

Article

Simulation and Optimization of Urban Multiscale Ecological Networks Integrating Human Demand and Natural Processes

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Abstract

Constructing ecological networks (ENs) is an effective measure to mitigate the conflict between urban development and ecological conservation. However, existing simulating methods lack adequate consideration of human ecological demands and the spatial scale differences between these demands and natural ecological processes. This might lead to issues such as incomplete ecological process cycles or structural mismatches being overlooked during ENs simulations. To address these gaps, this study proposed an urban multi-scale nested ENs simulating framework that integrates human ecological demands with natural ecological processes. The framework first simulated an ENs focused on natural ecological process cycles at a global scale (GS). Then, it simulated an ENs centered on human ecological needs within the core urban areas at local scale (LS). Finally, it nested these multi-scale ENs by using cross-scale ecological supply sources as connecting points. This framework was applied to simulate spatio-temporal pattern changes in ENs of Jinan City, a core city in downstream of the Yellow River in China, aiming to mitigate cross-scale ecological conflicts between human–nature interactions under the background of urbanization. The study's findings revealed that the area of demand sources increased by 8.56 times over 20 years. the area of cross-scale supply sources decreased by 15 km² relative to 2000, and the deterioration in connectivity was more pronounced in GS compared to LS, with a decline of approximately 13.8%. These changes indicate the presence of incomplete ecological process cycles and structural mismatches across the multi-scale boundaries within the study area, which have been worsening annually. We recommend optimizing Jinan City's multi-scale ecological network through three key strategies: rectifying internal structural mismatches, protecting core ecological areas, and aligning regional ecological demands. Implementing these strategies could significantly improve the network structure, reduce cross-scale mismatches, and enhance ecological connectivity by about 9%. This study highlights the importance of addressing structural mismatches and promoting complete ecological cycles in urban multi-scale ENs simulating, providing valuable insights for formulating urban multi-scale ecological conservation and restoration policies.

Keywords: multi-scale ecological networks; scale nesting; urbanization process; human ecological demands

Academic Editor: Alexandros A. Lavdas

Received: 7 December 2025

Revised: 25 January 2026

Accepted: 28 January 2026

Published: 30 January 2026

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1. Introduction

Since the 20th century, the global urbanization process has accelerated continuously, posing severe threats to the ecological environment [1,2]. The conflict between human social development and ecological conservation has become increasingly prominent. To date, governments worldwide have implemented various measures to mitigate this conflict, such as the construction of ecological networks (ENs) [3], ecosystem restoration [4], and the construction of green ecological parks [5]. Among these, the construction of ENs is considered one of the most effective strategies for balancing urban ecological conservation with human social development [6,7]. Its role in urban ecological planning and national spatial planning has been recognized globally [8]. However, urbanization levels, ecological resource distribution and functions, and ecological processes exhibit significant spatial scale effects [9]. The conflicts between human development and ecological conservation may vary considerably across different scales [10]. Therefore, it is crucial to construct multi-scale urban ecological networks. This is of paramount importance for promoting the sustainable development goal of harmonious coexistence between humans and nature, as well as for maintaining the integrity of ecological processes [11].

Early ENs were conceived as greenway systems that connected green parks, nature reserves, and cultural landscapes, primarily aimed at urban landscape planning and environmental management [12,13]. Over time, ENs have evolved to focus on mitigating the conflict between human social development and natural ecological conservation [14]. This evolution has promoted the establishment of a fundamental research paradigm [15,16]: identifying ecological sources—constructing ecological resistance surfaces—extracting ecological corridors—evaluating ecological networks. However, a critical issue that still needs attention is the significant differences in the ecological resource functions and characteristics of ecological processes across various urban spatial scales. Specifically, when considering the whole city as a large spatial scale, the primary ecological processes involve biological migration and the circulation of matter and energy between ecological sources [17]. The main function of ecological resources at this scale is to maintain regional ecosystem stability and biodiversity [18]. In contrast, the core urban areas, which are characterized by intense human activity and high levels of urban development, represent a smaller spatial scale. Here, the ecological resources not only need to sustain basic ecological processes and facilitate species migration but also have to provide ecosystem services to human society [19]. This indicates unique and pronounced human ecological demands in this scale. Therefore, simulating multi-scale ENs is a necessary approach to address the needs of both human and natural systems.

In existing studies [20,21], scholars typically simulate ecological networks at different scales separately and then construct a multi-scale ecological network by directly overlaying these individual networks. Although this method achieves multi-scale integration, it pays relatively little attention to the connection issues at cross-scale boundaries [17,22]. This may lead to the lack of connections between different scales in the internally constructed multi-scale ecological network and the incompleteness of the ecological process cycle simulation. Moreover, in the simulation of small-scale ENs, current studies [17,23] often focus solely on the obstructive effects of human activities on ecological processes, neglecting the significant issue of human ecological demands [19,24]. This oversight hampers the creation of an urban ENs system that genuinely fosters harmonious coexistence between humans and nature. Therefore, there is an urgent need to conduct research on the simulation and optimization of multi-scale ecological networks that integrate human ecological demands. This approach aims to fulfill human well-being while advancing the protection and planning of ecological environments.

The Yellow River, as the largest river in northern China, flows through 33 cities and covers a basin area exceeding 750,000 km², holding significant social, economic, and

ecological strategic importance [25]. The urbanization process in the Yellow River basin has been extremely intense, with rapid population growth, yet the region's ecosystems are highly fragile and sensitive, with poor environmental carrying capacity [16]. Jinan, as the core city of the Shandong Peninsula urban agglomeration and the downstream of the Yellow River basin [26], faces even more acute conflicts between human social development and ecological conservation. However, we have observed that the current formulation of ecological management policies and implementation of ecological restoration measures often lacks consideration of human demands and the spatial scale differences between human demands and natural ENs. This oversight might give the appearance of overall urban ecological improvement, but in reality, numerous underlying ecological issues may persist. These include spatial structure problems such as disharmonious cross-scale ecological process connections and structural mismatches within natural ENs, as well as ecological function issues like incomplete ecosystem service flows and neglected human ecological demands. This situation hinders the achievement of sustainable development goals that promote harmonious coexistence between humans and nature. It urgently necessitates the adoption of appropriate optimization measures to address these gaps.

To address these issues, we used Jinan, a typical city in downstream of the Yellow River basin, as a case study. We simulated ecological networks dominated by natural ecological processes and dominated by human ecological demands at the global scale (GS) and local scale (LS), respectively. Following this, we employed cross-scale sources linkage approach to nest and couple ENs of both scales, and evaluated their ecological connectivity. Finally, we proposed optimization strategies for the ENs based on the study findings and current policies, and validated the effects of the optimizations. This study aims to address the following key objectives: (1) Simulate multiscale urban ecological networks integrating human ecological demand and natural ecological processes. (2) Analyze changes in ENs elements and network connectivity across scales under urbanization. (3) Optimize multiscale ecological networks by jointly considering human demand and natural processes. The study findings will provide theoretical reference and scientific basis for the construction of multi-scale urban ecological networks, ecological resource conservation, and sustainable development. They are crucial for advancing the goal of achieving harmonious coexistence between humans and nature.

2. Materials and Methods

2.1. Study Area

Jinan, located in the central part of Shandong Province, China (Figure 1), is situated on the North China Plain and exemplifies a temperate monsoon climate city [26]. The study area features a topography that slopes from high elevations in the south to lower elevations in the north. The Yellow River and Tuhai River traverse the central and northern parts of the study area, while the Taishan Mountains are situated in the southern region [27]. The study area has a forest coverage rate of 50%, predominantly in the southern mountainous regions, whereas the northern plains are mainly covered by agricultural green spaces. The primary urban area boasts a greening coverage rate of over 40%. According to the Jinan Statistical Yearbook, by the end of 2022, Jinan's GDP reached 1202.75 billion yuan, with an urbanized area of 854 km² and a resident population of 8.1995 million. The central urban area is home to 7.1984 million people, constituting 87.8% of the total population [28]. In recent years, the ongoing urbanization process has led to a rapid population increase, significantly boosting ecological demands in the core urban areas. Consequently, the ecological environment has suffered substantial degradation, and the integrity and stability of the urban ecosystem have gradually declined. Against this backdrop, it has become increasingly critical to effectively manage the conflict between human development and ecological protection within the study area.

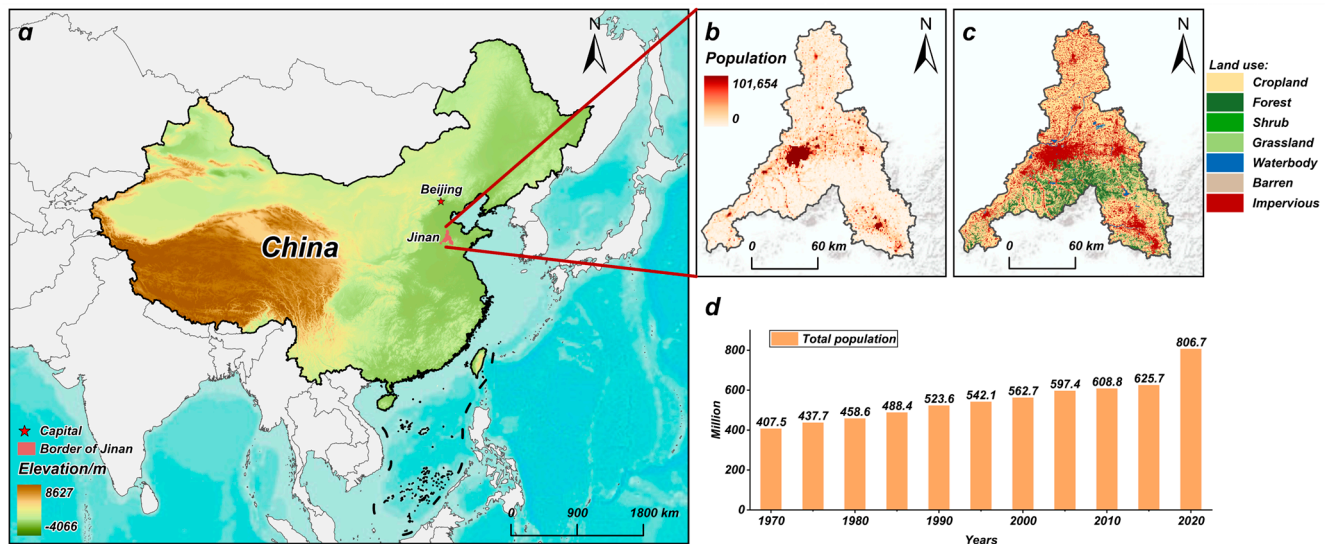


Figure 1. Study Area Overview: (a) The regional location of Jinan City within China. (b) The population density distribution of Jinan City in 2022. (c) Land use/land cover of Jinan City. (d) Population statistics of Jinan City from 1970 to 2020. (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

Based on the ecological issues at different scales and the national land spatial planning, this study divides Jinan into two spatial scales: (1) Global Scale (GS): This scale considers Jinan as a whole and is the optimal scale for conducting large-scale urban ecological planning [10,29]. At this scale, characterized by wide-ranging ecological process cycles, extensive material and energy flows, and high ecosystem stability, it stands as the optimal one for maintaining biodiversity. Meanwhile, human activities in this area are relatively scattered, mainly encompassing farming, road construction, and urban expansion. The conflict between urban spatial expansion and biodiversity conservation is particularly prominent. (2) Local Scale (LS): This scale focuses on the main core urban areas of Jinan and represents a smaller spatial scale. It is the region where human socio-ecological demands and activities are most intense. At this scale, human activities are relatively concentrated, complex, and intense, leading to low ecosystem stability. Simultaneously, human socio-ecological demands are prominent—the ecosystem must meet such demands of human society while sustaining its own stability. However, ecological resources are often relatively scarce and exhibit a high degree of fragmentation at this scale, making efforts related to ecological protection and restoration particularly challenging. This implies that the conflict between human socio-ecological demands and ecological environment restoration is most prominent at the LS. Among these, the scope of the LS was defined by integrating Jinan’s urban development planning and current status, nighttime light distribution, population density distribution, as well as ecological resources distribution.

