the three scenarios are as follows:

(1) BAU scenario: This scenario is based on historical land use trends of the Yellow River Delta from 2000 to 2020, excluding the effects of policies or other external drivers. It

represents minimal human intervention and reflects the intrinsic evolutionary dynamics of land use structure. All land use demands were projected using the Markov chain model.

(2) PUD scenario: This scenario prioritizes urban development and is informed by the National Territorial Space Planning Outline (2021–2035), the Shandong Provincial Territorial Space Master Plan, and the study of Nie et al. (2023) [28]. In this scenario, the probability of converting cultivated land, forest land, grassland, and unused land into construction land was increased by 25%, whereas the probability of converting construction land into other land types was reduced by 30%. The probability of converting construction land back into cultivated land remained unchanged.

(3) PEP scenario: This scenario was designed to expand ecological land and restrict the encroachment of construction land, seeking a balance between socioeconomic development and ecological conservation. Based on the Ecological Protection and High-Quality Development Plan for the Yellow River Basin and the studies of Ma et al. (2024) and Nie et al. (2023) [28,29], the probability of converting farmland, forest land, grassland, water bodies, and unused land into construction land was reduced by 30%, while the probability of converting construction land into other land types (excluding farmland) was increased by 15%.

In all scenarios, water bodies are designated as ecological constraint zones because they are non-developable. Furthermore, land use transition probabilities are adjusted for each scenario according to land use data obtained from Markov chain simulations.

2.6. Ecological Security Pattern Construction

2.6.1. Identification of Ecological Source Areas

Ecological sources are regarded as essential habitat patches that sustain ecological processes, safeguard ecosystem integrity, and provide substantial ecological functions and services. Such areas play an indispensable role in maintaining ecosystem functioning and are typically characterized by high species richness, strong ecological resilience, and significant contributions to ecosystem service provision [13,38–40]. To identify these sources, the InVEST 3.14.2 model was first applied to evaluate habitat quality within the Yellow River Delta. Habitat quality values were categorized into five grades using the natural breakpoint method, of which levels IV and V were incorporated into Morphological Spatial Pattern Analysis (MSPA). The MSPA results were subsequently processed in the Conefor26 software to assess landscape connectivity, and habitat patches with dPC values exceeding 0.2 were classified as core areas.

1. Habitat quality

Habitat quality represents a fundamental measure of ecological value and is closely linked to biodiversity at the regional scale. In this study, the InVEST model was adopted to compute a habitat quality index that reflects the overall condition of the ecological environment [41–43]. The index ranges from 0 to 1, where higher values signify greater biodiversity and reduced human disturbance. Details of the threat factors incorporated into the model are listed in Supplementary Materials Table S1. The calculation formula is presented as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + K^z} \right) \right] \quad (2)$$

where Q_{xj} denotes the habitat quality of assessment unit x of land type j , D_{xj} denotes the threat level of unit x of land type j , H_j denotes the habitat suitability of land type j , K denotes the half-saturation constant, which is usually equal to half of the maximum value of D_{xj} , and z denotes the normalization constant, which is usually specified as 2.5.

2. MSPA

The MSPA methodology is applied to examine spatial patterns and morphological characteristics and is therefore particularly suited for analyzing landscape structure and spatial distribution. This approach quantifies the morphological attributes of landscape patches, elucidates the relationship between spatial patterns and ecological functions, and thus, provides insights into their ecological significance and associated processes [13,28]. Based on the characteristics of the Yellow River Delta and previous studies [44,45], water bodies and forested areas were identified as critical habitats that play a central role in sustaining regional biodiversity and supporting ecosystem services. Accordingly, a value of 2 was assigned to water bodies and forested areas, whereas all other land use types were assigned a value of 1.

3. Landscape Connectivity Calculation

Following the completion of the MSPA, connectivity assessments were performed on the core patches identified by MSPA, as well as other critical landscape elements. Core patches extracted through MSPA were used as ecological source units, with their areas and spatial coordinates calculated, and a patch-to-patch distance matrix constructed based on the shortest Euclidean edge-to-edge distances. Subsequently, Conefor26 software was applied to calculate three landscape connectivity metrics: Probability of Connectivity (PC), Integral Index of Connectivity (IIC), and the patch-level contribution index (dPC). Patches with dPC values greater than 0.2 were classified as core patches [15,29,46]. The formulas are as follows:

$$PC = \frac{1}{A_L^2} \sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij} \quad (3)$$

$$IIC = \frac{1}{A_L^2} \sum_{i=1}^n \sum_{j=1}^n \frac{a_i a_j}{1 + l_{ij}} \quad (4)$$

$$dPC_K = \frac{PC - PC_k}{PC} \times 100\% \quad (5)$$

Here, a_i and a_j denote the areas of ecological source sites; p_{ij} represents the probability of corridor connectivity, reflecting the corridor's role in maintaining the overall ecological network; and l_{ij} refers to the number of edges in the shortest corridor path between two source sites, quantifying its contribution to the topological structure. The PC value ranges from 0 to 1, with higher values indicating stronger landscape connectivity and lower values indicating weaker connectivity. The dPC value evaluates the relative importance of ecological source areas in maintaining connectivity: a higher dPC value indicates greater importance, whereas a lower value denotes lesser importance.

2.6.2. Ecological Resistance Surface

The resistance surface denotes the baseline values that govern ecological processes among different habitat patches and captures the cost implications of species dispersal and energy transfer across heterogeneous landscapes [47,48]. In this study, both natural and socioeconomic dimensions were integrated into the resistance surface design. Five key variables were incorporated, including land use category, normalized difference vegetation index (NDVI), proximity to settlements, proximity to rivers, and distance from major roads. Factor weighting was determined using the Analytic Hierarchy Process (AHP), with subsequent adjustments tailored to reflect the objectives of each scenario. For the BAU scenario, the weights of the resistance factors were assigned according to current development trajectories, thereby ensuring a relatively balanced contribution across all variables. In contrast, the PUD scenario, which emphasizes urban growth, was characterized by reduced weights for socioeconomic proximity factors such as distance from roads and settlements, while

natural factors were assigned higher resistance values. Under the PEP scenario, where ecological conservation is prioritized, the resistance contribution of natural factors was markedly strengthened, whereas the relative importance of socioeconomic elements was reduced. A judgment matrix was developed to derive the factor weights and verify their consistency ($CR < 0.1$). The resulting weight distributions for each scenario are presented in Table 4, with detailed parameters provided in Supplementary Materials Table S7.

Table 4. Resistance factor weights for each scenario.

Resistance Factor	Weights			
	2020	BAU	PUD	PEP
Land use type	0.19	0.14	0.26	0.32
NDVI	0.09	0.10	0.07	0.10
Distance to water	0.09	0.29	0.07	0.10
Distance to railroad	0.31	0.22	0.29	0.23
Distance to residential point	0.31	0.22	0.29	0.23
Consistency Ratio	0.011	0.065	0.003	0.044

2.6.3. Extraction of Ecological Corridors and Pinch Points

An ecological corridor is a linear or strip-shaped ecological landscape that integrates ecological, cultural, and social functions and serves as a vital conduit for the exchange of matter, energy, and information within ecosystems [49–51]. In this study, LinkageMapper v 3.1.0. software was applied to extract ecological corridors and pinch points based on circuit theory. Voltage sources were assigned to ecological source sites to simulate species dispersal origins, while ground terminals were placed at potential sink sites, thus establishing complete current conduction pathways [21]. Current values represent the probability distribution of species dispersal across different resistance surfaces, thereby delineating the spatial patterns of corridors. To minimize arbitrary parameterization, relevant studies [21,52] were consulted, and standardized resistance values along with fixed voltage differences were employed to ensure comparability among different source sites. Unlike the single-path optimization of the Minimum Cumulative Resistance (MCR) model, circuit theory identifies multiple potential corridors and “pinch points” through random current walks, thus providing a more accurate representation of species dispersal processes in heterogeneous landscapes [53].

Current density was evaluated using the Pinchpoint Mapper function embedded in the Linkage Mapper toolbox. Based on the natural breakpoint classification, current density values were divided into five categories. Pinchpoints were then identified as those locations exhibiting the highest current density within each category. The corresponding calculation formula is given as follows:

$$I = V/R_{eff} \quad (6)$$

where I represents current, V represents voltage, and R_{eff} is the resistance of one or more conductors. It is regarded as an index of spatial isolation between ecological sources since R_{eff} in a parallel circuit decreases with the number of circuit paths and the corresponding current increases. The higher the value of I , the higher the probability of migration of species or genes.

2.6.4. Univariate and Multivariate Comparisons Based on Hexagonal Binning

To quantitatively compare ecological pattern differences across scenarios, this study applied hexagonal binning to standardize and aggregate spatial data. This approach replaces administrative units or irregular grids with regular hexagonal cells, thereby reducing scale-induced bias while balancing local detail and overall patterns, ensuring spatial

comparability across multiple scenarios [54,55]. Determining the grid scale is a critical step in spatial analysis. In this study, the side length of each hexagon was set to 10 km (area $\approx 260 \text{ km}^2$) based on the following principles: (1) this scale corresponds to the daily home ranges (5–15 km) of key protected species in the Yellow River Delta (e.g., Oriental Stork and Red-crowned Crane) [56], thus capturing population-level habitat use and connectivity; (2) the study area covers approximately $26,500 \text{ km}^2$, yielding 102 hexagonal units, which provides an adequate sample size ($n > 100$) for robust statistical inference [57]; and (3) a larger grid scale smooths local spatial dependencies, creating appropriate analytical units for spatial autocorrelation tests [58,59].

Because ecological elements (sources, corridors, and pinch points) may exhibit spatial dependence, potentially violating the independence assumption of traditional parametric tests, spatial autocorrelation was first assessed for all indicators. The global Moran's I statistic was employed to evaluate the degree of spatial clustering across scenarios [60,61]. To account for spatial autocorrelation, a spatially robust permutation test was employed as the primary method for statistical inference. This procedure produces a null distribution through the random permutation of scenario labels while maintaining the spatial structure. First, the observed F-statistic (F_{obs}) was calculated. Next, scenario labels were permuted 9999 times, with the F-statistic (F_{perm}) calculated for each permutation. Finally, the p -value was obtained as follows [62,63]:

$$P = \frac{\sum (F_{perm} \geq F_{obs}) + 1}{9999 + 1} \quad (7)$$

Univariate analyses were conducted to compare ecological source area coverage, corridor density, and pinch-point intensity among the three scenarios. For indicators without significant spatial autocorrelation ($p > 0.05$), traditional ANOVA was applied, whereas for those with significant autocorrelation, permutation tests were used. For multivariate analysis, multiple ecological indicators (ecological integrity index, landscape connectivity index, habitat quality index) were integrated, and permutational MANOVA (PERMANOVA) was performed to holistically test differences among scenarios, thus providing a comprehensive assessment of the overall impact of land use changes on ecological security patterns [64–66].

