Stability of Regional Ecological Supply–Demand Is Enhanced by Complex Network Modeling: Evidence From the Xuzhou Metropolitan Area, China

Zixuan Li, Jiang Chang, Ziyi Wang, Yedong Chen, and Cheng Li

***Abstract*—In the era of urbanization, the imperative to safeguard ecological security and navigate toward sustainable development is paramount. The emergence of remote sensing technologies has unveiled a nuanced approach to understanding and refining regional ecological networks, which are crucial for achieving these objectives. However, in constructing regional ecological networks, the spatial integration of ecological supply and demand frequently goes unaddressed. The balance of supply and demand for ecosystem services is a complex challenge. In addition, there is an absence of comprehensive effectiveness assessment for regional ecological networks constructed based on element evaluation. To address these challenges, this study focuses on the highly urbanized Xuzhou metropolitan area (XMA) in eastern China, utilizing remote sensing data to develop an ecological network focused on balancing ecological supply and demand. The study adeptly applies complex network theory to model the ecological network, analyzing its structure and function to propose thorough and specific optimization strategies. The results indicate that the ecological network in the XMA encompasses 20 ecological supply sources, 21 demand sources, and various corridors and nodes, displaying a "dense in the center, sparse on the periphery" spider-web-like distribution. After postoptimization, the network integrates further stepping stones and corridors, evolving into a denser and more intricate structure. The study emphasizes the significance of constructing regional ecological networks based on ecological supply and demand, aiding the balance of ecosystem services in urbanized areas. It highlights the transformative potential of complex network models in ecological network optimization, facilitating effective ecosystem management and spatial planning.**

***Index Terms*—Complex network models, ecological networks, ecological supply and demand, sustainable development, Xuzhou metropolitan area (XMA).**

I. INTRODUCTION

URBANIZATION, a global phenomenon, has facilitated the regional aggregation of population and the advancement of economic development, particularly in developing countries in recent years [1]. As the size of cities gradually increases, the administrative boundaries of cities become increasingly blurred, evolving toward a "city-region" spatial form [2], [3]. In this process, the socioeconomic prosperity of the region develops, but ecological security faces challenges. Specifically, this is manifested in the concentration of central urban functions [4], saturation of urban construction space [5], dynamic changes in land use [6], and degradation of the ecological environment [7]. The original socioecological structure and functions undergo transformation, leading to an imbalance in the supply and demand of ecosystem services [8]. The health and stability of ecosystem structure and functions are vital foundations for regional integrated development and the promotion of human-centered urbanization [9]. Ecosystems provide a range of services to humans, which are significant for human welfare, health, life, and survival [10], [11]. Therefore, we must value the balance of ecosystem services supply and demand, ensure regional ecological security, and maintain the healthy development of the regional ecology. Overall, from the perspective of regional integrated development, attention needs to be paid not only to the construction of socioeconomic networks between cities but also to the improvement of regional ecosystem structures and functions [12], [13]. Considering natural environmental pressures and social resource stresses, drawing on the theory of ecosystem services supply and demand, the comprehensive construction of ecological networks that can both protect biodiversity and meet human needs has become an important issue for regional sustainable development [14], [15].

An ecological network refers to a complex interconnected system comprising many ecosystems, wherein these ecosystems are linked together through ecological processes, such as the exchange of resources and the movement of species [16]. It can effectively maintain and restore regional biodiversity, enhancing the stability and resilience of ecosystems [17]. The field of ecological networks has seen significant theoretical and methodological advancements [18], resulting in the establishment of a fundamental paradigm known as the "ecological source–resistance surface–ecological corridor–ecological node" [19], [20]. Although there are differences in the specific methods used by scholars in each step of constructing ecological networks, they all follow the same basic principles, which are to ensure the necessary and foundational functions of the components of the ecological network [21]. When selecting