2.2. Data Sources

In this study, we primarily utilized three categories of data: remote sensing imagery data, natural environmental data, and socio-economic data (Table 1). The remote sensing imagery data were used to interpret land use/cover (LULC) and to derive the Normalized Difference Vegetation Index (NDVI). Natural environmental data and statistical yearbook data were employed to quantify ecosystem services and construct the ecological resistance surface. Socio-economic development statistics were used to quantify the demand for ecosystem services, and socio-economic data were also used in constructing the ecological resistance surface. All data pertained to the spatial extent of Jinan City. The projection coordinate system was standardized to WGS 1984 UTM Zone 50 N, with a spatial

resolution unified to 30 m. The temporal intervals for the data were set for the years 2000, 2010, and 2020. For datasets with spatial resolutions not originally at 30 m, the downscaling to 30 m was performed using the resampling tool in ArcGIS 10.8.

Table 1. Data sources and profiles.

Types	Name	Sources	Spatial Scale
Remote sensing data	Landsat 5/8	America EROS (https://www.usgs.gov/centers/eros , accessed on 11 May 2024)	30 m
	Net primary productivity (NPP)	America LAADS DAAC (https://ladsweb.modaps.eosdis.nasa.gov , accessed on 10 May 2024)	500 m
Nature environmental data	Soil types	China soil map based harmonized world soil database (HWSD) (v1.1) (2009). National Tibetan Plateau/Third Pole Environment Data Center. (https://data.tpdc.ac.cn/ , accessed on 12 May 2024)	1:1,000,000
	Precipitation and Evaporation	China Resource and Environmental Science Data Registration and Publication System (http://www.resdc.cn , accessed on 10 May 2024)	1000 m
	DEM	Geospatial Data Cloud (https://www.gscloud.cn/ , accessed on 9 May 2024)	30 m
Socio-economic development statistics	Statistical Yearbook	Jinan Municipal Government Public Data	None
	Administrative Division Data	https://www.tianditu.gov.cn/ , accessed on 9 May 2024	1:7,400,000
Social economy data	Road networks	Open-Street-Map (https://www.openstreetmap.org/ , accessed on 11 May 2024)	1:100,000
	Population density	America LandScan Population (https://landscan.ornl.gov/ , accessed on 10 May 2024)	1000 m

2.3. Methods

The technical framework of this study (Figure 2) primarily comprises four steps: (1) identifying ecological sources for GS and LS; (2) constructing ecological resistance surfaces for the supply side and the demand side, respectively; (3) extracting ecological supply corridors and ecological demand corridors using different methods; (4) evaluating the connectivity of the ecological networks at both the GS and LS.

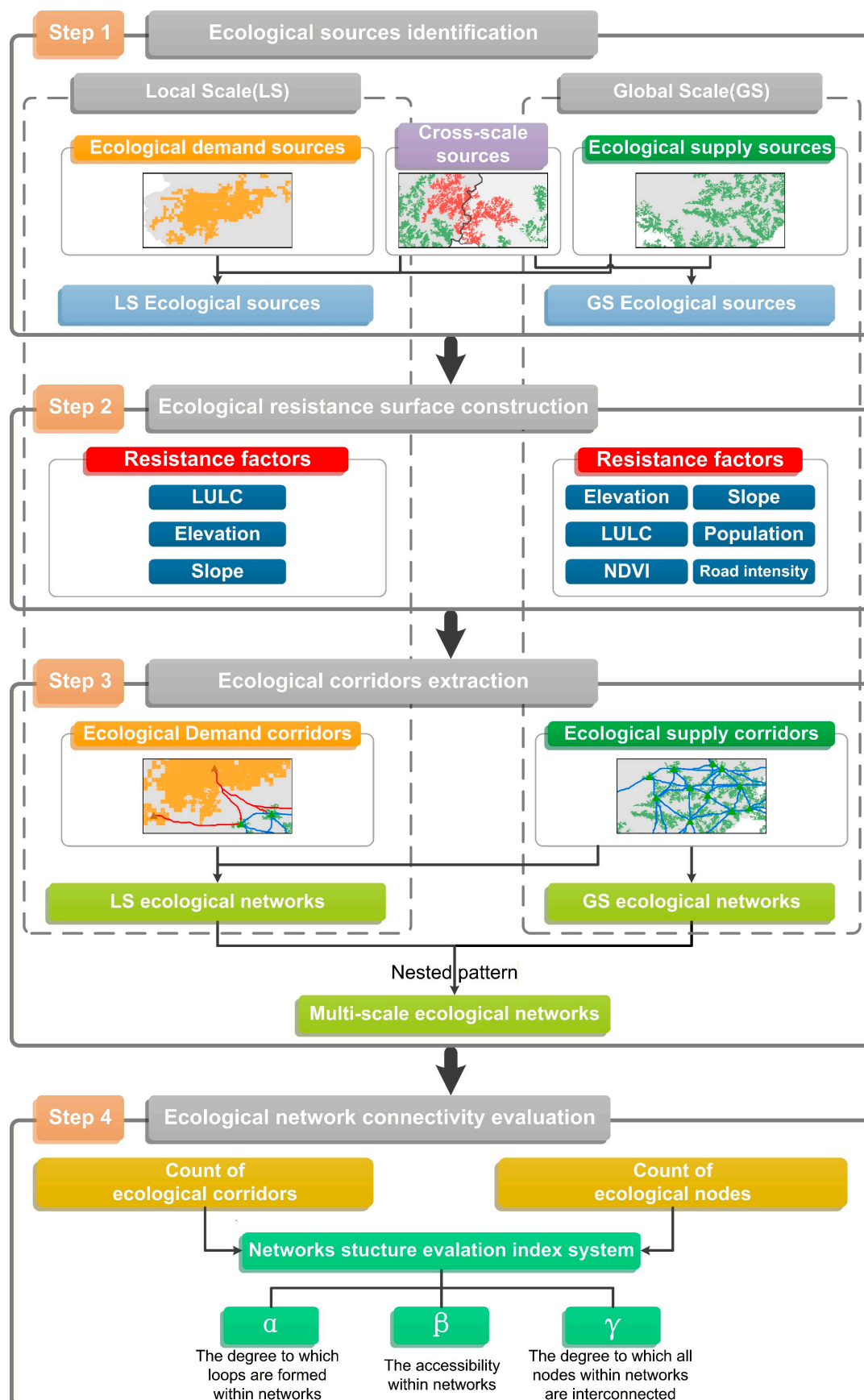


Figure 2. The technical framework: Land use/land cover (LULC); Normalized Difference Vegetation Index (NDVI).

2.3.1. Quantification of Ecosystem Services

In 2015, the United Nations introduced the Sustainable Development Goals (SDGs), aiming to comprehensively address issues in the social, economic, and environmental dimensions between 2015 and 2030 [30]. Within the first five targets of Goal 15, “Life on Land,” four primary ecosystem services (ESs) have been identified as crucial for global ecological conservation and restoration efforts [31]. These key ESs include water conservation, carbon sequestration, habitat quality, and soil conservation. In this study, we follow the methodologies from a previous study, primarily using the InVEST model, the ULSE formula, and other approaches to quantify the supply and demand functions of these four ESs (Table 2). The quantified ESs supply functions are used to identify ecological sources at both the GS and LS, while the quantified ESs demand functions are used exclusively for identifying demand sources at the LS.

Table 2. Methods and formulas for quantifying the supply function and demand function of ESs.

ESs Types	Function	Formula
Water Conservation	Supply function	$WR = \min \left(1, \frac{249}{Velocity} \right) \times \min (1, 0.3TI) \times \min \left(1, \frac{K_{sat}}{300} \right) \times WY_x \quad (1)$
		where WR represents the annual average water retention capacity, which signifies water conservation supply. $Velocity$ represents the flow velocity coefficient, TI represents the terrain index, K_{sat} represents the soil saturated hydraulic conductivity, WY_x represents the water yield per unit grid (calculated by the water yield module of the Invest model),
	Demand function	$D_{WY} = D_{perwater} \times P_{xpop} \quad (2)$ $D_{perwater} = D_{water} \div P \quad (3)$
		where D_{WY} represents the water resource usage demand per unit grid, which indicates the demand capacity for water resource services. $D_{perwater}$ represents the per capita water consumption, P_{xpop} represents the population within a unit grid, D_{water} represents the total annual water consumption, P represents the total population.
Carbon Sequestration	Supply function	$S_{xcarbon} = 1.63 \times NPPx \quad (4)$
		where $S_{xcarbon}$ represents the total carbon supply in a unit grid, which is carbon sequestration supply. $NPPx$ represents the total net primary productivity in a unit grid.
	Demand function	$D_{xcarbon} = D_{percarbon} \times P_{xpop} \quad (5)$ $D_{percarbon} = D_{carbon} \div P \quad (6)$ $D_{carbon} = E_{all} \times C_t \quad (7)$
		where $D_{xcarbon}$ represents the total carbon emissions. E_{all} represents the total electricity consumption, including residential, industrial, and agricultural electricity data for the entire society. C_t represents the carbon emission coefficient. P represents the total population. $D_{percarbon}$ represents the per capita carbon emissions. P_{xpop} represents the population count in a unit grid. $D_{xcarbon}$

		represents the carbon emissions in a unit grid, which represents carbon sequestration demand services.
		$A = R \times K \times LS \times (1 - C \times P) \quad (8)$
Soil Conservation	Supply function	where A represents the annual average soil conservation amount, R represents the rainfall erosivity factor, K represents the soil erodibility factor (calculated based on the percentage of silt, sand, clay, and organic matter in the soil), LS represents the topographic factor, C represents the crop management factor, and P represents the conservation practice factor.
	Demand function	InVEST model SDR module
Habitat Quality	Supply function	InVEST model habitat quality module
	Demand function	$HQD = \begin{cases} HQD_{st} - Q_x, & Q_x < HQD_{st} \\ 0, & Q_x \geq HQD_{st} \end{cases} \quad (9)$ where HQD represents the habitat quality demand, Q_x represents the habitat quality supply index, which is the habitat quality supply capacity calculated based on Invest, HQD_{st} represents the habitat quality demand standard.