3. Results

3.1. Land Use Projections Under Different Scenarios for 2040

The PLUS model was used to simulate land use patterns under three scenarios for the year 2040. To facilitate comparison of land category expansion across scenarios, changes in land use in 2040 relative to 2020 were extracted (Figure 4). Under the BAU scenario (Figure 4d), construction land, water bodies, and grassland experienced varying degrees of expansion. According to Table 4, construction land increased by 454.03 km^2 and water bodies by 31.87 km^2 , while arable land, unutilized land, and forest land decreased by 610.63 km^2 , 25.84 km^2 , and 7.6 km^2 , respectively. The BAU scenario follows the same trend observed from 2000–2020, with growth in construction land, grassland, and water bodies mainly resulting from the conversion of cultivated land, while smaller portions of cultivated and unutilized land were converted to water bodies and grassland (Figure 5). Under the PEP scenario (Figure 4e), ecological land area experienced substantial expansion, with forest land, grassland, and water bodies increasing by 257.54 km^2 , 403.62 km^2 , and 11.19 km^2 , respectively. Conversely, cultivated land, unutilized land, and construction land decreased by 234.27 km^2 , 9.54 km^2 , and 429.26 km^2 , respectively. This scenario prioritizes ecological conservation, thus minimizing the conversion of agricultural and ecological land into built-up areas. The increase in ecological land primarily results from the conversion of farmland

and construction land into forest and grassland, with minor mutual conversions. Expansion of water bodies primarily results from the conversion of small portions of farmland and unutilized land. In the PUD scenario (Figure 4f), construction land underwent the most pronounced expansion, while grasslands and water bodies also increased. As indicated in Table 5, construction land increased by 851.46 km², with grassland and water bodies expanding by 263.61 km² and 114.92 km², respectively. Cultivated land, forest land, and unutilized land decreased by 1097.39 km², 31.22 km², and 101.38 km², respectively. This scenario emphasizes urban economic development, thereby increasing the probability of converting ecological land into built-up areas. Consequently, agricultural and ecological land areas experienced substantial reductions. The expansion of construction land was primarily driven by the conversion of cultivated land, while grassland growth was primarily driven by mutual conversion between forest land and grassland and minor conversion from unutilized land.

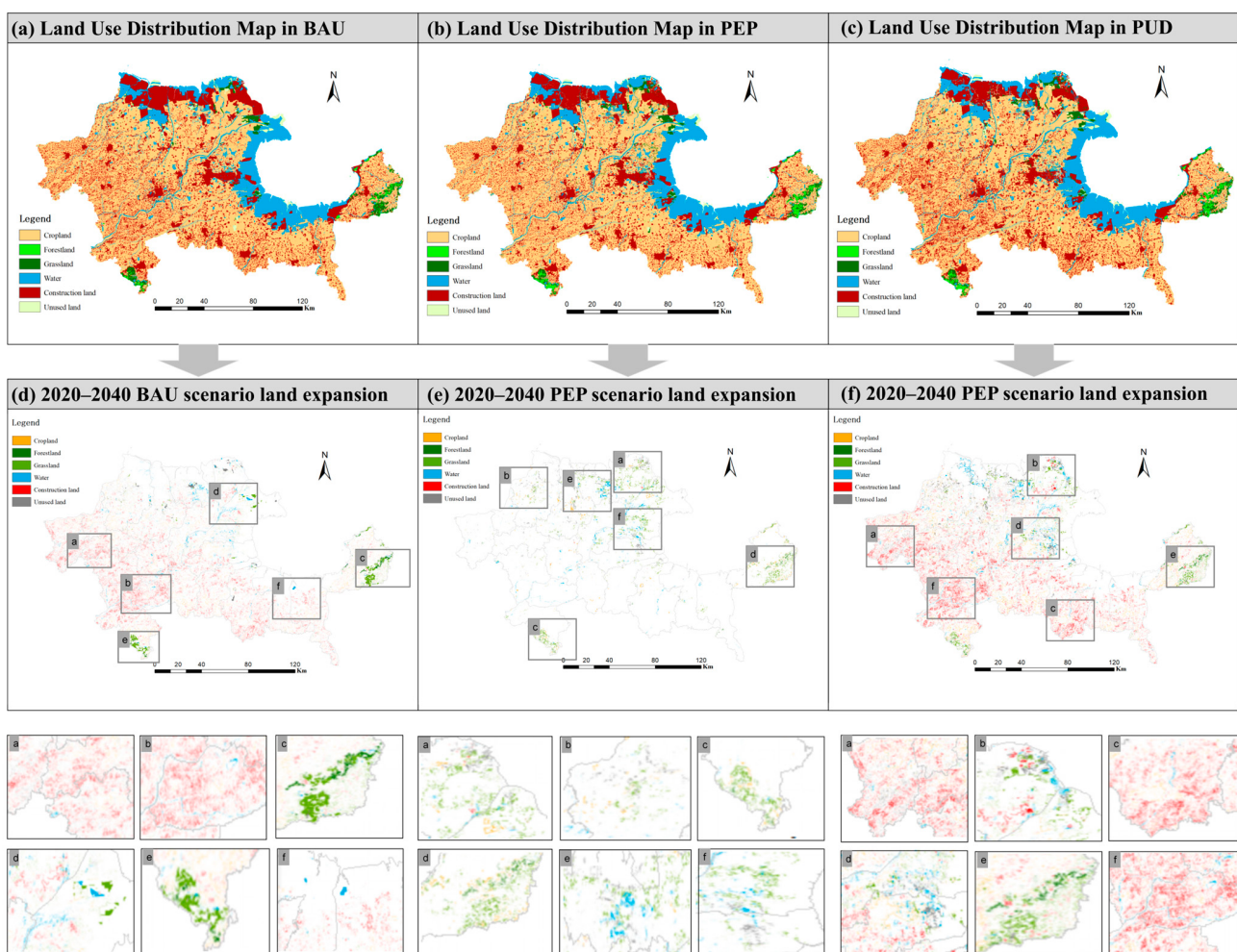


Figure 4. Projected Land Use Patterns in the Yellow River Delta under Different Scenarios in 2040. (a–c) Land Use Distribution Map Under BAU, PEP and PUD; (d–f) Land Use Expansion Under Different Scenarios.

Overall, all three scenarios experienced varying degrees of reduction in cultivated and unutilized land. Both the BAU and PUD scenarios experienced substantial increases in built-up areas, indicating rapid urbanization. In contrast, the PEP scenario exhibits the greatest expansion of ecological land and a decrease in built-up area, indicating that it represents the most favorable scenario for ecological conservation in the Yellow River Delta.

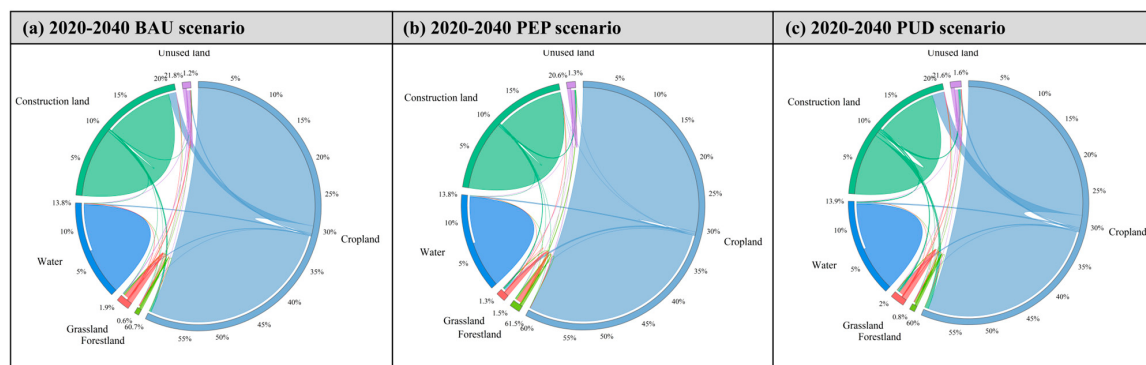


Figure 5. Changes in Land Use Types Under Different Scenarios.

Table 5. Land use analysis of three scenarios in the Yellow River Delta (unit: km²).

Landuse Type	2020	Years and Different Scenarios		
		BAU	PEP	PUD
Cropland	17,895.82	17,285.19	17,661.55	16,798.43
Forestland	148.67	141.07	406.21	117.45
Grassland	134.15	292.32	537.77	397.76
Water	4327.75	4359.62	4339.66	4442.67
Construction land	6063.12	6517.15	5633.86	6914.58
Unused land	305.32	279.48	295.78	203.94

3.2. Construction and Comparison of Ecological Security Patterns

3.2.1. Identification of Ecological Source Sites

By integrating high-value habitat quality distribution areas in the Yellow River Delta (Figure 6) with the results of the Multi-Scale Pattern Analysis (MSPA), 14 ecological source areas were identified in 2020, encompassing a total area of 3280.14 km². The average patch size was 243.30 km², with an average dPC index of 13.24. Among these, 10 patches had dPC > 5 (see Supplementary Materials Tables S2 and S3), accounting for 11.35% of the total area of the Yellow River Delta. Nature reserves and large forested areas provide habitats that support species survival and reproduction, contribute to climate regulation and air purification, and thus, serve as important ecological sources. Accordingly, the Yellow River Estuary Nature Reserve was designated as the primary ecological source area, followed by the extensive coastal wetlands with high ecological value. Forested regions in the western and southern parts of the Delta were also prioritized as ecological sources. Under the BAU scenario, 15 ecological source areas were identified, encompassing 3117.55 km² with an average patch size of 207.84 km² and an average dPC index of 13.42. Twelve patches had dPC > 5 (see Supplementary Materials Tables S2 and S4), covering 10.78% of the total area, with distribution patterns similar to those in 2020. Under the PEP scenario, 16 ecological source areas were identified, encompassing 3580.42 km² (12.39% of the total area), with an average patch size of 223.78 km² and an average dPC index of 11.40. Among these, 13 patches had dPC > 5 (see Supplementary Materials Tables S2 and S5). In this scenario, ecological source areas exhibited the most extensive and well-preserved coverage, with expansions in the central plains and eastern coastal wetlands. Under the PUD scenario, 12 ecological source areas were identified, encompassing 2696.33 km², with an average patch size of 224.69 km² and an average dPC index of 15.18. Nine patches had dPC > 5 (see Supplementary Materials Tables S2 and S6), accounting for 9.3% of the total area. Compared with 2020, ecological source areas decreased substantially under this scenario, mainly reflecting the prioritization of urban development, which led to reductions in ecological land.