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ecological sources, various strategies are employed to ensure that these sources consist of a collection of expansive functional areas that offer substantial ecological services [22]. A direct method involves selecting ecological patches of a specific size as sources, including nature reserves and large forested and grassland areas [23], [24]. This method is quite subjective. In addition, some scholars determine ecological sources from a graph theory perspective or based on specific ecological indicators, such as the morphological spatial pattern analysis (MSPA) approach, ecosystem services [25], and landscape connectivity [12]. Research indicates that combining landscape connectivity as a source selection index with the MSPA method can improve the accuracy, rationality, and objectivity of selecting ecological sources, suitable for highly urbanized areas with severe landscape fragmentation [26]. The ecological resistance surface is a quantitative measure used to assess the level of spatial resistance encountered by ecological elements during movement [27]. During the initial phases of the study, resistance values were assigned according to land use types, posing challenges in accurately capturing the internal variations within a given land use type [28]. Some scholars have employed artificial indicators, such as nighttime light intensity and human density, in order to modify the ecological resistance surface [29]. Nevertheless, these methodologies continue to depend on land use types as the fundamental framework for allocating resistance values. The scientific and objective allocation of these basic resistance values poses a significant challenge [30], [31]. Hence, several scholars have suggested employing the reciprocal of regional habitat quality as the ecological resistance surface, where higher habitat quality implies higher biodiversity and, thus, lower ecological resistance. This not only avoids the subjective allocation of basic resistance values for different land use types but also effectively reflects the difficulty of species migration and energy flow in urban areas [32]. Ecological corridors are key ecological lands that ensure the connectivity of ecological processes and the completeness of ecological functions. The extraction methods of ecological corridors can mainly be divided into three models:

1) minimum-cumulative-resistance (MCR) model [33];
2) circuit theory model [34];
3) hydrological analysis model [35].

Ecological nodes refer to ecological areas on ecological corridors that play a key role in ecological processes between patches [36], and their identification is closely related to the extraction of ecological corridors. They can be classified into intersections of minimum cost paths [37], intersections of corridors of different levels [38], ecological "pinchpoints" identified based on circuit theory [19], etc. Each of these models has its advantages and disadvantages, and current research methods and ideas are mostly based on one type of identification method for the extraction of ecological corridors and identification of ecological nodes, with less comprehensive identification research involving multiple methods and objectives.

The review of present studies regarding regional ecological networks reveals a clear emphasis on topics, such as the conservation of biodiversity, the sustenance of ecosystem services, and the safeguarding of landscape integrity [12], [17], [39]. There is a relatively limited amount of attention given to the relationship between ecological space and the spatial requirements for ecosystem services, as well as their contribution to regional ecological security. The integration between the human socioeconomic system and the natural ecological system remains incomplete [40]. Furthermore, current ecological network research methods mainly focus on identifying ecological supply sources and constructing resistance surfaces, with less exploration in identifying ecological demand sources and ecological corridor construction. The demand for ecosystem services, as the endpoint of socioecological systems, is a crucial element in achieving ecological security [41]. Ecological corridors, which facilitate the movement of ecosystem services, not only have inherent ecological service functions but also play a crucial role in connecting ecological areas with urban growth areas [42]. The establishment of corridors between the two entities holds significant importance in attaining regional ecological security and promoting sustainable development of the socioecological system. Therefore, exploring the construction of regional ecological networks from a supply and demand perspective can effectively fill the aforementioned research gaps and contribute to the balance of ecosystem services supply and demand in highly urbanized areas.