2.3.2. Identification of Ecological Sources

Ecological supply sources emphasize different ecological functions when participating in ecological processes at various spatial scales [17]. Furthermore, regardless of the scale, the connectivity and type of patches within a landscape directly influence their involvement in ecological processes [5,32]. In summary, drawing on previous studies [33,34], we use the “core” results from the Morphological spatial pattern analysis (MSPA) [35] as the basic ecological source areas and then further identify ecological source areas using different ecosystem service indicators, considering the characteristics of ecological processes at different scales.

Considering that ecological patches at the GS primarily function to maintain biodiversity and facilitate natural material cycles, we identified ecological supply sources using a combination of ecosystem service supply function evaluation, MSPA, and landscape connectivity evaluation. For the LS, where ecological patches need to support biodiversity, maintain ecological process cycles, and provide ecosystem services to human society, we identified ecological supply sources using a combination of the ecosystem supply-demand ratio [19], MSPA, and landscape connectivity evaluation. The ecosystem supply-demand ratio is based on the ecosystem service supply and demand functions. Furthermore, considering the differences in spatial coverage between scales, we retained only source areas with landscape connectivity greater than 1 and an area larger than 1 km² at the GS scale, and those with landscape connectivity greater than 1 and an area larger than 0.5 km² at the LS scale. The core of constructing a multi-scale ENs lies in the proper integration of cross-scale boundaries. In this study, we considered ecological supply sources spanning both GS and LS boundaries as the core ecological supply sources, which play a crucial role in connecting ENs across different scales.

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

$$dPC = \frac{PC - PC'}{PC} \times 100\% \quad (2)$$

where n represents the total number of landscape patches, a_i and a_j represent the areas of patches i and j , respectively. A_L is the total landscape area of the study region. P_{ij} represents the maximum product of probabilities for all paths between patch i and j . PC represents the potential connectivity of landscape patches, PC' represents the potential connectivity of the remaining patches after removing a certain patch.

$$SDR = \frac{ES_s - ES_d}{ES_s + ES_d} \quad (3)$$

In this equation, SDR represents the supply-demand ratio within a single grid, ES_s represents the supply function of ESs per grid and ES_d represents the demand function of ESs per grid. When $SDR > 0$, it indicates that the supply of ESs within the unit grid exceeds the demand, suggesting a surplus in ES supply and the absence of supply-demand imbalance. When $SDR = 0$, it indicates that the ES supply within the unit grid exactly meets the demand, resulting in a supply-demand balance. When $SDR < 0$, it indicates that the ES supply within the unit grid is insufficient to meet the demand, indicating a supply-demand imbalance.

Relying solely on the ecological supply-demand ratio to identify ecological supply sources primarily reflects the supply-demand issues within the supply sources themselves and fails to adequately capture the significant human ecological needs in the LS. Therefore, in this study, we introduced ecological demand sources in the LS to effectively address human ecological demands. Ecological demand sources are areas of human habitation with high demands for ecosystem services such as air quality, carbon sequestration, and water resources. To identify these ecological demand sources, we quantified the demand functions for four ecosystem services and derived a composite demand function by equally weighting and aggregating these services. The results of the composite ecosystem service demand function were then categorized into five levels using a combination of natural breaks and manual breakpoints. This approach effectively avoids the subjectivity of arbitrary classification and the potential biases of purely data-driven methods. We classified the top two levels as high ecological demand areas and identified them as ecological demand sources.

2.3.3. Construction of Ecological Resistance Surface

When ecological processes flow or cycle across heterogeneous landscapes, they are jointly influenced by both natural environmental conditions and human social activities [36]. The ecological resistance surface refers to a type of spatial field [37] used to quantify the magnitude of such influences [38]. Typically, it is derived through the overlay analysis and calculation of multiple resistance factors. Existing studies [10] suggest that supply-side and demand-side ecological processes encounter varying levels of resistance. Therefore, in this study, On the basis of considering the ecological resistance factors of the supply side and the demand side, we have constructed their corresponding resistance surfaces, respectively.

(1) Ecological resistance surface of supply side

The supply-side ecological processes primarily involve the exchange of materials and energy between ecological supply sources and the migration of species. These processes, whether at the GS or LS, are fundamental to maintaining the integrity and ecological security of regional ecosystems. These processes are subject to cumulative resistance from various factors. LULC are the most direct and primary factors affecting species migration and the cyclical nature of ecological processes, thereby bearing significant weight. Human activities, especially in densely populated areas, can significantly disrupt natural ecological cycles. Additionally, surface transportation routes can strongly hinder species migration. Natural terrain and vegetation cover also directly impact ecological processes, with

low elevation, flat terrain, and high vegetation cover favoring the diffusion of biological processes. Given the considerable topographic variability in the study area, slope is considered to have a higher weight than elevation. Vegetation cover, having a relatively minor impact on surface ecological processes, is assigned a lower weight. Therefore, taking into account both natural and human-induced resistance factors, we selected NDVI, slope, elevation, LULC, population density, and road intensity as resistance factors. Drawing on previous studies [34,39,40] and the specific analysis of the resistance effect, we assigned weights and resistance values to these factors (Table 3), and constructed the supply-side resistance surface through weighted overlay.

Table 3. Classification, resistance values and weights of supply-side resistance factors.

Resistance Factors	Classification	Value	Weight
NDVI	0–0.437	20	0.09
	0.437–0.590	40	
	0.590–0.682	60	
	0.682–0.757	80	
	0.757<	100	
DEM	10–99 m	20	0.10
	99–225 m	40	
	225–350 m	60	
	350–500 m	80	
	500 m<	100	
Slope	0.000–1.071°	20	0.12
	1.071–3.013°	40	
	3.013–5.289°	60	
	5.289–8.235°	80	
	8.235°<	100	
LULC	Grassland	10	0.33
	Woodland	15	
	Waterbody	40	
	Cropland	60	
	Bare ground	80	
	Construction land	100	
Population density	0–908	20	0.21
	908–3290	40	
	3290–7300	60	
	7300–15,940	80	
	15,940<	100	
Distance intensity	0–0.5 km	20	0.15
	0.5–1 km	40	
	1–3 km	60	
	3–5 km	80	
	5 km<	100	

(2) Ecological resistance surface of demand side

Unlike supply-side ecological processes, demand-side ecological processes primarily refer to the ecological processes between ecological supply sources and ecological demand sources, aimed at meeting human ecological demands. This implies that the mechanisms of flow between the two differ to some extent. Certain resistance factors that impede supply-side ecological processes can actually promote demand-side ecological processes. These factors include population density and road intensity. Specifically, areas with

higher population density and proximity to roads indicate higher human activity intensity, which in turn suggests higher ecological demand, thereby promoting demand-side ecological processes. On the other hand, topographic factors and land use types continue to present varying degrees of resistance to these processes. This indicates that land use type remains the most crucial influencing factor for the demand-side resistance surface and should be assigned a relatively high weight. Topographic factors rank second; however, consistent with the supply side, the impact of slope is more significant, and its weight is higher than that of elevation. Therefore, considering the unique characteristics of demand-side ecological processes, we selected only elevation, slope, and land use type as the resistance factors for constructing the demand-side ecological resistance surface. We then assigned weights and resistance values to these three factors accordingly (Table 4).

Table 4. Classification, resistance values and weights of demand-side resistance factors.

Resistance Factors	Classification	Value	Weight
DEM	10–99 m	20	0.14
	99–225 m	40	
	225–350 m	60	
	350–500 m	80	
	500 m<	100	
Slope	0.000–1.071°	20	0.19
	1.071–3.013°	40	
	3.013–5.289°	60	
	5.289–8.235°	80	
	8.235°<	100	
LULC	Grassland	10	0.67
	Woodland	15	
	Waterbody	40	
	Cropland	60	
	Bare ground	80	
	Construction land	100	

2.3.4. Extraction of Ecological Corridors

Considering the differences between supply-side and demand-side ecological processes, in this study we extracted ecological supply corridors and ecological demand corridors based on different ecological resistance surfaces using different methods.

(1) Ecological supply corridors

Ecological supply corridors connect two ecological sources and facilitate the flow of ESs, natural material and energy cycles, and species migration between them. In this ecological process, the ecological supply source acts both as a supplier and a demander of ecological services. Consequently, this ecological process exhibits a “bidirectional” flow characteristic. Additionally, considering that species migration also occurs within this ecological process, it inherently includes the “random flow” characteristic unique to species migration. Given these characteristics, ecological supply corridors embody both “bidirectional flow” and “random flow.” Considering these characteristics, we found that circuit theory [41,42] is more adaptable for simulating ecological corridors in this context. Consequently, we used the Circuitscape tool and the Linkage Mapper plugin based on ArcGIS 10.8 software to extract ecological supply corridors, leveraging the supply-side ecological resistance surface for this purpose.