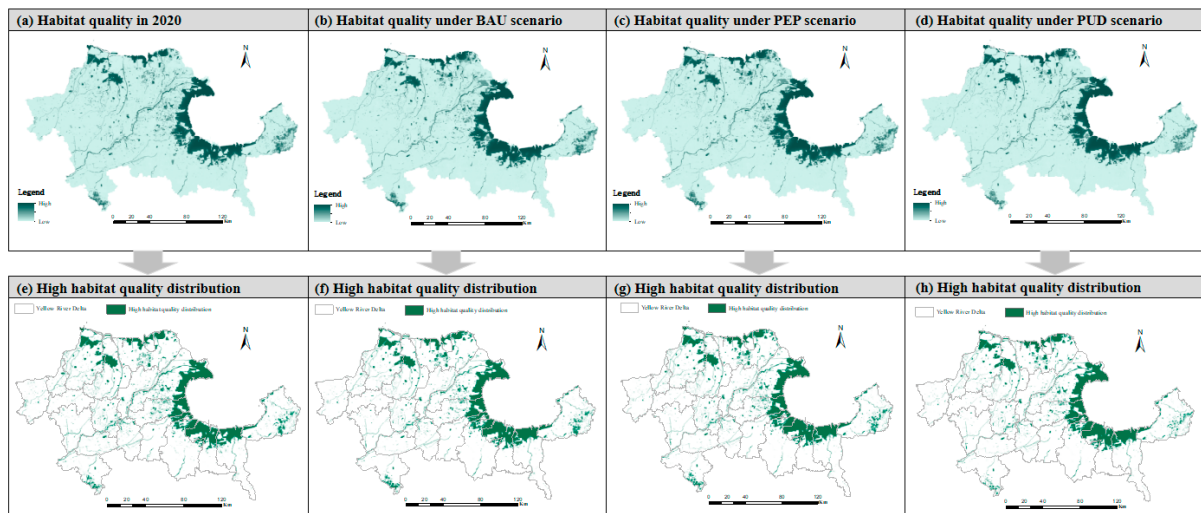


Figure 6. Habitat Quality Distribution Map of the Yellow River Delta in 2020 and Under Different Scenarios. (a–d) 2020 Habitat Quality Distribution Maps for BAU, PEP, and PUD; (e–h) 2020 High-Value Distribution Map of BAU, PEP, and PUD Habitat Quality.

As illustrated in Figure 7, the spatial distribution of ecological source sites in the Yellow River Delta is highly uneven. These areas are concentrated in the eastern coastal zone and the Yellow River Mouth Nature Reserve, which are predominantly composed of forest and water bodies. These regions provide high-quality habitats characterized by dense vegetation, minimal human disturbance, a favorable ecological environment, and low degradation risk. By contrast, ecological source areas are less abundant in the peripheral zones, and the central part of the delta contains relatively fewer source sites.

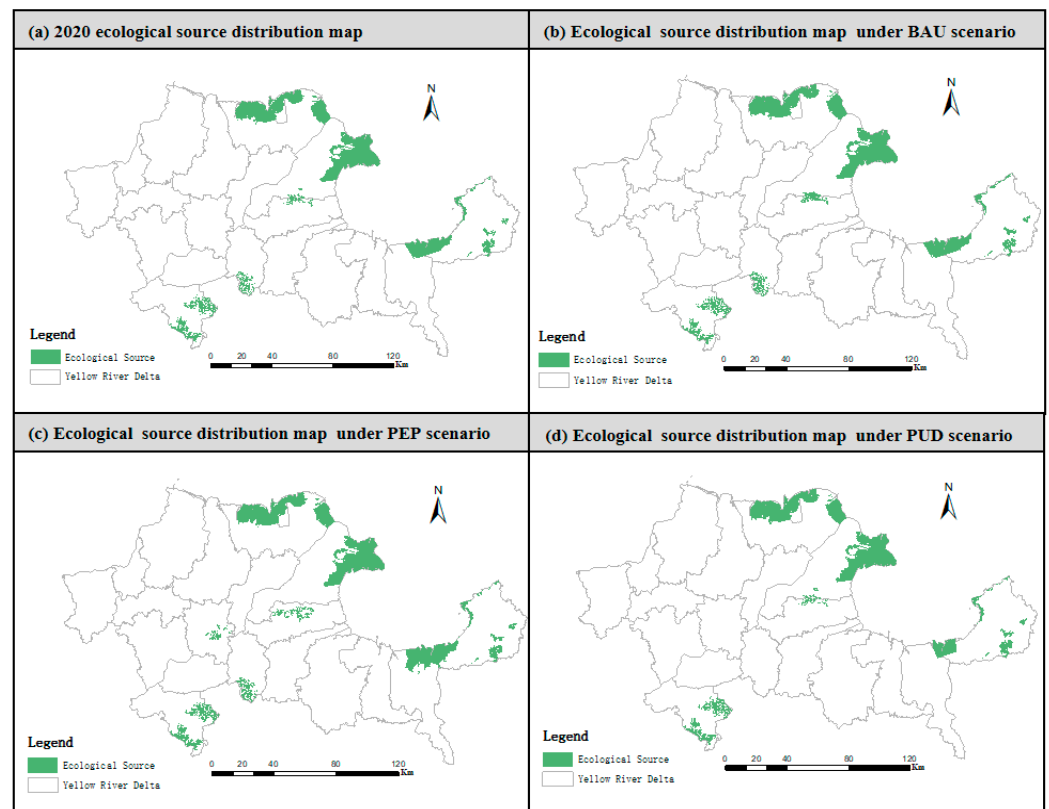


Figure 7. Spatial Pattern of Ecological Sources in the Yellow River Delta. (a–d) Ecological source distribution map in 2020, BAU, PEP and PUD.

3.2.2. Ecological Resistance Surface Construction

The ecological resistance values ranged from 0 to 1. As shown in Figure 8, most areas within the Yellow River Delta exhibited low to moderate resistance levels, particularly in regions characterized by high ecological quality, dense river networks, and limited anthropogenic disturbance. Higher resistance values were predominantly observed in zones with extensive construction land and in transitional areas between cropland and water bodies, where human activity is more intensive and vegetation coverage is relatively low.

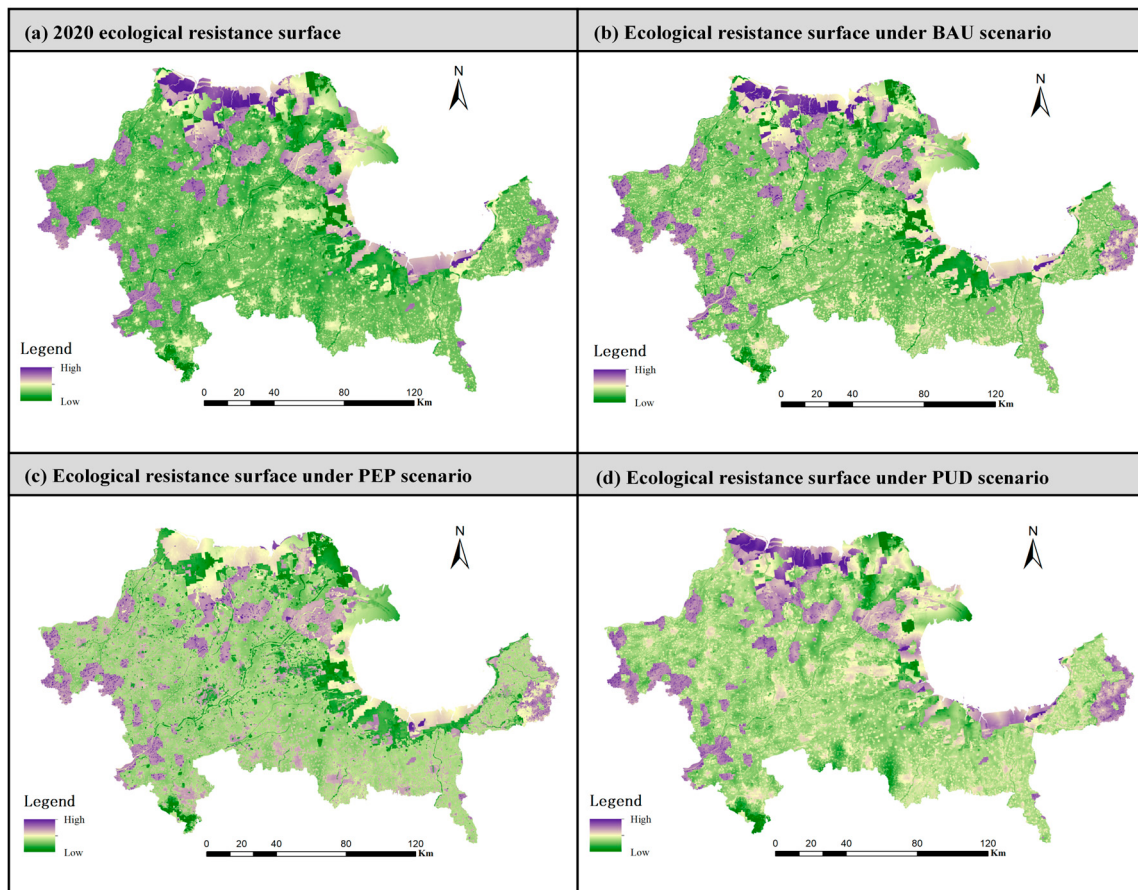


Figure 8. Distribution of ecological resistance surfaces in the Yellow River Delta. (a–d) Ecological resistance surfaces distribution map in 2020, BAU, PEP and PUD.