After constructing the ecological network, scientifically assessing its structure and proposing optimization methods are key supplements to ecological network research [43]. Since ecological networks are complex systems with many dynamic variables, it is uncertain whether the network's stability and overall efficiency can remain stable under external risk disturbances, making ecological network optimization and sustainable development a challenge. Evaluations of ecological network structures mainly focus on assessing the elements of ecological supply sources and corridors, such as classifying ecological supply sources based on ecological importance [44], connectivity [19], and zoning [24]; and categorizing ecological corridors using gravity models [45]. There is a lack of overall benefit assessment for regional ecological spatial networks constructed based on element evaluations. In terms of ecological network optimization, most scholars focus on network structure identification and propose some optimization strategy recommendations or spatial planning schemes [22], [46]. These optimization strategies or schemes are quite macroscopic, lacking practical and specific measures, and there is a shortage of quantitative descriptions and comparisons of ecological networks before and after optimization. Therefore, viewing the ecological network as a whole complex system, quantitatively assessing network structural characteristics, and proposing practical optimization measures are key to coupling and coordinating ecological networks with human activities, maintaining stable efficiency, and sustainable development. Complex network theory is a new perspective and method for studying complex systems by analyzing the topological structure of interconnected roles of individuals [45], [47]. Ecological networks can be understood as a vast and complex systems composed of three landscape elements: regional ecological sources, corridors, and nodes [48]. Based on the complex network analysis and optimization, ecological networks are one of the frontier directions in this field, capable of quantitatively analyzing and understanding the functions of ecological network systems to further guide the optimization of ecological networks.

For the purposes of this study, the Xuzhou metropolitan area (XMA) has been selected as the study area. The XMA is one of the three primary zones located within the Huai River Economic Belt in Eastern China. The area under consideration encompasses a total of ten urban centers spanning across four provinces. These cities are notable for their high population density and vibrant socioeconomic dynamics [49]. Despite its relative economic and social development, this region is confronted with the simultaneous challenges of limited natural resources and growing ecological demands. This study aims to establish a regional ecological network by considering ecological supply and demand, with the objective of attaining a mutually beneficial outcome for both regional ecology and the economy. This study seeks to foster an equilibrium between the supply and demand of ecosystem services. Moreover, the objective is to enhance the efficiency of the ecological network through the utilization of complex network models. The study aims to achieve the following specific objectives:

1) to use ecological corridors to connect ecological supply sources and demand sources, extract ecological radiation corridors, and construct an ecological supply and demand network;
2) to employ complex network models to abstract the ecological supply and demand network into a directed unweighted topological network and analyze its structure and function;
3) to comprehensively optimize the ecological supply and demand topological network under the guidance of complex network theory;
4) to compare the structure and functional characteristics of the ecological supply and demand topological network before and after optimization, and its overall stability when subjected to attacks.

The rest of this article is organized as follows. Section II elaborates on the study area and data sources. Section III introduces the research methodology. Section IV describes the research results. Section V discusses the research findings. Finally, Section VI concludes this article.

II. STUDY AREA AND DATA SOURCES

A. Study Area

The XMA, located in the eastern part of China, is a typical and representative region for this study due to its unique geographical and ecological characteristics (see Fig. 1). According to the "Development Plan for the Huai River Ecological Economic Belt" issued by the National Development and Reform Commission in 2018, the XMA, a vital part of the Huai River Economic Belt, includes 80 counties (cities and districts) in four cities in Shandong Province (Jining, Zaozhuang, Linyi, and Heze), one city in Henan Province (Shangqiu), two cities in Anhui Province (Huaibei and Suzhou), and three cities in Jiangsu Province (Xuzhou, Lianyungang, and Suqian), with a total area of approximately 95 750 km^2.

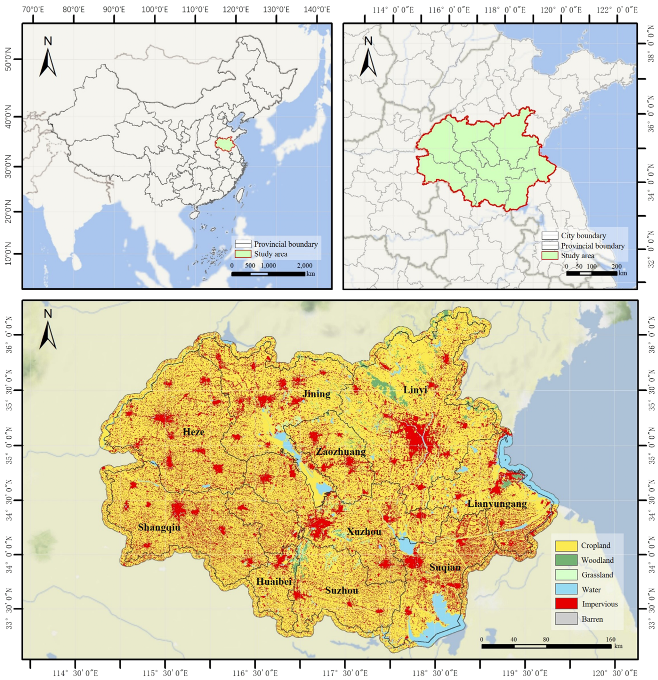


Fig. 1. Geographical location and land cover of the study area.