(2) Ecological demand corridors

Unlike ecological supply corridors, ecological demand corridors are pathways that connect ecological supply sources to ecological demand sources, facilitating ecological processes that flow from supply sources to demand sources, thereby meeting human ecological demands. Specifically, as areas of high human population density, ecological demand sources have a strong demand for various ecosystem services such as water, fresh air, and carbon sequestration, which they consume as these services are provided to the demand sources. Ecological demand corridors do not encompass the ecological processes of species migration; they solely cover the ecological processes of ecosystem services flow directed towards human society [43]. Given these characteristics, we identify that the ecological processes supported by ecological demand corridors exhibit a “unidirectional” flow. In this context, the path selection tends to favor the route that overcomes the least cumulative resistance. The Minimum Cumulative Resistance (MCR) model determines ecological corridors by calculating the least cumulative resistance between the source and the target points based on the resistance surface [24,44]. The extraction results of this method are highly suitable for ecological demand corridors. In high-resistance spaces at the LS, the MCR model can extract the optimal and shortest paths between sources. Therefore, in this study, we utilized the MCR model based on the demand-side ecological resistance surface to extract ecological demand corridors within this spatial scale.

$$MCR = f * \min \sum_{j=n}^{i=m} (D_{ij} \times R_i) \quad (4)$$

where f represents a function of $(D_{ij} \times R_i)$ between MCR and variables, D_{ij} represents the distance from patch i to patch j , R_i represents the resistance coefficient of patch i to ecological processes, n is the number of sources, and m is the number of grid cells in the resistance surface.

2.3.5. Evaluation of ENs

The connectivity between ecological corridors and ecological nodes is considered fundamental for assessing the connectivity and spatial complexity of ENs [45]. The evaluation index system for complex network structures based on graph theory reveals the complexity and connectivity of ENs through three specific indicators by counting the number of ecological corridors and nodes [46,47]. These indicators are detailed in Table 5. All three are positive indicators, meaning that higher values indicate better spatial connectivity of the ENs. In this study, we first evaluated the connectivity of the GS ENs. Then, we assessed the connectivity of the LS ENs. Finally, we conducted a comparative analysis by combining the evaluation results from both spatial scales.

Table 5. Complex network evaluation indicators’ formulas and meanings.

Index	Formula	Meaning
α	$\alpha = \frac{l-v+1}{2v-5} \quad (1)$	α represents the ratio of the actual number of loops to the maximum possible number of loops in the network, indicating the degree to which loops are formed within the ENs.
β	$\beta = \frac{l}{v} \quad (2)$	β describes the ratio of the number of corridors to the number of nodes in the ENs, reflecting the accessibility within the network.
γ	$\gamma = \frac{l}{3(v-2)} \quad (3)$	γ represents the ratio of the actual number of corridors to the maximum possible number of nodes that could be connected by corridors, effectively

reflecting the degree to which all nodes within the network are interconnected.

l represents the count of corridors, v represents the count of nodes.

3. Results

3.1. Spatio-Temporal Patterns of Ecological Sources

From the results of the MSPA spatiotemporal pattern (Figure 3a) analysis and the landscape type statistics (Figure 3c), we found that the core is the predominant ecological landscape type in the study area, accounting for over 60%. Furthermore, its area has been gradually increasing from 2000 to 2020, with a particularly notable increase of 5% in the last decade. On the other hand, islets represent the smallest proportion, at just 2.7%, and have shown no change over the 20-year period. Additionally, patches such as perforations, loops, bridges, and branches, which contribute to landscape connectivity, have been gradually decreasing in proportion.

The results of the identification of ecological supply sources (Figure 3b) indicate that the ecological sources in the study area exhibit a spatial pattern of being “concentrated in the central part and dispersed at both ends.” In terms of area (Figure 3d), the areas of ecological supply sources at both the GS and LS scales initially increased and then decreased, but in 2020, the area was larger compared to 2000, showing an overall increase. The cross-scale source area also showed a trend of initially increasing and then decreasing, with a significant reduction of 15 km² in 2020 compared to 2000. This reduction may be due to the erosion of cross-scale sources by urban boundary expansion, leading to a shrinkage in their area. This could potentially disrupt the connectivity of cross-scale ecological processes. Unlike these trends, the area of demand sources increased rapidly over the 20-year period, expanding by 8.56 times. Rapid social development and intense urbanization in recent years have further increased ecological demands, leading to the expansion of the area of demand sources. Additionally, we found that demand sources are gradually isolating the two core sources, the Yellow River and the Taishan Mountains, in spatial terms, which will lead to a decline in the integrity of regional ecological circulation, especially in cross-scale boundary areas.

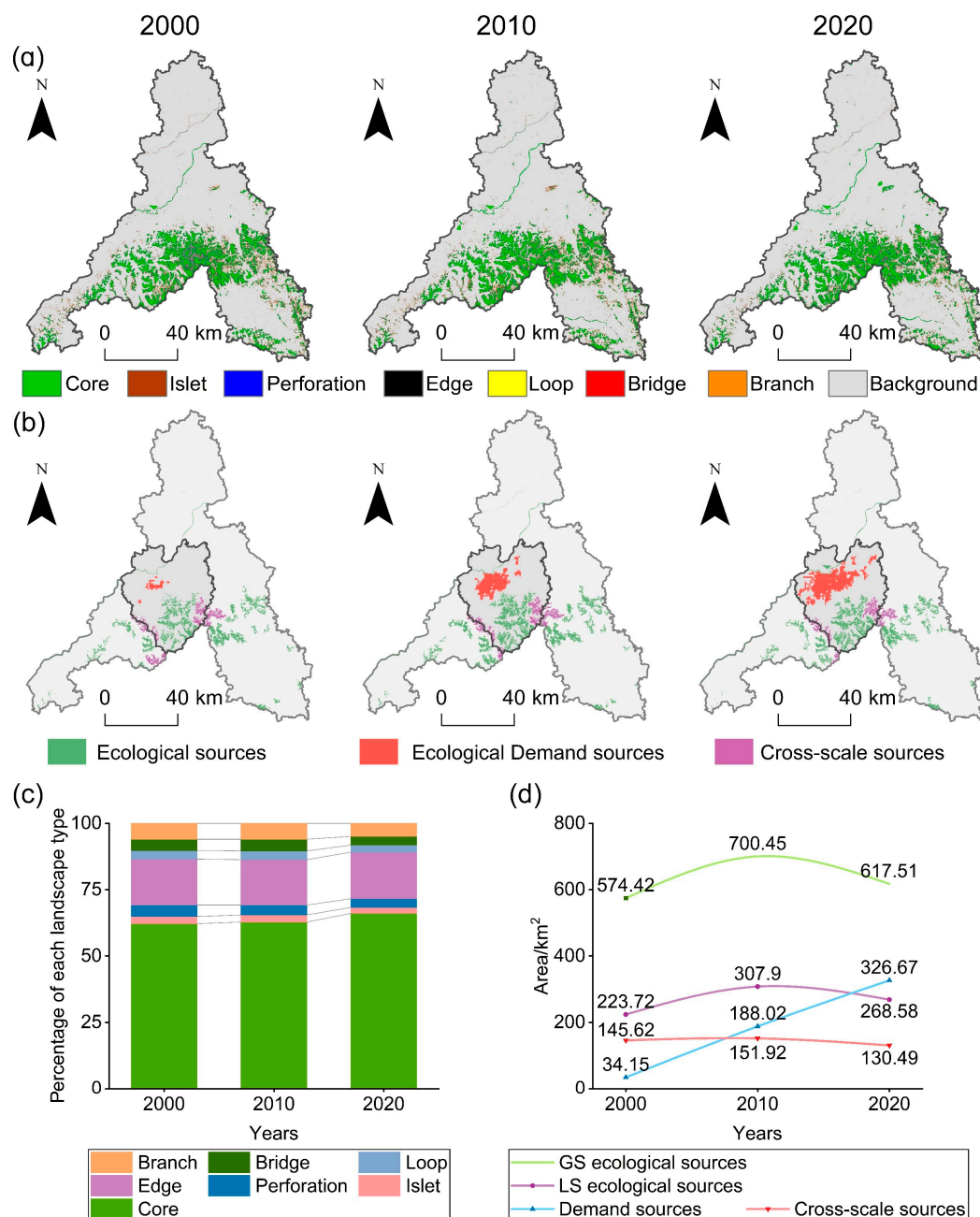


Figure 3. Results of the MSPA analysis and the identification of ecological source areas in the study area: (a) MSPA landscape type identification results; (b) ecological sources identification results; (c) statistical results of the proportion changes of MSPA landscape types; (d) statistical results of the area changes of various ecological sources. (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

3.2. Spatio-Temporal Patterns of Ecological Resistance Surface

The results of the integrated resistance surface construction are shown in Figure 4. From the results of the supply-side resistance surface construction (Figure 4a), it is evident that the ecological resistance surface exhibits a “central focus with multiple coexisting points” spatial distribution pattern. Specifically, the central core built-up area is the region with the highest ecological resistance, and over the past 20 years, the high-resistance areas have gradually expanded. Additionally, there are multiple clusters of human activity in the study area, characterized by numerous high-value areas that are spatially dispersed. This spatial pattern is quite similar to Jinan’s urban development model. Due to population growth and urban expansion, the high-value areas of the demand-side resistance

surface have gradually expanded. Considering the topographical characteristics of the LS, the demand-side resistance surface (Figure 4b) shows a “low in the south, high in the north” spatial pattern. We conducted statistical analysis on the average values of the resistance surfaces for both sides. From the statistical results (Figure 4c), it was found that the average values of the supply-side resistance surface remained relatively stable, while the average values of the demand-side resistance surface showed a very significant increasing trend. We found that urban expansion is the primary factor driving the increase in the average value of the demand-side resistance surface.