3.2.3. Ecological Corridor Extraction

Ecological corridors, functioning as the primary low-resistance pathways, are essential for strengthening ecological connectivity. In the Yellow River Delta, these corridors link fragile ecological sources in the Yellow River Estuary Nature Reserve with adjacent forest and wetland ecosystems distributed to the east and south. Circuit theory simulations revealed 29 ecological corridors in 2020 (Figure 9), with an average length of 44.97 km, the longest extending 171.85 km. The mean dPC index was 7.18, and 17 of the identified corridors recorded values above 5 (Supplementary Materials Tables S2 and S8). Within the BAU scenario, 32 corridors were delineated, totaling 1363.86 km, with a mean length of 42.62 km and a maximum length of 170.62 km. The average dPC index was 6.43, and 17 corridors displayed values exceeding 5 (Supplementary Materials Tables S2 and S9). The PEP scenario yielded 34 corridors, with a cumulative length of 1228.17 km, an average of 36.12 km, and the longest measuring 170.89 km. The corresponding mean dPC index was 6.68, with 21 corridors surpassing the threshold of 5 (Supplementary Materials Tables S2 and S10), indicating stronger connectivity among ecological sources. In contrast, the PUD scenario

produced 23 corridors, extending 1284.33 km in total, with an average of 55.84 km and a maximum of 197.30 km. Here, the mean dPC index rose to 9.19, with 14 corridors above 5 (Supplementary Materials Tables S2 and S11). Among all scenarios, the PEP case demonstrated the greatest number of ecological corridors and the highest count with dPC values over 5.

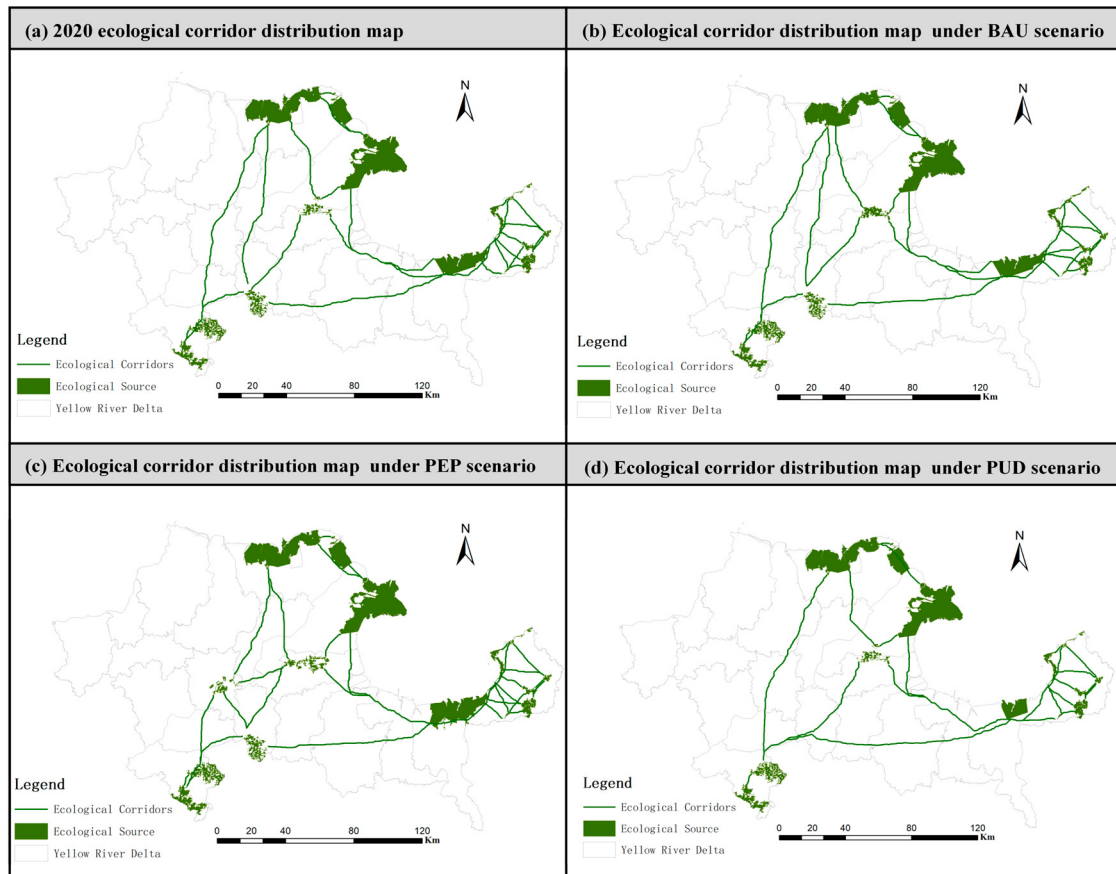


Figure 9. Distribution of ecological corridors in the Yellow River Delta. (a–d) Ecological corridors distribution map in 2020, BAU, PEP and PUD.

Ecological pinch points are indispensable for sustaining corridor connectivity, as they represent locations where species movement is concentrated. Circuit theory analysis identified 122 pinch points in 2020, covering 59.62 km² and mainly distributed across the Yellow River Estuary Nature Reserve, the central-eastern plains, and forested regions in the south and east. Dominant land use types in these areas included farmland, woodland, grassland, and aquatic systems. In the BAU scenario, 107 pinch points were recognized, covering 46.07 km², reflecting a notable reduction in both number and area compared with 2020. Under the PUD scenario, 99 pinch points were mapped, covering 40.35 km² and concentrated largely in central and eastern zones with relatively high density. By contrast, the PEP scenario produced 104 pinch points occupying 44.5 km², predominantly distributed in ecological corridors associated with the Daji Mountain forests in the east and the Hecuan Mountain forests in the south.

3.2.4. Multi-Scenario Ecological Security Pattern Construction

The construction of an Ecological Security Pattern (ESP) seeks to balance trade-offs between ecological protection and socioeconomic growth. By incorporating human demands, regulating ecological processes, and maintaining essential ecosystem functions, ESP provides a framework for advancing sustainable regional development. In the Yellow

River Delta, the past two decades have witnessed rapid expansion of construction land at the expense of ecological land, thereby intensifying conflicts between urbanization and conservation. As a result, ESP planning has become an indispensable approach to alleviating these pressures. The multi-scenario ESP (Figure 10) illustrates the uneven distribution of ecological resources across the region. Concentrations are found mainly in areas with limited human interference and dense vegetation cover, such as forest and aquatic habitats in the Yellow River Estuary Nature Reserve, the eastern Daji Mountain Reserve, and the southern Hebaishan Forest Area. Ecological corridors extend across farmland, forests, and wetlands, acting as vital conduits for species dispersal. Ecological nodes are concentrated in the central, eastern, and southern subregions, where land use is dominated by farmland, woodland, grassland, and aquatic systems. These nodes play a decisive role in maintaining corridor connectivity and therefore deserve prioritized protection. Across the three future scenarios, the general configuration of ecological security patterns resembles the 2020 baseline, though distinct differences exist. In the BAU scenario, the spatial extent and location of ecological sources remain comparable to 2020, with corridors and nodes in the northern estuary and southern mountain areas showing stability. However, ecological pinch points become more clustered in the eastern forest and waterbody zones. In the PUD scenario, intensified anthropogenic disturbance aggravates landscape fragmentation, leading to a marked decline in ecological source areas, greater structural complexity of corridors, reduced connectivity efficiency, and an overall deterioration of the ecological network. In contrast, the PEP scenario results in a substantial increase in ecological land, with additional ecological sources emerging in the central and western delta. This scenario supports the largest number of corridors and significantly strengthens network integrity and ecological connectivity.

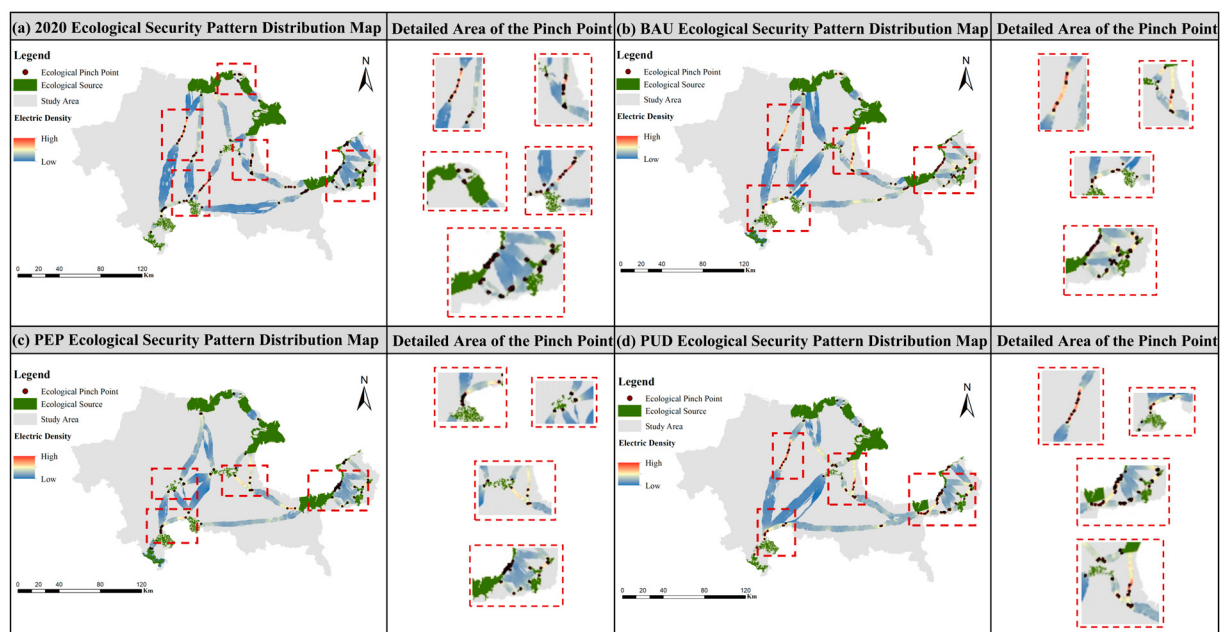


Figure 10. Distribution of Ecological Security Patterns in the Yellow River Delta. (a–d) Ecological security patterns distribution map in 2020, BAU, PEP and PUD.