The topography of the XMA gradually descends from west to east, with the western part being the Yudong Mountains in Henan, the central part being the plain in the middle and lower reaches of the Huai River, and the eastern part being the coastal plain along the coast. This unique terrain and topography provide rich diversity to the ecosystems in the XMA. The blend of urban and rural areas, coupled with the challenges of balancing economic growth and ecological preservation, mirrors broader trends seen in Eastern China and similar regions. The Huai River, as the lifeline of this region, not only provides precious water resources for cities and farmland but also forms a series of lakes and wetlands, such as Hongze Lake. These lakes and wetlands not only offer vital ecological services but also highlight the region's intricate balance between human development and ecological sustainability. The spatial relationship between the ecological space and human demand areas in the XMA is of paramount importance for regional sustainability. As such, the XMA presents a unique opportunity to study the complex interplay of urbanization, ecological networks, and regional sustainability.

B. Data Sources

The comprehensive analysis presented in this study was based on a diverse set of data sources, ensuring a robust and detailed understanding of the XMA. These include multiple sources of remote sensing data and statistical data. The data sources employed are as follows.

1) Land cover data of the XMA for the year 2020 with a spatial resolution of 30 m, obtained from the GlobeLand30 (http://www.globalandcover.com/). This dataset, developed by the National Geomatics Center of China using

a pixel-object-knowledge approach, is a high-quality remote sensing product. The 2020 version of GlobeLand30 utilized 16 m high-resolution multispectral images to enhance the accuracy of land cover classification. With an overall accuracy of 85.72% and a Kappa coefficient of 0.82, this dataset ensures a reliable representation of the land cover. For the XMA, land cover data were reclassified into categories, such as cropland (including dry and paddy fields), woodland (including forest and shrubs), grassland, water bodies, impervious surfaces (encompassing urban construction land, rural settlements, industrial, and mining land), and barren area.

2) GDP data of the XMA for the year 2020 with a spatial resolution of 1 km, obtained from the China Resources and Environment Science Data Center (RESDC) (http://www.resdc.cn/). This spatial grid dataset was produced through spatial interpolation based on subcounty national GDP statistics. It integrates factors, such as land use types, nighttime light intensity, and settlement density, all closely linked to human economic activities and GDP, ensuring a more accurate representation of the spatial distribution of GDP.
3) Population density data of XMA for the year 2020 with a spatial resolution of 1 km, obtained from the China RESDC (http://www.resdc.cn/). This dataset employs national county-level population statistics and incorporates factors, such as land use types, nighttime light intensity, and settlement density, which are significant indicators of population distribution. The multifactor weight distribution method was used to spatially allocate population data, using administrative districts as the primary statistical units, onto a spatial grid, thus effectively spatializing population data.
4) Data on main roads, secondary roads, and railways in the XMA in 2020, obtained from the OpenStreetMap (https://www.openstreetmap.org/).
5) Administrative data of the XMA, obtained from the China RESDC (http://www.resdc.cn/).
6) Data on grain production, unit price, and sown area in the XMA in 2020 were obtained from the Jiangsu Statistical Yearbook, Shandong Statistical Yearbook, Henan Statistical Yearbook, Anhui Statistical Yearbook, and China Agricultural Products Price Survey Yearbook.

Considering the integrity of the landscape elements in the border area of the XMA and combining the maximum influence range of each resistance factor, the study area was buffered outward by 5 km to carry out data analysis. All spatial data were converted to the spatial coordinate system (WGS_1984, UTM Zone 50N).