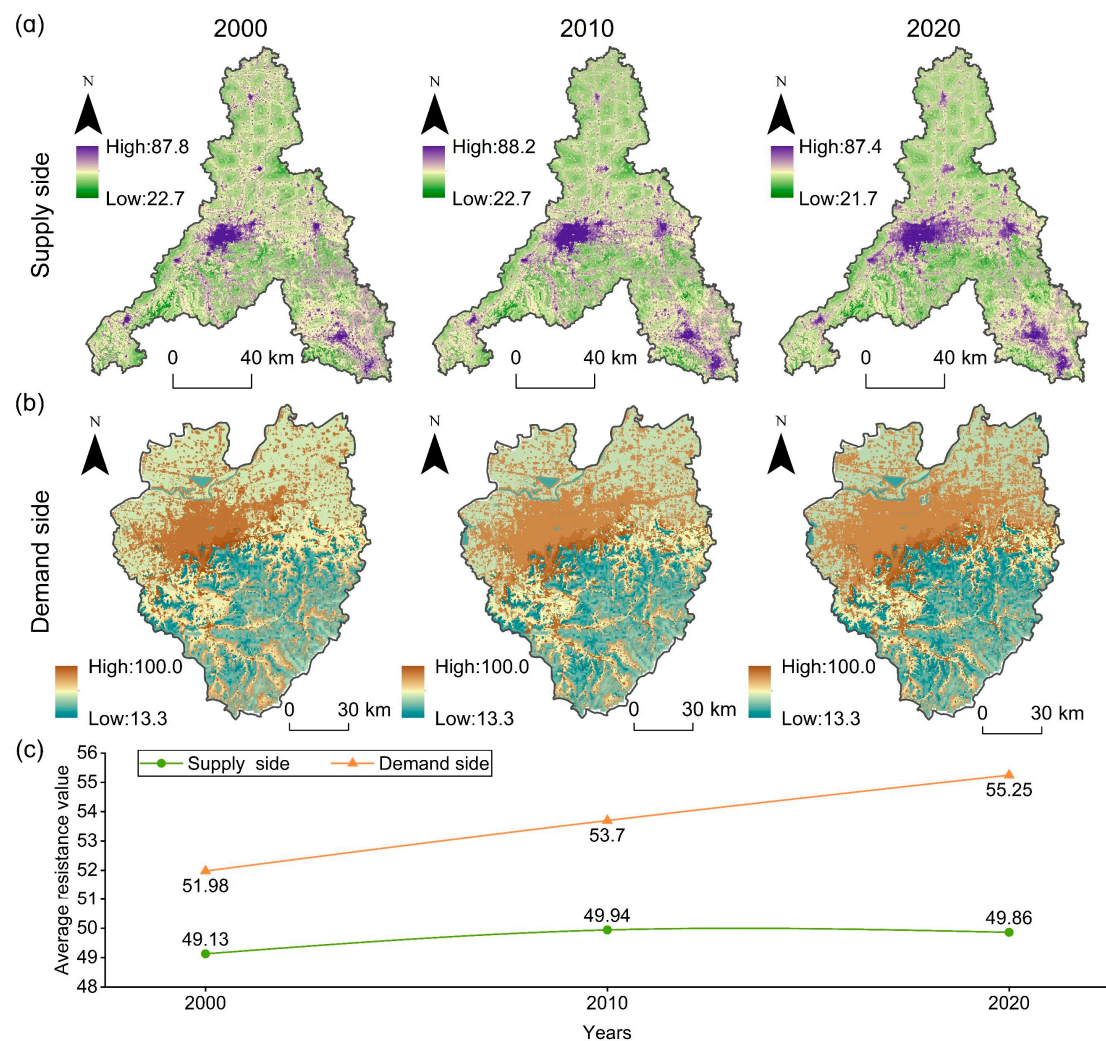


Figure 4. Ecological resistance surfaces in the study area: (a) spatio-temporal pattern of supply-side ecological resistance; (b) spatio-temporal pattern of demand-side ecological resistance; (c) average ecological resistance change statistics at different scales. (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

3.3. Spatio-Temporal Pattern of Ecological Corridors

The GS ENs simulation results (Figure 5a) indicate that the network structure has undergone minimal changes over the past 20 years. Additionally, we observed that the spatial compactness of the network structure gradually decreases as it moves away from the LS boundary. Figure 5b shows that the LS ENs is concentrated in the southern part of the study area, characterized by high compactness, numerous corridor intersections, and complex structures. This spatial pattern arises because the southern region of the study area is a focal point for ecological function zones and a core ecological protection area, maintaining a high overall integrity of ecological processes. We also found that there are

certain structural deficiencies and incompleteness in the multi-scale ENs on the east and west sides of the study area, which could potentially affect the overall integrity of regional ecological process cycles. Due to the significant urbanization and rapid population growth within the LS over the past 20 years, the ecological demand has substantially increased, leading to a gradual rise in the number of ecological demand corridors. Furthermore, we observed an annual increase in the number of long-distance corridors exceeding 30 km (Figure 5c). The expansion of high-resistance areas leads to an increase in the number of long-distance corridors (Figure 5d). However, an excessive number of long-distance corridors is not conducive to enhancing the stability of the ENs structure.

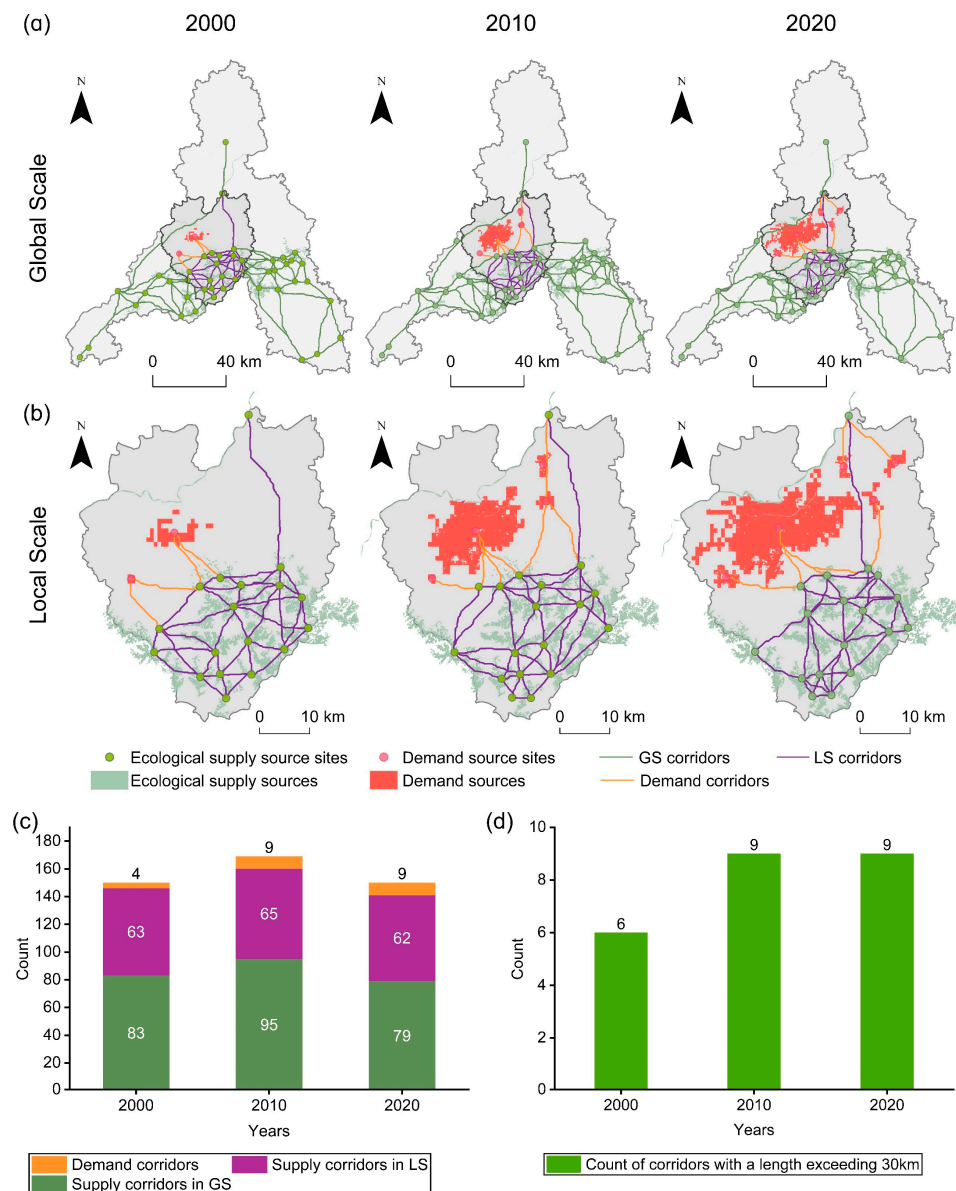


Figure 5. ENs in the study area: (a) spatio-temporal pattern of GS ENs; (b) spatio-temporal pattern of LS ENs; (c) statistics on the count of ecological corridors; (d) statistics on the count of ecological corridors exceeding 30 km in length. (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

3.4. Structural Deficiencies of Multi-Scale ENs

Furthermore, although the main structure of the external ENs in the LS has not undergone significant changes, there are certain structural deficiencies (Figure 6). These

deficiencies manifest in three key areas. First, there is a lack of “vertical” corridors at the LS boundary (a symbol in Figure 6), resulting in a weak connection between the two core ecological sources, the Yellow River in the north and the Taishan Mountains in the south. Second, the missing ecological patches in the middle of the “horizontal” long-distance corridors on both sides lead to higher ecological vulnerability in the corridor’s midsection (b symbol in Figure 6), making it prone to disruption or damage. Third, there is a lack of an external ENs on the eastern boundary of the LS (c symbol in Figure 6), causing a disconnection between the northern and southern networks. However, based on an analysis of current policies in Jinan, we found that the city’s existing ecological protection and restoration strategies fail to address these issues. This oversight hinders the realization of regional “integrated” sustainable development.

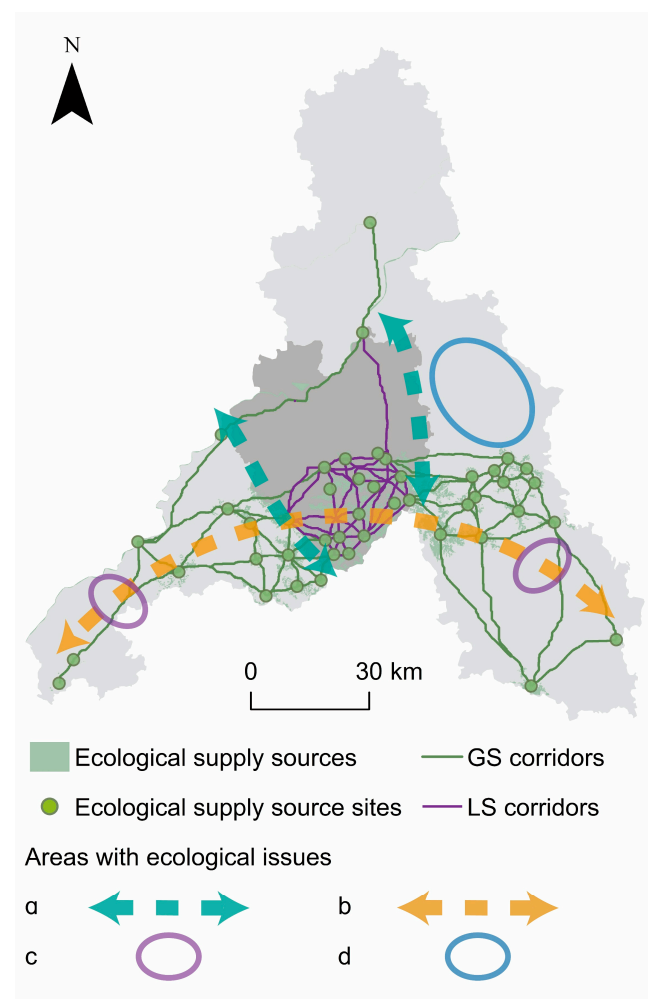


Figure 6. Overview of deficiencies in the ENs structure of Jinan City: a and b represent the corridor structural deficiencies of EN in the study area, while c and d denote the structural deficiencies of EN’s sources. (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

3.5. Evaluation of Multi-Scale ENs

Over the past 20 years, the connectivity of the spatial structure of the ENs in the study area has undergone significant changes. From the results (Figure 7a), we found that the connectivity of the GS ENs has gradually deteriorated. This deterioration was especially pronounced in the last decade, with the average decline across three indicators being approximately 13.8%. Similarly, the connectivity of the LS ENs has also been gradually decreasing (Figure 7b). However, the extent of deterioration in the LS network is noticeably

less severe than that in the GS network. The differing levels of connectivity decline may be due to urban expansion disrupting the ENs structure, particularly in cross-scale boundary areas, leading to varying degrees of deterioration and causing misalignment in the network structure across the urban cross-scale boundaries.