Across the three simulated scenarios, the overall configuration of ecological security patterns resembled that of 2020. To evaluate potential differences, hexagonal binning was employed to facilitate both univariate and multivariate analyses. Moran's I spatial autocorrelation test was used to assess spatial dependence among ecological components (Supplementary Materials Table S12). Univariate comparisons indicated that in terms of

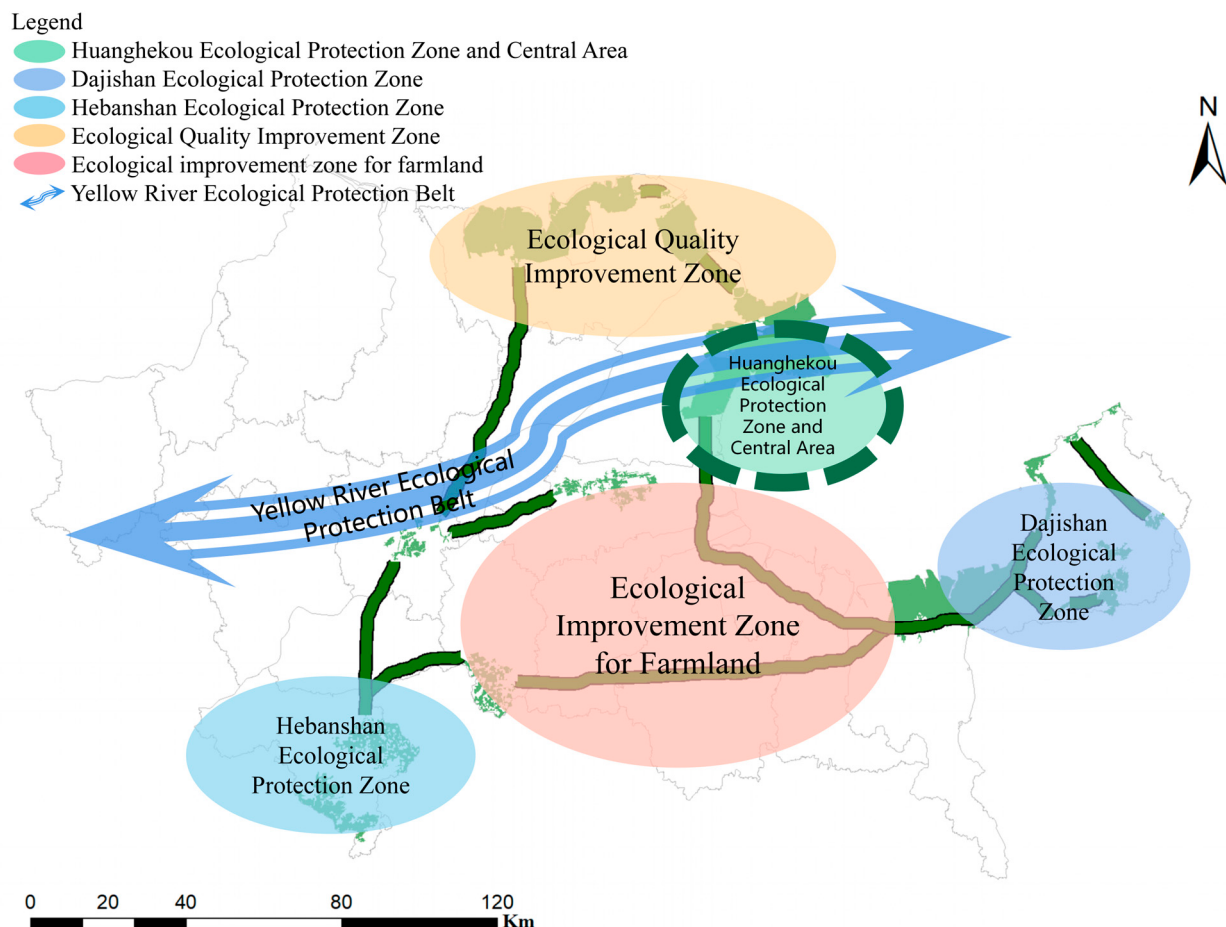
ecological source area coverage, the PEP scenario exhibited a value of 0.235, the BAU scenario 0.232, and the PUD scenario 0.231, suggesting that PEP yields slightly greater coverage with a stronger tendency toward continuous and concentrated distribution. Across all scenarios, ecological sources showed very low spatial autocorrelation ($I = 0.033\text{--}0.115$, $p > 0.05$), confirming that hexagonal binning effectively achieved spatial independence. Accordingly, traditional ANOVA was applied, yielding $F = 0.358$ and $p = 0.714$, indicating no significant differences in source coverage. These results suggest that ecological sources are largely shaped by baseline habitat conditions rather than planning scenarios. For corridor connectivity, the PEP scenario exhibited a score of 8, while BAU and PUD each exhibited scores of 6, indicating more continuous connectivity under PEP. Corridors displayed significant positive spatial autocorrelation (BAU: $I = 0.278$, $p < 0.001$; PEP: $I = 0.275$, $p < 0.001$; PUD: $I = 0.524$, $p < 0.001$), reflecting their inherent linear continuity. Due to this spatial dependence, a permutation test was employed (Supplementary Materials Table S13), which revealed no significant scenario differences in corridor density ($F = 0.254$, $p = 0.774$), length ($F = 0.254$, $p = 0.774$), or connectivity ($F = 0.018$, $p = 0.982$). For ecological pinch points, the PEP scenario exhibited an intensity of 400, BAU 600, and PUD 1000, indicating higher ecological risks under PUD, whereas PEP exhibited minimal pressure, greater spatial concentration, and more effective risk mitigation. Moran's I indicated mixed spatial patterns: BAU and PEP exhibited non-significant clustering ($I = 0.143$ and 0.101 , $p > 0.05$), whereas PUD showed significant aggregation ($I = 0.254$, $p = 0.036$), indicative of development-driven aggregation of bottlenecks. Permutation tests further confirmed significant differences in bottleneck density ($F = 3.459$, $p = 0.033$), number ($F = 3.459$, $p = 0.033$), and intensity ($F = 12.958$, $p < 0.001$). The average bottleneck density in PUD (0.020 points/km²) exceeded that of BAU and PEP by 54% (0.013 points/km²), and its maximum density was 2.3 times higher (0.108 vs. 0.046 points/km²). Multivariate analysis indicated that the ecological integrity index was highest under PEP (0.12), followed by BAU (0.10) and PUD (0.09), indicating the highest ecological integrity under PEP and the lowest under PUD. For landscape connectivity, both PEP and BAU scored 0.8 , while PUD scored 0.5 , reflecting pronounced landscape fragmentation under PUD. Habitat quality was also highest under PEP (0.20), moderate under BAU (0.12), and lowest under PUD (0.10), with PUD showing significant degradation and fragmentation. Moran's I confirmed significant positive spatial autocorrelation across all indicators (Supplementary Materials Table S13), with specific values as follows: BAU—integrity 0.281 , habitat quality 0.542 , and connectivity 0.286 ; PEP— 0.224 , 0.434 , and 0.250 ; PUD— 0.314 , 0.720 , and 0.524 (all $p < 0.001$), among which habitat quality under PUD exhibited the strongest clustering ($I = 0.720$). Finally, PERMANOVA results based on 9999 permutations indicated significant multivariate differences among scenarios (Pseudo- $F = 2.321$, $p = 0.043$; Supplementary Materials Table S14).

In summary, univariate and multivariate comparative analyses based on the hexagonal grid method demonstrate that the PEP scenario outperforms other scenarios across all principal dimensions of ecological conservation. It exhibits the highest ecological source coverage, strongest ecological integrity, optimal habitat quality, greatest landscape connectivity, and minimal ecological pinch point risk. These results indicate that ecological environmental quality is maximized under the PEP scenario, indicating that it represents the most favorable scenario for ecological development in the Yellow River Delta. The PUD and BAU scenarios represent contrasting outcomes: the PUD scenario performs poorly across all ecological conservation indicators, exhibits severely compromised network resilience, and faces systemic ecological risks, whereas the BAU scenario demonstrates moderate performance, representing a balanced development scenario that preserves spontaneous connectivity effects within ecological networks under natural conditions.

4. Discussion

4.1. Research on Ecological Restoration Strategies Based on Ecological Security Patterns

Based on the established ecological security pattern of the Yellow River Delta, the basin exhibits an imbalanced ecological structure. High-quality habitats and areas providing key ecosystem services are primarily concentrated in the Yellow River Estuary Nature Reserve, Daji Mountain, and Heban Mountain forest zones. Consequently, ecological restoration, biodiversity conservation, and enhancement of ecosystem services in the central and eastern regions are constrained, highlighting the need to optimize the basin's ecological security pattern. Ecological restoration strategies for the Yellow River Delta should consider ecological function importance, ecosystem vulnerability, connectivity, and sustainable agricultural practices. Guided by principles of spatial interaction and coordinated symbiosis, these strategies aim to strengthen existing ecological security patterns, protect and restore regional biodiversity, maintain ecosystem structure and process integrity, and enhance the ecological quality of land spaces [67,68]. Building on these insights, this study proposes an ecological restoration framework for the Yellow River Delta, structured as “five zones, one belt, one center, and multiple corridors” (Figure 11). The strategy encompasses five conservation and restoration zones (wetlands, forests, farmland improvement areas, riparian zones, and coastal conservation areas), one ecological belt (the Yellow River Estuary Ecological Belt), one ecological center (the Yellow River Estuary National Nature Reserve), and several ecological corridors that interconnect fragmented habitats. This spatial strategy provides a scientific basis for enhancing the ecological sustainability of the Yellow River Delta.



The “Five Zones” are divided into ecological conservation areas and ecological restoration areas. Ecological conservation areas prioritize regions with larger ecological source areas, higher habitat quality indices ($HQI > 0.6$), greater landscape connectivity (dPC values), or higher forest coverage. The Yellow River Estuary Nature Reserve, with an ecological source area of 571 km², an $HQI > 0.8$, and a landscape connectivity index of 8.15, represents the preferred ecological conservation area. However, recent soil salinization has caused wetland shrinkage and increased fragmentation, highlighting the need for ecological restoration measures. Restoration efforts include ditch dredging, grass planting, stock enhancement, converting farmland to wetlands, transforming aquaculture ponds to tidal flats, and wetland restoration. Coastal flood defenses should be strengthened, and impacts from oil extraction, aquaculture reclamation, and port activities mitigated. A systems-thinking approach should guide basin-wide ecological compensation, water and sediment regulation, and safeguarding of estuarine wetland flows, ensuring biodiversity protection and habitat connectivity through microcirculation restoration, bird habitat islands, and local ecological pattern optimization [69,70]. The Daji Mountain Provincial Nature Reserve in Laizhou City encompasses 89 km² of ecological source areas, dominated by natural red pine forests and mixed coniferous-broadleaf woodlands. It serves as the headwaters for multiple rivers, including the Baisha River. Habitat quality ranges from 0.6 to 0.85, with an average landscape connectivity index of 19.34, making it a key ecological conservation area. Conservation and restoration here are essential for protecting native red pine habitats, improving regional environments, and supporting sustainable development. Implementation of laws, regulations, and policies governing nature reserves, including resource archiving, rare plant protection, and endangered species rescue, is imperative [71]. Hebanshan National Forest Park in Zouping City encompasses an ecological source area of 285 km², with an HQI ranging from 0.6 to 0.82. Its 3.56 km² forested area features a 97% forest connectivity coverage rate, and the landscape connectivity index is 5.23, supporting its designation as an ecological conservation area. Conservation measures should minimize development in sensitive zones; protect existing forest land; enhance vegetation coverage; afforest slopes; restore bare mountains; construct reservoirs and ponds; and promote green ecological industries, such as ornamental planting, fruit cultivation, and ecotourism. Ecological restoration areas include ecological quality improvement zones and farmland ecological enhancement zones. Ecological quality improvement zones are located near high-value habitats, with strong connectivity but degraded ecological quality due to human disturbance. Within the Yellow River’s ancient course, wetlands span 600 km² with a landscape connectivity index of 11.94; however, prolonged anthropogenic activity has led to soil salinization, wetland degradation, biodiversity loss, and increased landscape fragmentation. Restoration measures should include saline–alkali land remediation, restoration of wetlands via farmland-to-wetland conversion, and locally tailored ecological improvements. Farmland ecological improvement zones comprise extensive farmland landscapes with low HQI (<0.3) but significant connectivity due to proximity to ecological sources or potential corridors. In the central Yellow River Delta and eastern coastal regions, farmland exhibits low HQI (0–0.3) but high connectivity (dPC = 15.34), rendering these areas suitable for targeted ecological restoration. These regions benefit from favorable climates, advanced agricultural technologies, and high urbanization levels. Shouguang City, known as the “National Vegetable Capital,” exemplifies high-value vegetable production. Restoration strategies should promote specialty and ecological agriculture, agritourism, and ecological services while advancing agricultural technologies to enhance farmland productivity and quality [72].