III. METHODS

The complete workflow of this study can be simplified into two core components: the construction and optimization of the ecological network (see Fig. 2). In the construction phase, this study is guided by the ecological supply–demand paradigm within the framework of ecological network standards. This includes the identification of ecological supply sources, identification of ecological demand sources, construction of ecological resistance surfaces, extraction of potential ecological corridors, and identification of ecological nodes. In the optimization phase, this study optimizes the constructed ecological network based on complex network models. Specifically, this involves the analysis of ecological topological network structure, ecological network optimization, and measurement of ecological network stability. The entire study holds significance for constructing a sustainable regional ecological network.

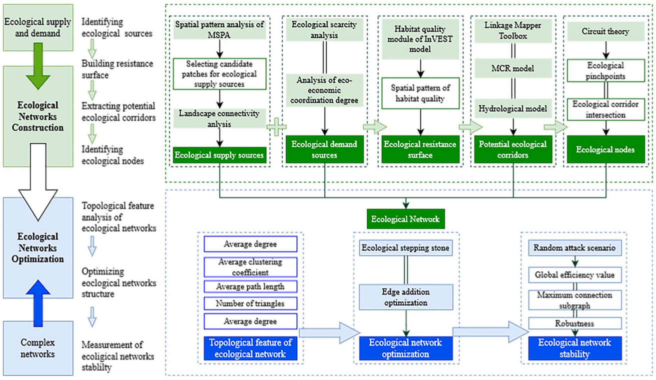


Fig. 2. Workflow of this study.

A. *Identifying Ecological Supply Sources and Demand Sources*

1) Identifying Ecological Supply Sources: Ecological supply sources refer to areas within an ecosystem that can provide crucial ecological services and functions to other areas, such as biodiversity, water conservation, and carbon sequestration [50]. These areas are crucial for maintaining the overall health and stability of the ecosystem [51]. In this study, a combination of the MSPA method and landscape connectivity index was employed to identify ecological supply sources. MSPA takes into account the relationships between pixels, allowing for the accurate capture of complex spatial patterns and structures, thereby improving the identification of significant ecological patches within the region [52], [53]. Landscape connectivity assessment is a quantitative method for measuring the degree of connectivity between ecological patches and can effectively reflect the level of species migration and energy flow between patches [54]. From a regional perspective, ecological patches with poor landscape connectivity function as ecological "islands" and are unable to provide adequate support for regional ecological security [55]. Therefore, regional ecological supply source areas should not only have a certain scale but also meet conditions of good landscape connectivity.

Specifically, first designate ecological land, such as forests, grasslands, and water bodies as the foreground, while categorizing other land uses as background. Utilizing the Guidos-Toolbox2.8 platform, process the foreground into seven distinct functional landscape types, categorized as core, islet, perforation, edge, bridge, loop, and branch. Among these, core patches represent larger habitat patches, implying greater habitat and ecological niches, thereby providing more abundant habitat space and resources [56]. Therefore, in conjunction with the existing research and the current state of the study area, core patches larger than 5 km^2 were designated as candidate ecological supply sources [19]. Subsequently, using the Conefor2.6 platform, we selected the integral index of connectivity (IIC) and probability of connectivity (PC) as evaluation indicators for landscape connectivity. Afterward, the dPC and dIIC indices were computed to assess the significance of patch connection. Once candidate patches with low dIIC and dPC values were eliminated, the final ecological supply sources were established. The equations used to compute these indices are as follows:

$$\mathrm{IIC} = \sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i \times a_j}{1+nl_{ij}}/A_L^2 \tag{1}$$

$$\mathrm{PC} = \sum_{i=1}^{n}\sum_{j=1}^{\bar{n}} a_i \times a_j \times P_{ij}^{*}/A_L^2 \tag{2}$$

$$dM\,(\%) = 100 \times (M - M_{\text{after}})\,/M \tag{3}$$

where n is the total number of nodes in the landscape; a_i and a_j are, respectively, the attributes of nodes i and j; nl_{ij} and P_{ij}^{*}, respectively, denote the links number in the shortest path and the maximum product probability of all paths between patches i and j; A_L refers to the maximum landscape attribute; M, respectively, indicates the value of IIC and PC when all initially existing nodes are present in the landscape; M_{after} is, respectively, the value of IIC and PC after the removal of the individual node from the landscape, and dM is, respectively, the important value of an existing node for maintaining IIC and PC. The distance threshold was set to 3000 m and the PC to 0.5.