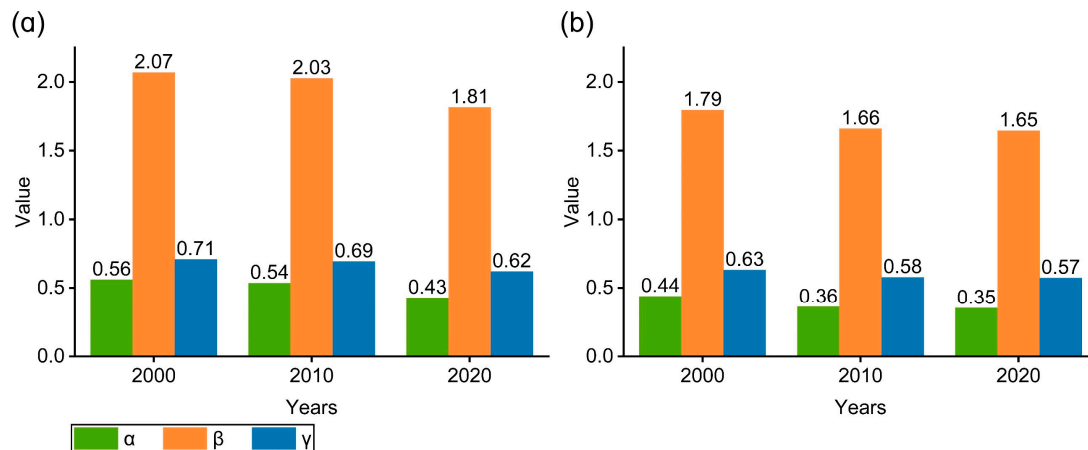


Figure 7. Evaluation of different scale ENs: (a) Results of the GS ENs connectivity assessment; (b) Results of the LS ENs connectivity assessment.

4. Discussion

4.1. Characterizations of Multi-Scale ENs in Jinan City

In this study, we observed that the characteristics of changes in ENs elements vary across different scales. For ecological sources, the magnitude of change in the area of GS supply sources is less pronounced than that of LS. This is because the southern part of LS is a large-scale open-pit mining concentration area in Jinan City [48], and it is also the core natural ecological protection area of the Taishan Mountain Range, leading to persistent contradictions between industrial and mining exploitation and ecological protection. Since 2000, the Chinese government has introduced a series of open-pit mining concentration areas restoration policies. The open-pit mining restoration areas in Jinan are mainly located in the southern part of LS [37], which has resulted in a phenomenon where the magnitude of change in ecological sources in LS is greater than that in GS. In contrast, the magnitude of change in the supply-side ecological corridors of GS is more significant than that of LS. Road construction and farmland reclamation hinder ecological processes, leading to the displacement of ecological corridors [37]. In this study, road construction and farmland reclamation outside LS are more extensive, which in turn gives rise to the phenomenon that the magnitude of change in GS corridors is higher than that in LS. At the same time, ecological demand is rapidly increasing, making it difficult to meet internal ecological demands. To sum up, this study concludes that the elements of the ecological network exhibit scale dependence. This dependence is mainly affected by two aspects: the over-exploitation and destruction of ecological resources by humans, and changes in ecological restoration measures at different stages.

4.2. Optimization Strategies for Multi-Scale ENs

Previous study on Jinan City [28,49] has predominantly concentrated on ENs studies within comprehensive spatial planning or specific small-scale areas, frequently overlooking the coupling and integration of multi-scale ENs. This oversight results in optimization strategies proposed by studies at different scales being isolated from one another, making effective transition and cohesion challenging. Consequently, the efficiency of ecological

conservation and planning policies is significantly diminished, leading to discordant and fragmented connections between ENs and resources across various regional scales.

Therefore, we propose a multi-scale nested ENs optimization strategy for Jinan City, taking into account the natural baseline of the study area, current policies, and study findings. This strategy addresses issues of internal structural mismatches and misalignment, core ecological area protection, and human ecological demand. The specific layout for optimized construction is illustrated in Figure 8a. First, we aim to advance the construction of “vertical” corridors along the LS boundary to strengthen the connectivity between the Yellow River source and the Taishan source. This will enhance the stability of boundary-scale connections and prevent disharmony caused by network structural mismatch at the boundary. Second, we propose accelerating the development of artificial ecological patches along the LS boundary. This serves two purposes: to address the decline in landscape connectivity caused by the absence of networks on the eastern side, and to provide ecosystem services to internal demand source areas within the LS, thereby alleviating internal ecological demand pressures. Third, we plan to establish key stepping stone patches on both sides of the study area. This approach, which involves adding “rest stations” [50], effectively increases the resilience of “horizontal” multi-segment long-distance corridors against human activities, ensuring the stable operation of an “integrated” ENs. We re-evaluated the ENs structure after the proposed restoration. The comparison of results (Figure 8b) shows a significant improvement in ENs connectivity in both the LS and GS, with an increase of over 9% in the LS. This demonstrates the effectiveness of our proposed optimization layout strategy, which has significantly improved the connectivity and addressed the structural misalignment issues of the multi-scale ENs in the study area. This provides valuable insights for the formulation of related ecological protection and restoration policies.

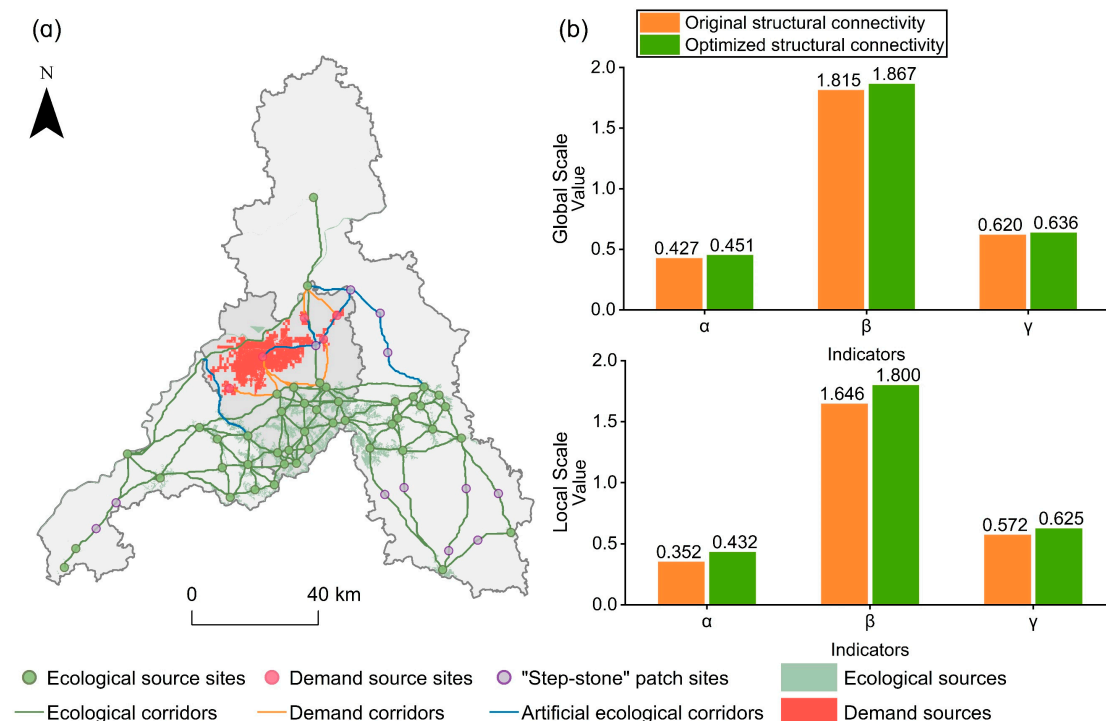


Figure 8. The optimization pattern of ENs in Jinan City (a) and the comparison of ENs connectivity before and after optimization at different scales (b). (Drawn using ArcGIS 10.8 software; URL: <https://www.esri.com/arcgis/geospatial-platform/overview>, accessed on 7 May 2024).

4.3. Simulation of Multi-Scale ENs

In this study, we divided the study area into two spatial scales, GS and LS, based on the differences in urbanization processes and natural environmental conditions. Among these scales, the urbanization process and human activities at the LS scale are more intense [48], accompanied by more prominent socio-ecological demands of human society. Here, ecological resources are required to meet substantial socio-ecological demands of human society while maintaining ecosystem health. In contrast, at the GS scale, human activities are relatively moderate, and maintaining ecological process cycles, material and energy flows, and biodiversity constitutes the primary functions of ENs. Therefore, considering the functional characteristics of ENs and the intensity of human activities across different scales, this study simulated ENs at the LS scale that integrate both the socio-ecological demands of human society and ecosystem health. At the GS scale, however, the simulation focused on ENs supporting natural ecological process cycles and material and energy flows. Subsequently, we coupled the GS and LS ENs through a scale-nesting approach. The cross-scale sources were used as key ecological elements to link ENs at both scales, thereby constructing a multi-scale ENs that simultaneously accounts for human ecological demands and cross-scale ecological process cycles has been constructed for the study area.

Compared to previous studies [51–53], this approach not only reflects the characteristics of urbanization levels and ecological processes at different scales but also ensures internal connectivity within the multi-scale network, promoting its healthy functioning. In addition, the construction of multiscale ecological networks in this study explicitly incorporates human ecological demand in core urban areas. In contrast, most previous studies primarily focused on the obstructive effects of human activities on ecological process cycles, while largely neglecting the equally critical dimension of human well-being. Furthermore, compared with the ENs constructed under a single scale, the network built through this method is more comprehensive and detailed. It can provide better references for the formulation of ecological planning and management measures at different scales. Consequently, the construction of multi-scale ENs helps to advance the goal of achieving sustainable development through harmonious coexistence between humans and nature.