The “one belt” refers to the ecological protection belt formed by the Yellow River, which plays a significant role in safeguarding the ecological security of the entire Yellow

River Delta. As the second-longest river in China, the Yellow River is the “Mother River” of the Chinese nation. It deposits vast amounts of sediment into the Bohai Sea, forming the Yellow River Delta, which provides crucial habitats and supports biodiversity. Additionally, the river is vital for agricultural irrigation in the Delta. The river’s flow and sediment transport directly influence the geomorphology and coastline of the region, making it crucial for environmental and climate studies. To address the unique challenges of the Yellow River’s lower reaches, it is essential to allocate water resources effectively, enhance river basin protection, and implement coordinated land–sea management. Strengthening wetland conservation, ensuring ecological water replenishment, and improving water resource conservation are vital for the health of the Yellow River Delta ecosystem [71,72].

The “One Center, Multiple Corridors” approach focuses on the Yellow River Estuary Nature Reserve, involving the selection of 12 key ecological corridors to interconnect ecological source functional zones while minimizing intrusion into the central urban area. This design is intended to enhance regional ecological connectivity, thereby supporting overall ecosystem stability and facilitating sustainable development.

This approach aims to enhance regional ecological connectivity and foster the overall stability and sustainable development of the ecosystem.

4.2. Comparative Analysis Across Different Study Areas

Existing studies generally adopt an integrated approach combining land use simulation and landscape connectivity assessment to construct ecological security patterns across various regions. Li et al. (2023) [10] simulated the evolution of ecological security patterns under four scenarios—natural development, economic development, food security, and ecological priority—in the Pearl River Delta by integrating the FLUS model with the Minimum Cumulative Resistance (MCR) method. Their results indicated that the ecological network structure was most complete under the ecological priority scenario. Ma et al. (2024) [30] applied the PLUS model to simulate future construction land expansion in the Guangdong-Hong Kong-Macao Greater Bay Area. By integrating these simulations with ecological risk assessments and conducting overlay analyses, they identified the spatial distribution of ecological security vulnerabilities across scenarios. The study revealed that rapid construction land expansion under the economic priority scenario caused fragmentation of ecological source areas and reduced connectivity. In contrast, under the ecological conservation scenario, strict constraints on land use conversion preserved the integrity of ecological source areas and maintained the most stable corridor network, representing the optimal solution. Zhang et al. (2025) [73] employed long-term land use data to assess ecological network evolution under diverse development pathways using trend extrapolation and landscape connectivity metrics (e.g., IIC, PC). Their findings highlighted the persistent influence of cumulative historical human activities on ecological connectivity, with the ecological conservation scenario exhibiting substantially higher source area coverage and connectivity metrics, indicating enhanced resilience and network stability.

Compared with the present study, these prior works differ in content, methodology, and resistance surface construction. Li et al. (2023) [10] focused on the evolution of ecological security patterns under different development strategies in the Pearl River Delta, emphasizing trade-offs among economic growth, food security, and ecological conservation. They combined the FLUS and MCR models to identify ecological source areas and corridors, with resistance surfaces primarily derived from empirical values and literature references. This approach identified a single optimal path via MCR, potentially overlooking multi-path connectivity in complex landscapes. Ma et al. (2024) [30] examined the Guangdong-Hong Kong-Macao Greater Bay Area, emphasizing the spatial differentiation of urban expansion and ecological risks under multiple scenarios. They integrated PLUS simulations with

ecological risk assessments to develop a risk-warning framework, constructing resistance surfaces using literature values and suitability analyses to prioritize risk-sensitive areas. Zhang et al. (2025) [73] utilized long-term land use data to reveal cumulative effects of historical human activities on ecological networks, linking past LUCC trajectories to future patterns. Resistance surfaces were dynamically adjusted to account for cumulative historical land use impacts, with trend extrapolation and connectivity metrics employed to assess ecological network evolution.

4.3. Regional Ecological Security Patterns and Sustainable Development

The concept of sustainable development emphasizes the coordinated integration of ecology, society, and economy, seeking to satisfy present needs while safeguarding the capacity of future generations to meet theirs. In national territorial spatial planning and ecological conservation, this principle manifests as ensuring both the integrity and connectivity of ecosystems while accommodating reasonable socioeconomic demands [74]. The findings of this study indicate that the PEP scenario effectively limits construction land expansion while significantly enhancing the connectivity of ecological source areas and corridors, thereby strengthening the regional ecological security pattern. This highlights the practical significance of sustainable development at the regional scale. Ecologically, the PEP scenario embodies the principle of “ecological priority” by controlling construction land expansion and preserving ecological sources and corridors. Protecting wetlands, forests, and other high-ecosystem-service areas enhances carbon sequestration and climate regulation, aligning with UN SDGs 13 (Climate Action) and 15 (Life on Land). Socially, the PEP scenario mitigates urban heat island effects and flood risks while maintaining ecological connectivity, providing residents with higher-quality living environments consistent with SDG 11 (Sustainable Cities and Communities). Economically, protecting key corridors and source areas under the PEP scenario supports ecotourism, green industries, and ecological compensation mechanisms, promoting green economic transformation in line with SDG 8 (Decent Work and Economic Growth) [75,76]. Optimizing the ecological security pattern (ESP) is not merely a scientific exercise but also a policy and governance challenge. As a national strategic zone, the Yellow River Delta is guided by policies such as the Outline Plan for Ecological Conservation and High-Quality Development of the Yellow River Basin, the “dual carbon” goals, and ecological conservation red lines. Therefore, future ESP optimization should integrate these policy objectives into scenario simulations to enhance relevance and applicability. Effective implementation also relies on collaborative governance among multiple stakeholders: local governments regulate land use, communities participate in conservation, and industrial sectors contribute to green transformation. Only through the synergy of policy constraints, scientific modeling, and stakeholder engagement can the Yellow River Delta achieve a dynamic balance among ecological restoration, optimized land use, and sustainable regional development.

In contrast, the PUD scenario, while promoting short-term economic growth, exacerbates ecological fragmentation, increases regional ecological security risks, and undermines long-term social and ecosystem stability. The BAU scenario maintains current conditions but yields limited improvements. These findings underscore that rational land use planning, the balance between ecological conservation and economic development, and the integration of policy guidance with multi-stakeholder coordination are key pathways for advancing regional sustainable development.

4.4. Research Limitations and Future Directions

Although this study systematically assessed the impacts of future land use changes on regional ecological patterns in the Yellow River Delta through multi-scenario simula-

tions and ecological security pattern construction, thereby offering practical guidance for harmonizing economic development with ecological conservation in other ecologically sensitive delta regions, certain limitations remain. First, the analysis of ecological resistance surfaces relied on a limited set of five factors, which may partially overlook the influence of other determinants on ecological pattern identification in the Yellow River Delta. To enhance the accuracy and comprehensiveness of assessments, it is recommended to incorporate additional natural factors (e.g., net primary productivity) and anthropogenic factors (e.g., landform morphology, landscape fragmentation, population density, and nighttime light index). Second, while the scenarios established in this study reflect different regional development orientations, they do not fully account for uncertainties such as climate change, extreme weather events, and socioeconomic policy adjustments, potentially introducing biases in future pattern projections. Furthermore, this study primarily focuses on regional-scale ecological sources, corridors, and nodes, without conducting detailed, integrated analyses of local ecological processes (e.g., dynamic changes in habitat quality and species migration behavior) [77,78].

Future research could be extended in several directions. First, employ multi-source remote sensing and ecological monitoring data to conduct long-term tracking and validation of dynamic changes in ecological security patterns. Second, explore integrating ecosystem service valuation with ecological security pattern construction to better capture the coordination between ecological conservation and regional development. Third, enhance multi-scale integrated research to reveal the intrinsic mechanisms of ecological processes from regional to local levels.

5. Conclusions

An integrated framework was established to combine land use simulation, multi-scenario ecological security pattern construction, and scenario comparison analysis. By incorporating the PLUS model, Morphological Spatial Pattern Analysis (MSPA), habitat quality assessment, circuit theory, and hexagonal partitioning, the framework was used to quantitatively evaluate the impacts of future land use changes in the Yellow River Delta under different development scenarios on ecological security patterns. The results indicate that under the Prioritizing Ecological Protection (PEP) scenario, ecological source areas were estimated at 3580.42 km² (12.39% of the total area), which is considerably greater than 3117.55 km² (10.79%) under the Business-As-Usual (BAU) scenario and 2696.33 km² (9.33%) under the Prioritizing Urban Development (PUD) scenario. In terms of connectivity, the highest landscape and corridor connectivity indices were observed in the PEP scenario, with an ecological integrity index of 0.12. In contrast, substantial expansion of construction land was observed in the PUD scenario, leading to a reduction in ecological source areas and an increase in landscape fragmentation, with the fragmentation index rising to 0.31—about 63% higher than in the PEP scenario—thereby indicating greater ecosystem vulnerability. Overall, the PEP scenario is shown to not only maintain ecological connectivity but also to enhance habitat quality and preserve the spatial balance of the ecological network.