2) Identifying Ecological Demand Sources: Ecological demand sources refer to areas within an ecosystem that have a high demand for one or more ecological services and are often particularly sensitive to the supply of these services. This study adopts the perspectives of the authors in [57] and [58], selecting ecological scarcity and ecological–economic harmony (EEH) as two comprehensive indicators to extract ecological demand sources. Ecological scarcity is represented by per capita ecosystem service value (ESV) to measure the scarcity of ESV relative to the population. The lower the per capita ESV, the higher the ecological demand level. EEH is measured by the ratio of per unit area ESV to GDP, representing the coordination between annual economic development and the ecological environment. In ArcGIS 10.5, after normalizing the ecological scarcity and EEH of the XMA and overlaying them with equal weight, the high-value regions were identified as ecological demand sources.

In this regard, the assessment of ESV refers to the improved method of ecosystem service valuation by Xie et al. [59], which is adjusted in conjunction with local factors, such as grain yield and planting area. The ESV factor is calculated as one-seventh of the product of the regional average grain yield and the grain purchase price. Combining the average grain yield and purchase prices of the ten prefecture-level cities in the XMA, the equivalent factor for ESV in the XMA was calculated to be 2217.12 yuan/hectare. Based on the ESV factor table and corresponding values, the ESV coefficients for various land use types in the study area were determined (see Table I). Combined with the ESV formula proposed by Costanza et al., a 1 km × 1 km grid was established in the ArcGIS 10.5 platform to calculate the spatial distribution of ESV in the XMA.

B. Constructing Ecological Resistance Surface

Ecological resistance surfaces describe the extent to which certain areas in an ecosystem impede the movement of organisms or ecological processes. They are closely related to habitat quality. Places with high habitat quality are more favorable for species migration and survival, resulting in lower ecological resistance; whereas areas with low habitat quality pose greater obstacles to species, leading to higher ecological resistance [60], [61]. Therefore, representing ecological resistance surfaces using the reciprocal of habitat quality provides a clear and intuitive reflection of the obstacles faced by species during migration within a region.

This study utilized the habitat quality module in InVEST 3.11.0 to calculate the habitat quality in the study area. Table II lists the threat factor data, while Table III displays the habitat types and their sensitivity to threats. Based on the relevant existing research and the actual conditions of the study area, impervious surfaces, main roads, secondary roads, and railways were designated as sources of threat, while woodland, grassland, water, cropland, and barren were considered as land types providing habitat. The calculation formula for habitat quality Q_{xj} is given as follows:

$$Q_{xj} = H_j\left[1 - \frac{D_{xj}^{Z}}{D_{xj}^{Z} + k^{z}}\right] \tag{4}$$

where

Q_{xj} habitat quality of raster x in land cover type j;
H_j the habitat suitability of land cover type j;
D_{xj} total threat level of raster x in land cover type j;
Z a scaling parameter and is 2.5 in this article;
k a half-saturation constant, typically assigned a value of 0.5.

C. Extracting Potential Ecological Corridors

1) Extracting Potential Corridors Between Ecological Supply Sources: The potential corridors between ecological supply sources refer to the ecological pathways that connect two or more ecological supply sources. Their purpose is to facilitate species migration and energy flow, thereby maintaining biodiversity and ecosystem stability [62]. In this study, the linkage pathway tool from the Linkage Mapper 3.0 toolbox was used to extract potential ecological corridors between ecological supply sources. This tool comprehensively considers the size, shape, and relative position of ecological supply sources, and can calculate the cumulative resistance value overcome by species migrating through different resistance landscapes between sources. This effectively simulates the ecological processes between ecological supply sources. In addition, the tool can rapidly and accurately identify ecological corridors based on ecological resistance surfaces,