4.4. Limitations and Future Work

In this study, we did not determine the width of ecological corridors. In fact, the issue of corridor width has always been a key focus in ENs research. However, in practical ecological processes, the width of ecological corridors varies across different segments [54]. Currently, existing methods cannot accurately determine the width of corridors with this random variability. Secondly, in our study, we only fully considered the relationship between human societal ecological demands and natural environmental ecological supply when identifying LS ecological sources. However, this approach primarily reveals the “static” relationship between supply and demand in ecosystem services to identify ecological sources. In reality, ecological processes also include a “dynamic” relationship between supply and demand [55]. There is still a lack of evaluation methods for this “dynamic” supply-demand relationship. In future work, we should consider both the “static” and “dynamic” characteristics of ENs to construct a multi-scale ecological supply-demand network that takes into account both natural ecological supply and human ecological demand. We should also aim to propose protection and restoration strategies for multi-scale ecological supply-demand networks.

5. Conclusions

Constructing multi-scale ENs in urban areas can effectively reveal ecological problems arising from differences in urbanization at various spatial scales, thereby assisting

policymakers in proposing more comprehensive optimization and restoration measures. Using Jinan, a typical city in downstream of the Yellow River, as an example, this study comprehensively considered human ecological demands and adopted a novel nested approach to construct an urban multi-scale ENs that integrates both human ecological demands and natural ecological processes. The main conclusions are as follows:

- (1) This method overcomes the shortcomings of previous studies by addressing cross-scale boundary integration, while also revealing that urbanization has intensified ecological demand and disrupted network connectivity.
- (2) At cross-scale boundaries, the area of cross-scale boundary sources has reduced by 15%. These spatio-temporal patterns in the network elements and spatial structure of the networks at different scales indicate that there are issues of incomplete ecological process circulation or mismatch of network structures at internal cross-scale boundaries within the study area, which have become increasingly severe over time.
- (3) Based on these findings, we proposed an optimized multi-scale EN layout focusing on structural repair, core area protection, and demand satisfaction, which improved overall connectivity by approximately 9%.
- (4) This study is limited by the use of uniform corridor widths and the unclear dynamic relationships between supply and demand within ENs, which should be addressed in future studies.
- (5) In the future, it is suggested to adopt a combined approach of “static” and “dynamic” characteristics to construct a multi-scale ENs that considers supply-demand relationships, and to evaluate and optimize it. This would provide valuable insights for policy formulation regarding regional ecological space protection and restoration.

Author Contributions: F.J.: Conceptualization, Methodology, Validation, Formal analysis, Writing—review and editing. Y.F.: Conceptualization, Methodology, Writing—original draft. Z.Z.: Resources, Data curation, Methodology, Validation. Q.W.: Writing—review and editing, Funding acquisition, Project administration. Y.S.: Visualization, Supervision, Investigation. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Ph.D. Programs Foundation of Shandong Jianzhu University (XNBS1984), and Fundamental Research Program of Shandong Collaborative Innovation Center for Smart City (003160401).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be made available on request. Please contact the corresponding author for data access.

Acknowledgments: The authors are grateful to the Urban Ecology Big Data Analysis and Modeling Research Group for providing data and technical support.

Conflicts of Interest: Author Yougui Feng was employed by the company Zhejiang Zhengyuan Geographical Information Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Yang, X.; Wei, G.; Liang, C.; Yang, Z.; Fang, H.; Zhang, S. Construction of ecological security pattern based on ecosystem service evaluation and minimal cumulative resistance model: A case study of Hefei City, China. *Env. Dev. Sustain.* **2023**, *64*, 233. <https://doi.org/10.1007/s10668-023-03170-8>.

2. Hasan, S.S.; Zhen, L.; Miah, M.G.; Ahamed, T.; Samie, A. Impact of land use change on ecosystem services: A review. *Environ. Dev.* **2020**, *34*, 100527. <https://doi.org/10.1016/j.envdev.2020.100527>.
3. Gavrilidis, A.A.; Niță, M.R.; Onose, D.A.; Badiu, D.L.; Năstase, I.I. Methodological framework for urban sprawl control through sustainable planning of urban green infrastructure. *Ecol. Indic.* **2019**, *96*, 67–78. <https://doi.org/10.1016/j.ecolind.2017.10.054>.
4. Li, Y.; Li, Y.; Zhou, Y.; Shi, Y.; Zhu, X. Investigation of a coupling model of coordination between urbanization and the environment. *J. Environ. Manage.* **2012**, *98*, 127–133. <https://doi.org/10.1016/j.jenvman.2011.12.025>.
5. Cui, L.; Wang, J.; Sun, L.; Lv, C. Construction and optimization of green space ecological networks in urban fringe areas: A case study with the urban fringe area of Tongzhou district in Beijing. *J. Clean. Prod.* **2020**, *276*, 124266. <https://doi.org/10.1016/j.jclepro.2020.124266>.
6. Peng, J.; Pan, Y.; Liu, Y.; Zhao, H.; Wang, Y. Linking ecological degradation risk to identify ecological security patterns in a rapidly urbanizing landscape. *Habitat Int.* **2018**, *71*, 110–124. <https://doi.org/10.1016/j.habitatint.2017.11.010>.
7. Peng, J.; Yang, Y.; Liu, Y.; Hu, Y.; Du, Y.; Meersmans, J.; Qiu, S. Linking ecosystem services and circuit theory to identify ecological security patterns. *Sci. Total Environ.* **2018**, *644*, 781–790. <https://doi.org/10.1016/j.scitotenv.2018.06.292>.
8. Yang, Y.; Feng, Z.; Wu, K.; Lin, Q. How to construct a coordinated ecological network at different levels: A case from Ningbo city, China. *Ecol. Inform.* **2022**, *70*, 101742. <https://doi.org/10.1016/j.ecoinf.2022.101742>.
9. Scolozzi, R.; Geneletti, D. A multi-scale qualitative approach to assess the impact of urbanization on natural habitats and their connectivity. *Environ. Impact Assess. Rev.* **2012**, *36*, 9–22. <https://doi.org/10.1016/j.eiar.2012.03.001>.
10. Lu, J.; Jiao, S.; Han, Z.; Yin, J. Promoting ecological restoration of deeply urbanized hilly areas: A multi-scale ecological networks approach. *Ecol. Indic.* **2023**, *154*, 110655. <https://doi.org/10.1016/j.ecolind.2023.110655>.
11. Geng, W.; Li, Y.; Zhang, P.; Yang, D.; Jing, W.; Rong, T. Analyzing spatio-temporal changes and trade-offs/synergies among ecosystem services in the Yellow River Basin, China. *Ecol. Indic.* **2022**, *138*, 108825. <https://doi.org/10.1016/j.ecolind.2022.108825>.
12. Guan, H.; Bai, Y.; Tang, Y.; Zhang, C.; Zou, J. Spatial identification and optimization of ecological network in desert-oasis area of Yellow River Basin, China. *Ecol. Indic.* **2023**, *147*, 109999. <https://doi.org/10.1016/j.ecolind.2023.109999>.
13. Tao, L.; Chen, Y.; Chen, F.; Li, H. Construction of Green Ecological Network in Qingdao (Shandong, China) Based on the Combination of Morphological Spatial Pattern Analysis and Biodiversity Conservation Function Assessment. *Sustainability* **2023**, *15*, 16579. <https://doi.org/10.3390/su152416579>.
14. Lu, Z.; Li, W.; Wang, Y.; Zhou, S. Bibliometric Analysis of Global Research on Ecological Networks in Nature Conservation from 1990 to 2020. *Sustainability* **2022**, *14*, 4925. <https://doi.org/10.3390/su14094925>.
15. Zhang, L.; Peng, J.; Liu, Y.; Wu, J. Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: A case study in Beijing–Tianjin–Hebei region, China. *Urban Ecosyst.* **2017**, *20*, 701–714. <https://doi.org/10.1007/s11252-016-0629-y>.
16. Zhang, Y.; Zhao, Z.; Fu, B.; Ma, R.; Yang, Y.; Lü, Y.; Wu, X. Identifying ecological security patterns based on the supply, demand and sensitivity of ecosystem service: A case study in the Yellow River Basin, China. *J. Environ. Manage.* **2022**, *315*, 115158. <https://doi.org/10.1016/j.jenvman.2022.115158>.
17. Yu, H.; Wang, Y.; Eme, C.; Fan, X.; Rong, Y.; Zhang, Q.; Liang, Z. Construction of Ecological Network Based on Multi-Scale Conversion and Nesting. *Water* **2021**, *13*, 1278.
18. Yang, Q.; Liu, G.; Lombardi, G.V.; Yang, Z. Attribution of upstream-downstream transitive natural and human imprint on watershed ecosystem services variations. *J. Clean. Prod.* **2023**, *413*, 137421. <https://doi.org/10.1016/j.jclepro.2023.137421>.
19. Zhao, X.; Xu, Y.; Pu, J.; Tao, J.; Chen, Y.; Huang, P.; Shi, X.; Ran, Y.; Gu, Z. Achieving the supply-demand balance of ecosystem services through zoning regulation based on land use thresholds. *Land Use Policy* **2024**, *139*, 107056. <https://doi.org/10.1016/j.landusepol.2024.107056>.
20. Huang, L.; Wang, J.; Fang, Y.; Zhai, T.; Cheng, H. An integrated approach towards spatial identification of restored and conserved priority areas of ecological network for implementation planning in metropolitan region. *Sustain. Cities Soc.* **2021**, *69*, 102865. <https://doi.org/10.1016/j.scs.2021.102865>.
21. Larondelle, N.; Lauf, S. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. *Ecosyst. Serv.* **2016**, *22*, 18–31. <https://doi.org/10.1016/j.ecoser.2016.09.008>.
22. Zhang, S.; Li, X.; Chen, R.; Huang, X.; Peng, J. Construction of urban-rural ecological networks with multi-scale nesting and composite functions based on the “red-green-blue” spatial perspective: A case study of Dali City, China. *Heliyon* **2024**, *10*, e37870. <https://doi.org/10.1016/j.heliyon.2024.e37870>.
23. Zhang, Y.; Lu, M.; Ma, W.; Meng, Q.; Li, Z.; Wu, Y. Urban multi-scale ecological network sequence and spatial structure optimization: A case study in Nanjing city, China. *Ecol. Indic.* **2024**, *167*, 112622. <https://doi.org/10.1016/j.ecolind.2024.112622>.