Based on these findings, an ecological restoration framework was proposed, consisting of five zones, one belt, one center, and multiple corridors. These consist of three ecological conservation zones, two ecological restoration zones, one ecological belt (the Yellow River Estuary Ecological Belt), one ecological center (the Yellow River Estuary National Nature Reserve), and multiple ecological corridors that link fragmented habitats. This framework provides a practical approach for coordinating economic development and ecological conservation in the Yellow River Delta. Furthermore, the limitations of earlier multi-scenario simulations were addressed, as these frequently lacked quantitative comparisons and statistical validation, thereby providing scientific evidence for optimizing ecological

security patterns and spatial planning in estuarine delta regions. It also serves as a reference for the formulation of sustainable strategies in other ecologically fragile areas worldwide. Finally, through parameter sensitivity analysis, historical data validation, and spatial substitution tests, the stability of the simulation results and the robustness of the statistical inferences were confirmed.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17209061/s1>, Figure S1: Land Use Distribution Maps of the Yellow River Delta in 2000 and 2020; Table S1: Threat Factors Table; Table S2: Results of Ecological Source Areas and Ecological Corridors in 2020 and Under Three Scenarios; Table S3: 2020 Ecological Source Area Connectivity Index; Table S4: BAU Scenario Ecological Source Connectivity Index; Table S5: PEP Scenario Ecological Source Area Connectivity Index; Table S6: PUD Scenario Ecological Source Area Connectivity Index; Table S7: Judgment Matrix; Table S8: 2020 Ecological Corridor Connectivity Index; Table S9: AU Scenario Ecological Corridor Connectivity Index; Table S10: PEP Scenario Ecological Corridor Connectivity Index; Table S11: PUD Scenario Ecological Corridor Connectivity Index; Figure S2: Univariate Analysis of Ecological Security Patterns Based on the Hexagonal Binning Method; Figure S3: Multivariate Analysis of Ecological Security Patterns Based on the Hexagonal Partitioning Method; Table S12: Results of the Univariate Spatial Autocorrelation Test; Table S13: Results of the Single Variable Permutation test; Table S14: Multivariate Permutation Test Result.

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References

1. Hu, S.; Niu, Z.; Chen, Y.; Li, L.; Zhang, H. Global wetlands: Potential distribution, wetland loss, and status. *Sci. Total Environ.* **2017**, *586*, 319–327. [\[CrossRef\]](#)
2. Foley, J.A.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; et al. Global consequences of land use. *Science* **2005**, *309*, 570–574. [\[CrossRef\]](#)
3. Van Vliet, J. Direct and indirect loss of natural area from urban expansion. *Nat. Sustain.* **2019**, *2*, 755–763. [\[CrossRef\]](#)
4. Zeng, W.; He, Z.; Bai, W. Identification of ecological security patterns of alpine wetland grasslands based on landscape ecological risks: A study in Zoigê County. *Sci. Total Environ.* **2024**, *928*, 172302. [\[CrossRef\]](#)
5. Li, Y.; Huang, S.; Kong, X. Ecological effects of surface water evolution in the Yellow River Delta. *Sustainability* **2022**, *14*, 13544. [\[CrossRef\]](#)
6. Su, Y.; Chen, X.; Liao, J. Modeling the optimal ecological security pattern for guiding the urban constructed land expansions. *Urban For. Urban Green.* **2016**, *19*, 35–46. [\[CrossRef\]](#)
7. Zhao, C.; Wu, S.; Yang, L. Evaluating ecological conservation effectiveness of security patterns under multiple scenarios: A case study of Hubei Province. *Ecol. Indic.* **2024**, *166*, 112528. [\[CrossRef\]](#)
8. Li, J.; Liang, L.; Chao, Y. Construction of the ecological security pattern of Mu Us sandy land on the basis of the “Source—Resistance—Corridor” theory. *Ecol. Indic.* **2025**, *171*, 113162. [\[CrossRef\]](#)

9. Wang, W.; Feng, C.; Liu, F. Biodiversity conservation in China: A review of recent studies and practices. *Environ. Sci. Ecotechnol.* **2020**, *2*, 100025. [\[CrossRef\]](#)
10. Li, L.; Huang, X.; Wu, D. Construction of ecological security pattern adapting to future land use change in Pearl River Delta, China. *Appl. Geogr.* **2023**, *154*, 102946. [\[CrossRef\]](#)
11. Yu, K. Security patterns and surface model in landscape ecological planning. *Landscape Urban Plan.* **1996**, *36*, 1–17. [\[CrossRef\]](#)
12. Dong, J.; Peng, J.; Xu, Z. Integrating regional and interregional approaches to identify ecological security patterns. *Landscape Ecol.* **2021**, *36*, 2151–2164. [\[CrossRef\]](#)
13. Chen, W.; Liu, H.; Wang, J. Construction and optimization of regional ecological security patterns based on MSPA-MCR-GA Model: A case study of Dongting Lake Basin in China. *Ecol. Indic.* **2024**, *165*, 112169. [\[CrossRef\]](#)
14. Vogt, P.; Riitters, K. GuidosToolbox: Universal digital image object analysis. *Eur. J. Remote Sens.* **2017**, *50*, 352–361. [\[CrossRef\]](#)
15. Li, Y.Y.; Zhang, Y.Z.; Jiang, Z.Y. Integrating morphological spatial pattern analysis and the minimal cumulative resistance model to optimize urban ecological networks: A case study in Shenzhen City, China. *Ecol. Process.* **2021**, *10*, 63. [\[CrossRef\]](#)
16. Huang, K.; Peng, L.; Wang, X. Integrating circuit theory and landscape pattern index to identify and optimize ecological networks: A case study of the Sichuan Basin, China. *J. Environ. Sci. Pollut. Res.* **2022**, *29*, 66874–66887. [\[CrossRef\]](#)
17. Saura, S.; Pascual-Hortal, L. A new habitat availability index to integrate connectivity in landscape conservation planning: Comparison with existing indices and application to a case study. *Landscape Urban Plan.* **2007**, *83*, 91–103. [\[CrossRef\]](#)
18. Saura, S.; Torné, J. Conefor Sensinode 2.2: A software package for quantifying the importance of habitat patches for landscape connectivity. *Environ. Model. Softw.* **2009**, *24*, 135–139. [\[CrossRef\]](#)
19. Fida, T.; Mohammadi, A.; Almasieh, K.; Bosso, L.; Din, S.U.; Shamas, U.; Nawaz, M.A.; Kabir, M. Species distribution modelling and landscape connectivity as tools to inform management and conservation for the critically endangered Himalayan brown bear (*Ursus arctos isabellinus*) in the Deosai National Park, Pakistan. *Front. Ecol. Evol.* **2025**, *12*, 1477480. [\[CrossRef\]](#)
20. Zhang, T.; Chen, W.; Sheng, Z.; Wang, P.; Guan, F. Ecological network construction and identification of important elements based on morphological spatial pattern analysis and circuit theory in Xi'an City. *J. Nat. Conserv.* **2025**, *86*, 126902. [\[CrossRef\]](#)
21. McRae, B.H.; Beier, P. Circuit theory predicts gene flow in plant and animal populations. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 19885–19890. [\[CrossRef\]](#)
22. McRae, B.H.; Dickson, B.G.; Keitt, T.H. Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology* **2008**, *89*, 2712–2724. [\[CrossRef\]](#)
23. Liang, X.; Guan, Q.; Clarke, K.C. Understanding the drivers of sustainable land expansion using a patch-generating land use simulation (PLUS) model: A case study in Wuhan, China. *Comput. Environ. Urban Syst.* **2021**, *85*, 101569. [\[CrossRef\]](#)
24. Batty, M.; Xie, Y. From cells to cities. *Environ. Plan. B Plan. Des.* **1994**, *21*, S31–S48. [\[CrossRef\]](#)
25. Verburg, P.H.; Soepboer, W.; Veldkamp, A.; Limpiada, R.; Espaldon, V.; Mastura, S.S.A. Modeling the spatial dynamics of regional land use: The CLUE-S model. *Environ. Manag.* **2002**, *30*, 391–405. [\[CrossRef\]](#)
26. Liu, X.; Liang, X.; Li, X.; Xu, X.; Ou, J.; Chen, Y.; Li, S.; Wang, S.; Pei, F. A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects. *Landscape Urban Plan.* **2017**, *168*, 94–116. [\[CrossRef\]](#)
27. Shu, R.; Wang, Z.; Guo, N. Multi-Scenario Land Use Optimization Simulation and Ecosystem Service Value Estimation Based on Fine-Scale Land Survey Data. *Land* **2024**, *13*, 557. [\[CrossRef\]](#)
28. Nie, W.; Xu, B.; Yang, F. Simulating future land use by coupling ecological security patterns and multiple scenarios. *Sci. Total Environ.* **2023**, *859*, 160262. [\[CrossRef\]](#)
29. Ma, J.; Mei, Z.; Wang, X. Ecological Security Pattern Construction and Multi-Scenario Risk Early Warning (2020–2035) in the Guangdong–Hong Kong–Macao Greater Bay Area, China. *Land* **2024**, *13*, 1267. [\[CrossRef\]](#)
30. Yu, B.; Zang, Y.; Wu, C. Spatiotemporal dynamics of wetlands and their future multi-scenario simulation in the Yellow River Delta, China. *J. Environ. Manag.* **2024**, *353*, 120193. [\[CrossRef\]](#)
31. Guan, H.; Bai, Y.; Zhang, C. Research on ecosystem security and restoration pattern of urban agglomeration in the Yellow River basin. *Sustainability* **2022**, *14*, 11599. [\[CrossRef\]](#)
32. Sheng, X.; Cao, Y.; Zhou, W. Multiple scenario simulations of land use changes and countermeasures for collaborative development mode in Chaobai River region of Jing-Jin-Ji, China. *Habitat Int.* **2018**, *82*, 38–47. [\[CrossRef\]](#)
33. Wu, J.; Luo, J.; Zhang, H. Projections of land use change and habitat quality assessment by coupling climate change and development patterns. *Sci. Total Environ.* **2022**, *847*, 157491. [\[CrossRef\]](#)
34. Pontius, R.G.; Boersma, W.; Castella, J.-C.; Clarke, K.; de Nijs, T.; Dietzel, C.; Duan, Z.; Fotsing, E.; Goldstein, N.; Kok, K.; et al. Comparing the input, output, and validation maps for several models of land change. *Ann. Reg. Sci.* **2008**, *42*, 11–37. [\[CrossRef\]](#)
35. Landis, J.R.; Koch, G.G. The measurement of observer agreement for categorical data. *Biometrics* **1977**, *33*, 159–174. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Liu, X.; Wei, M.; Li, Z. Multi-scenario simulation of urban growth boundaries with an ESP-FLUS model: A case study of the Min Delta region, China. *Ecol. Indic.* **2022**, *135*, 108538. [\[CrossRef\]](#)