TABLE I
ESV COEFFICIENTS FOR THE XMA (UNIT: YUAN/HECTARE)

Type of ecosystem service	**Food production**	**Raw material production**	**water supply**	**gas regulation**	**climate regulation**	**Clean up the environment**	**hydrological regulation**	**soil conservation**	**Maintaining nutrient cycling**	**biodiversity**	**aesthetic landscape**
cropland	2217	147	-4288	1810	929	277	4434	16	310	342	147
woodland	1337	3081	1598	10140	30322	8820	18894	12341	946	11232	4923
grassland	1141	1679	929	5901	15601	5152	11428	7189	554	6537	2886
water	1067.5	595	88685	2176	4801	7458.5	103088	2641	203.5	8493.5	5396
impervious	0	0	0	0	0	0	0	0	0	0	0
barren	0	0	0	33	0	163	49	33	0	33	16

TABLE II
THREAT FACTOR PARAMETER SETTING

Threat	**MAX_Dist**	**Weigh**	**Decay**
Impervious	10	1	exponential
Main roads	5	1	linear
Secondary roads	1	0.6	linear
Railways	3	0.8	linear

TABLE III
SENSITIVITY OF LAND COVER TYPES TO EACH THREAT

Land cover	**Habitat**	**Threat factor**			
		Impervious	**Main roads**	**Secondary roads**	**Railways**
Nodata	0	0	0	0	0
Cropland	0.4	0.4	0.1	0.1	0.15
Woodland	1	0.75	0.55	0.45	0.65
Grassland	0.8	0.45	0.15	0.1	0.25
Water	0.9	0.8	0.55	0.45	0.65
Impervious	0	0	0	0	0
Barren	0.2	0.5	0.3	0.15	0.2

avoiding the manual elimination of repetitive and redundant corridors [63], [64]. Specifically, the first step involved calculating the cost-weighted distance (CWD) between source areas based on the established ecological resistance surfaces and ecological supply sources. Subsequently, a CWD surface was created to identify the least-cost path (LCP) and determine the location and shape of the corridor.

2) Extracting Potential Corridors Between Ecological Supply Sources and Demand Sources: The potential corridors between ecological supply sources and demand sources are ecological pathways connecting areas that provide crucial ecosystem services with areas highly in demand of these services. They serve as corridors linking urban spaces with ecological spaces, with the aim of ensuring the supply of ecosystem services to ecological demand sources and maintaining the integrity of the region's ecological health and functionality [65], [66]. In this study, the MCR model was employed to extract the MCR corridors between ecological supply sources and demand sources, serving as ecological corridors. This model can accurately identify the path of ecological flow with the lowest resistance based on ecological resistance surfaces. Compared with the linkage mapper method, the MCR model considers not only the single shortest path but also integrates all possible paths, ensuring the integrity and stability of ecological connectivity [66]. This is more in line with the ecological processes of ecological spaces and urban spaces. Specifically, using the cost distance tool in ArcGIS 10.5, the centroids of ecological supply source patches were used as origins, and the centroids of ecological demand source patches as destinations, to determine the minimum cost ecological demand corridor connecting ecological supply sources and demand sources. The calculation formula for MCR is given as follows:

$$\mathrm{MCR} = f_{\min} \sum_{J=0}^{i=m} (Dij \times R_i) \tag{5}$$

where MCR is the minimum-cumulative-resistance value, f represents the positive-correlation function between the MCR and the ecological process, Dij is the spatial distance of species from the ecological source j to the landscape unit i, and R_i is the resistance value of the landscape unit i to the movement of species.