24. Xu, Y.; Liu, Y.; Sun, Q.; Qi, W. Construction of Cultivated Land Ecological Network Based on Supply and Demand of Ecosystem Services and MCR Model: A Case Study of Shandong Province, China. *Sustainability* **2024**, *16*, 3745. <https://doi.org/10.3390/su16093745>.
25. Jiang, W.; Gao, W.; Gao, X.; Ma, M.; Zhou, M.; Du, K.; Ma, X. Spatio-temporal heterogeneity of air pollution and its key influencing factors in the Yellow River Economic Belt of China from 2014 to 2019. *J. Environ. Manage.* **2021**, *296*, 113172. <https://doi.org/10.1016/j.jenvman.2021.113172>.
26. Yu, G.; Liu, T.; Wang, Q.; Li, T.; Li, X.; Song, G.; Feng, Y. Impact of Land Use/Land Cover Change on Ecological Quality during Urbanization in the Lower Yellow River Basin: A Case Study of Jinan City. *Remote Sens.* **2022**, *14*, 6273. <https://doi.org/10.3390/rs14246273>.
27. Feng, Y.; Jin, F.; Wang, Q.; Zhang, Z.; Sun, Y.; Wang, F. Enhancing Ecological Network Connectivity Through Urban–Rural Gradient Zoning Optimization of Ecological Process Flow. *Land* **2025**, *14*, 668. <https://doi.org/10.3390/land14040668>.
28. Fan, J.; Wang, Q.; Ji, M.; Sun, Y.; Feng, Y.; Yang, F.; Zhang, Z. Ecological network construction and gradient zoning optimization strategy in urban-rural fringe: A case study of Licheng District, Jinan City, China. *Ecol. Indic.* **2023**, *150*, 110251. <https://doi.org/10.1016/j.ecolind.2023.110251>.
29. Miao, Z.; Pan, L.; Wang, Q.; Chen, P.; Yan, C.; Liu, L. Research on Urban Ecological Network Under the Threat of Road Networks—A Case Study of Wuhan. *ISPRS Int. J. Geo-Inf.* **2019**, *8*, 342. <https://doi.org/10.3390/ijgi8080342>.
30. Wu, X.; Fu, B.; Wang, S.; Liu, Y.; Yao, Y.; Li, Y.; Xu, Z.; Liu, J. Three main dimensions reflected by national SDG performance. *Innovation* **2023**, *4*, 100507. <https://doi.org/10.1016/j.xinn.2023.100507>.
31. Zhou, G.; Huan, Y.; Wang, L.; Lan, Y.; Liang, T.; Shi, B.; Zhang, Q. Linking ecosystem services and circuit theory to identify priority conservation and restoration areas from an ecological network perspective. *Sci. Total Environ.* **2023**, *873*, 162261. <https://doi.org/10.1016/j.scitotenv.2023.162261>.
32. Parker, K.; Head, L.; Chisholm, L.A.; Feneley, N. A conceptual model of ecological connectivity in the Shellharbour Local Government Area, New South Wales, Australia. *Landsc. Urban Plan.* **2008**, *86*, 47–59. <https://doi.org/10.1016/j.landurbplan.2007.12.007>.
33. Shen, Z.; Wu, W.; Tian, S.; Wang, J. A multi-scale analysis framework of different methods used in establishing ecological networks. *Landsc. Urban Plan.* **2022**, *228*, 104579. <https://doi.org/10.1016/j.landurbplan.2022.104579>.
34. Dai, L.; Liu, Y.; Luo, X. Integrating the MCR and DOI models to construct an ecological security network for the urban agglomeration around Poyang Lake, China. *Sci. Total Environ.* **2021**, *754*, 141868. <https://doi.org/10.1016/j.scitotenv.2020.141868>.
35. Zou, C.; Tang, X.; Tan, Q.; Feng, H.; Guo, H.; Mei, J. Constructing Ecological Networks for Mountainous Urban Areas Based on Morphological Spatial Pattern Analysis and Minimum Cumulative Resistance Models: A Case Study of Yongtai County. *Sustainability* **2024**, *16*, 5559. <https://doi.org/10.3390/su16135559>.
36. Wang, Y.; Pan, J. Building ecological security patterns based on ecosystem services value reconstruction in an arid inland basin: A case study in Ganzhou District, NW China. *J. Clean. Prod.* **2019**, *241*, 118337. <https://doi.org/10.1016/j.jclepro.2019.118337>.
37. Wei, Z.; Liu, T.; Liang, H.; Zhang, Z.; Wang, C.; Lv, Y.; Sun, J.; Wang, Q. Uncovering the impacts of LUCC on ecological connectivity in suburban open-pit mining concentration areas: A pattern collection of changing relationships between ecological resistance and ecological network elements. *Ecol. Model.* **2024**, *496*, 110815. <https://doi.org/10.1016/j.ecolmodel.2024.110815>.
38. Zhang, Z.; Wang, Q.; Yan, F.; Sun, Y.; Yan, S. Revealing spatio-temporal differentiations of ecological supply-demand mismatch among cities using ecological Network: A case study of typical cities in the “Upstream-Midstream-Downstream” of the Yellow River Basin. *Ecol. Indic.* **2024**, *166*, 112468. <https://doi.org/10.1016/j.ecolind.2024.112468>.
39. An, Y.; Liu, S.; Sun, Y.; Shi, F.; Beazley, R. Construction and optimization of an ecological network based on morphological spatial pattern analysis and circuit theory. *Landsc. Ecol.* **2021**, *36*, 2059–2076. <https://doi.org/10.1007/s10980-020-01027-3>.
40. Nie, W.; Shi, Y.; Siaw, M.J.; Yang, F.; Wu, R.; Wu, X.; Zheng, X.; Bao, Z. Constructing and optimizing ecological network at county and town Scale: The case of Anji County, China. *Ecol. Indic.* **2021**, *132*, 108294. <https://doi.org/10.1016/j.ecolind.2021.108294>.
41. Huang, K.; Peng, L.; Wang, X.; Deng, W.; Liu, Y. Incorporating circuit theory, complex networks, and carbon offsets into the multi-objective optimization of ecological networks: A case study on karst regions in China. *J. Clean. Prod.* **2023**, *383*, 135512. <https://doi.org/10.1016/j.jclepro.2022.135512>.
42. Wu, Q.; Dai, Y. Ecological Security Patterns Research Based on Ecosystem Services and Circuit Theory in Southwest China. *Sustainability* **2024**, *16*, 2835. <https://doi.org/10.3390/su16072835>.

43. Zhang, Z.; Wang, Q.; Feng, Y.; Sun, Y.; Liu, N.; Yan, S. The spatio-temporal evolution of spatial structure and supply-demand relationships of the ecological network in the Yellow River Delta region of China. *J. Clean. Prod.* **2024**, *471*, 143388. <https://doi.org/10.1016/j.jclepro.2024.143388>.
44. Ye, H.; Yang, Z.; Xu, X. Ecological Corridors Analysis Based on MSPA and MCR Model—A Case Study of the Tomur World Natural Heritage Region. *Sustainability* **2020**, *12*, 959. <https://doi.org/10.3390/su12030959>.
45. Huang, X.; Wang, H.; Shan, L.; Xiao, F. Constructing and optimizing urban ecological network in the context of rapid urbanization for improving landscape connectivity. *Ecol. Indic.* **2021**, *132*, 108319. <https://doi.org/10.1016/j.ecolind.2021.108319>.
46. Chen, H.; Yan, W.; Li, Z.; Wende, W.; Xiao, S. A framework for integrating ecosystem service provision and connectivity in ecological spatial networks: A case study of the Shanghai metropolitan area. *Sustain. Cities Soc.* **2024**, *100*, 105018. <https://doi.org/10.1016/j.scs.2023.105018>.
47. Wang, T.; Huang, Y.; Cheng, J.; Xiong, H.; Ying, Y.; Feng, Y.; Wang, J. Construction and optimization of watershed-scale ecological network based on complex network method: A case study of Erhai Lake Basin in China. *Ecol. Indic.* **2024**, *160*, 111794. <https://doi.org/10.1016/j.ecolind.2024.111794>.
48. Liu, H.; Wang, Q.; Liu, N.; Zhang, H.; Tan, Y.; Zhang, Z. The Impact of Land Use/Cover Change on Ecological Environment Quality and Its Spatial Spillover Effect under the Coupling Effect of Urban Expansion and Open-Pit Mining Activities. *Sustainability* **2023**, *15*, 14900. <https://doi.org/10.3390/su152014900>.
49. Wang, C.; Wang, Q.; Liu, N.; Sun, Y.; Guo, H.; Song, X. The impact of LUCC on the spatial pattern of ecological network during urbanization: A case study of Jinan City. *Ecol. Indic.* **2023**, *155*, 111004. <https://doi.org/10.1016/j.ecolind.2023.111004>.
50. Wu, Z.; Lei, S.; Yan, Q.; Bian, Z.; Lu, Q. Landscape ecological network construction controlling surface coal mining effect on landscape ecology: A case study of a mining city in semi-arid steppe. *Ecol. Indic.* **2021**, *133*, 108403. <https://doi.org/10.1016/j.ecolind.2021.108403>.
51. Gao, J.; Gong, J.; Li, Y.; Yang, J.; Liang, X. Ecological network assessment in dynamic landscapes: Multi-scenario simulation and conservation priority analysis. *Land Use Policy* **2024**, *139*, 107059. <https://doi.org/10.1016/j.landusepol.2024.107059>.
52. Wei, L.; Zhou, L.; Sun, D.; Yuan, B.; Hu, F. Evaluating the impact of urban expansion on the habitat quality and constructing ecological security patterns: A case study of Jiziwan in the Yellow River Basin, China. *Ecol. Indic.* **2022**, *145*, 109544. <https://doi.org/10.1016/j.ecolind.2022.109544>.
53. Huber, P.R.; Greco, S.E.; Thorne, J.H. Spatial scale effects on conservation network design: Trade-offs and omissions in regional versus local scale planning. *Landsc. Ecol.* **2010**, *25*, 683–695. <https://doi.org/10.1007/s10980-010-9447-4>.
54. Wang, C.; Zhou, Y.; Zhang, H.; Li, Y.; Liu, H.; Dong, B. Study on the rare waterbird habitat networks of a new UNESCO World Natural Heritage site based on scenario simulation. *Sci. Total Environ.* **2022**, *843*, 157058. <https://doi.org/10.1016/j.scitotenv.2022.157058>.
55. Wu, J.; Fan, X.; Li, K.; Wu, Y. Assessment of ecosystem service flow and optimization of spatial pattern of supply and demand matching in Pearl River Delta, China. *Ecol. Indic.* **2023**, *153*, 110452. <https://doi.org/10.1016/j.ecolind.2023.110452>.

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