37. Fu, X.; Wang, X.; Yang, Y.J. Deriving suitability factors for CA-Markov land use simulation model based on local historical data. *J. Environ. Manag.* **2018**, *206*, 10–19. [\[CrossRef\]](#)
38. Luo, X.; Le, F.; Zhang, Y. Multi-scenario analysis and optimization strategy of ecological security pattern in the Weihe river basin. *J. Environ. Manag.* **2024**, *366*, 121813. [\[CrossRef\]](#)
39. Wang, J.; Chen, T. A Multi-Scenario Land Expansion Simulation Method from Ecosystem Services Perspective of Coastal Urban Agglomeration: A Case Study of GHM-GBA, China. *Land* **2022**, *11*, 1934. [\[CrossRef\]](#)
40. Kang, J.; Zhang, X.; Zhu, X. Ecological security pattern: A new idea for balancing regional development and ecological protection. A case study of the Jiaodong Peninsula, China. *Glob. Ecol. Conserv.* **2021**, *26*, e01472. [\[CrossRef\]](#)
41. Zhao, Y.; He, L.; Bai, W. Prediction of ecological security patterns based on urban expansion: A case study of Chengdu. *Ecol. Indic.* **2024**, *158*, 111467. [\[CrossRef\]](#)
42. Fu, Y.; Shi, X.; He, J. Identification and optimization strategy of county ecological security pattern: A case study in the Loess Plateau, China. *Ecol. Indic.* **2020**, *112*, 106030. [\[CrossRef\]](#)
43. Du, P.; Huai, H.; Wu, X. Using XGBoost-SHAP for understanding the ecosystem services trade-off effects and driving mechanisms in ecologically fragile areas. *Front. Plant Sci.* **2025**, *16*, 1552818. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Fahrig, L. Effects of habitat fragmentation on biodiversity. *Annu. Rev. Ecol. Evol. Syst.* **2003**, *34*, 487–515. [\[CrossRef\]](#)
45. Gaillard, J.-M.; Hebblewhite, M.; Loison, A.; Fuller, M.; Powell, R.; Basille, M.; Van Moorter, B. Habitat–performance relationships: Finding the right metric at a given spatial scale. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 2255–2265. [\[CrossRef\]](#)
46. Qiu, M.; Zuo, Q.; Wu, Q.; Yang, Z.; Zhang, J. Water ecological security assessment and spatial autocorrelation analysis of prefectural regions involved in the Yellow River Basin. *Sci. Rep.* **2022**, *12*, 5105. [\[CrossRef\]](#)
47. Ding, M.; Liu, W.; Xiao, L.; Zhong, F.; Lu, N.; Zhang, J.; Zhang, Z.; Xu, X.; Wang, K. Construction and optimization strategy of ecological security pattern in a rapidly urbanizing region: A case study in central-south China. *Ecol. Indic.* **2022**, *136*, 108604. [\[CrossRef\]](#)
48. Xu, X.; Wang, S.; Rong, W. Construction of ecological network in Suzhou based on the PLUS and MSPA models. *Ecol. Indic.* **2023**, *154*, 110740. [\[CrossRef\]](#)
49. Huang, J.; Hu, Y.; Zheng, F. Research on recognition and protection of ecological security patterns based on circuit theory: A case study of an City. *Environ. Sci. Pollut. Res.* **2020**, *27*, 12414–12427. [\[CrossRef\]](#)
50. Li, F.; Ye, Y.; Song, B. Evaluation of urban suitable ecological land based on the minimum cumulative resistance model: A case study from Changzhou, China. *Ecol. Model.* **2015**, *318*, 194–203. [\[CrossRef\]](#)
51. Wang, S.; Wu, M.; Hu, M. Promoting landscape connectivity of highly urbanized area: An ecological network approach. *Ecol. Indic.* **2021**, *125*, 107487. [\[CrossRef\]](#)
52. Wang, Y.; Zhang, L.; Song, Y. Study on the construction of the ecological security pattern of the lancang river basin (Yunnan section) based on inVEST-MSPA-circuit theory. *Sustainability* **2022**, *15*, 477. [\[CrossRef\]](#)
53. Dickson, B.G.; Albano, C.M.; Anantharaman, R.; Beier, P.; Fargione, J.; Graves, T.A.; Gray, M.E.; Hall, K.R.; Lawler, J.J.; Leonard, P.B.; et al. Circuit-theory applications to connectivity science and conservation. *Conserv. Biol.* **2019**, *33*, 239–249. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Adriaensen, F.; Chardon, J.; De Blust, G.; Swinnen, E.; Villalba, S.; Gulinck, H.; Matthysen, E. The application of ‘least-cost’ modelling as a functional landscape model. *Landscape Urban Plan.* **2003**, *64*, s0169–s2046. [\[CrossRef\]](#)
55. Shu, Y.; Hu, Y.; Leng, W.; Zhu, S.; Shan, K. Habitat selection of red crowned crane in Yellow River Delta. *Chin. J. Ecol.* **2006**, *25*, 954. [\[CrossRef\]](#)
56. Birch, C.P.D.; Oom, S.P.; Beecham, J.A. Rectangular and hexagonal grids used for observation, experiment and simulation in ecology. *Ecol. Model.* **2007**, *206*, 347–359. [\[CrossRef\]](#)
57. Jurasinski, G.; Beierkuhnlein, C. Spatial patterns of biodiversity-assessing vegetation using hexagonal grids. *Biol. Environ. Proc. R. Ir. Acad.* **2006**, *106*, 401–411. [\[CrossRef\]](#)
58. Theobald, D.M. Estimating natural landscape changes from 1992 to 2030 in the conterminous US. *Landscape Ecol.* **2010**, *25*, 999–1011. [\[CrossRef\]](#)
59. Legendre, P.; Fortin, M.J. Spatial pattern and ecological analysis. *Vegetatio* **1989**, *80*, 107–138. [\[CrossRef\]](#)
60. Griffith, D.A. Effective geographic sample size in the presence of spatial autocorrelation. *Ann. Assoc. Am. Geogr.* **2005**, *95*, 740–760. [\[CrossRef\]](#)
61. Moran, P.A.P. Notes on continuous stochastic phenomena. *Biometrika* **1950**, *37*, 17–23. [\[CrossRef\]](#)
62. Anselin, L. Local indicators of spatial association—LISA. *Geogr. Anal.* **1995**, *27*, 93–115. [\[CrossRef\]](#)
63. Manly, B.F.J. *Randomization, Bootstrap and Monte Carlo Methods in Biology*; Chapman and Hall/CRC: New York, NY, USA, 2018. [\[CrossRef\]](#)
64. Good, P. *Permutation, Parametric and Bootstrap Tests of Hypotheses*; Springer: New York, NY, USA, 2005. [\[CrossRef\]](#)
65. Anderson, M.J. A new method for non-parametric multivariate analysis of variance. *Austral Ecol.* **2001**, *26*, 32–46. [\[CrossRef\]](#)

66. Anderson, M.J.; Walsh, D.C.I. PERMANOVA, ANOSIM, and the Mantel test in the face of heterogeneous dispersions: What null hypothesis are you testing? *Ecol. Monogr.* **2013**, *83*, 557–574. [[CrossRef](#)]
67. Hu, J.; Qing, G.; Wang, Y. Landscape ecological security of the lijiang river basin in China: Spatiotemporal evolution and pattern optimization. *Sustainability* **2024**, *16*, 5777. [[CrossRef](#)]
68. Yang, H.; Flower, R.J.; Thompson, J.R. Rural factories won't fix Chinese pollution. *Nature* **2012**, *490*, 342–343. [[CrossRef](#)]
69. Cai, Z.; Zhang, Z.; Zhao, F. Assessment of eco-environmental quality changes and spatial heterogeneity in the Yellow River Delta based on the remote sensing ecological index and geo-detector model. *Ecol. Inform.* **2023**, *77*, 102203. [[CrossRef](#)]
70. Yan, J.; Li, J.; Yao, X. Ecological security pattern construction based on landscape ecological risk assessment in the Yellow River basin. *Front. Environ. Sci.* **2025**, *13*, 1514599. [[CrossRef](#)]
71. Lu, C.; Cai, X.; Hao, C. Trade-offs and Synergies in Ecosystem Services of the High-Efficiency Ecological Economic Zone in the Yellow River Delta. *J. Appl. Ecol.* **2024**, *35*, 457–468. [[CrossRef](#)]
72. Li, D.; Xu, H.; Tang, J. Countermeasures for the management of ecological environment in the Shandong section of the lower Yellow River. *Environ. Prot.* **2023**, *51*, 23–26. [[CrossRef](#)]
73. Zhang, J.; Yan, F.; Lyne, V. Monitoring of ecological security patterns based on long-term land use changes in Langsa Bay, Indonesia. *Int. J. Digit. Earth* **2025**, *18*, 2495740. [[CrossRef](#)]
74. Sun, Y.; Dong, Y.; Chen, X. Dynamic evaluation of ecological and economic security: Analysis of China. *J. Clean. Prod.* **2023**, *387*, 135922. [[CrossRef](#)]
75. Li, C.; Chunjuan, W.; Fei, X. Integrating Ecological Security Pattern and Sustainable Development Goals: A Multi-Scale Framework for Arid Cities. *Land Degrad. Dev.* **2025**. [[CrossRef](#)]
76. Lai, S.; Li, X.; Sha, J. Comprehensive evaluation and future trend prediction of ecological security in Fuzhou City: A DIKW framework and multi-model integration analysis. *Hum. Ecol. Risk Assess. Int. J.* **2024**, *30*, 833–857. [[CrossRef](#)]
77. Bai, Y.; Zhao, J.; Shen, H.; Li, X.; Wen, B. The Evolution of Forest Landscape Connectivity and Ecological Network Construction: A Case Study of Zhejiang's Ecological Corridors. *Sustainability* **2024**, *16*, 5868. [[CrossRef](#)]
78. Bosso, L.; Panzuto, R.; Balestrieri, R.; Smeraldo, S.; Chiusano, M.L.; Raffini, F.; Canestrelli, D.; Musco, L.; Gili, C. Integrating citizen science and spatial ecology to inform management and conservation of the Italian seahorses. *Ecol. Inform.* **2024**, *79*, 102402. [[CrossRef](#)]

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