3) Extracting Ecological Radiation Corridors: Ecological radiation corridors refer to low-resistance pathways radiating out in multiple directions from a central ecological supply source. These corridors radiate out like rays and serve as connecting zones for the outflow of ecosystem services from the ecological supply source. As a supplementary potential corridor, ecological radiation corridors play a crucial role in strengthening the connection between ecological supply sources and the surrounding matrix [67]. This is different from the ecological corridors identified by the MCR model and linkage mapper method, and is beneficial for maintaining regional ecological flow and biodiversity. In this study, we applied the principles of hydrological analysis and utilized the ArcGIS 10.5 hydrological model. Utilizing the cumulative cost distance surface, we conducted hydrological analysis operations to derive the zone of MCR in valleys where ecological flow disperses from the ecological supply source to other areas. Building upon the research conducted by Liang and Zhao [68], it was established that when the cumulative accumulation value exceeds 50 000, the integrity and connectivity of the minimum cumulative cost path are relatively robust. By integrating the corridors extracted through the linkage pathway tool with the previously mentioned MCR model, redundant, intersecting, and overlapping pathways were eliminated. The remaining pathways, which radiate out, were selected as the final ecological radiation corridors.

D. Identifying Ecological Nodes

Ecological nodes are pivotal areas or locations within an ecological network that play a crucial role as hubs or relays in energy flow and species migration. The identification of ecological nodes is closely related to the methods used to extract ecological corridors. Therefore, this study identified ecological pinchpoints and the intersections of ecological corridors as ecological nodes in the ecological supply–demand network of the study area. On the one hand, regarding the intersections of ecological corridors, they can be specifically divided into intersections of supply and demand corridors, intersections of ecological radiation paths, and intersections between corridors among supply sources and supply–demand corridors (intersections of different levels of corridors). On the other hand, ecological pinchpoints are ecological nodes on corridors between ecological supply sources identified using circuit theory. Specifically, circuit theory combines landscape ecology with random walk theory in electronics. It treats the landscape as a conductive surface and species in complex landscapes as random walkers, simulating the migratory movement of organisms in heterogeneous landscapes [34], [69]. Through iterative calculations, the cumulative current density value for each pixel is obtained, and areas with high current density represent pinchpoints. Given that corridor width does not affect the position of pinchpoints and regional connectivity, in this study, the pinchpoint module of the linkage mapper tool was used to call the Circuitspace software in both all-to-one mode and pairwise mode to perform calculations.

E. Ecological Network Analysis and Optimization Based on Complex Network Models

1) Analyzing the Topology of Ecological Networks: The ecological network is composed of multiple ecological components, including ecological sources, corridors, and nodes, along with their interrelationships. This multilevel, multiscale structure and dynamic interaction bear resemblance to the nodes and connection relationships in complex networks [70]. Therefore, the ecological network can be abstracted as a complex network to facilitate further analysis of its structure and optimization [71]. In this study, the centroids of ecological supply sources, demand sources, and ecological nodes in the XMAs ecological network were abstracted as nodes in the complex network. By assuming bidirectional ecological energy flow between ecological supply sources along ecological corridors, unidirectional ecological energy flow from ecological supply sources to ecological demand sources along ecological corridors, and temporarily not considering the magnitude of ecological energy and information dissemination, the ecological corridors between different sources were extracted as edges in the topological network structure. Finally, the ecological network was abstracted as a directed, unweighted topological network structure.

In this study, five indicators were selected to represent the overall topological characteristics of the ecological network, each reflecting different aspects of its structure and function (see Table IV). These indicators were chosen because together they provide a comprehensive view of the network's complexity and connectivity, which are essential aspects of ecological network analysis.

TABLE IV
INDICATORS OF ECOLOGICAL SUPPLY AND DEMAND TOPOLOGICAL NETWORKS

Indicator	Meaning
Average Degree	It indicates the average number of connections per node in the network and reflects the connectivity of the network [72].
Average Clustering Coefficient	A measure of the extent to which nodes in a network tend to cluster together, indicating the resilience of the localized network [73].
Average Path Length	It is crucial for understanding the efficiency of the network in terms of energy and information flow [74].
Number of Triangles	Helping to identify the tightly connected groups present in the network is critical to maintaining ecological integrity and resilience [75].
Number of Communities	Identifying the different levels of structure and sub-networks in the network reflects the diversity and complexity of ecological networks [76].

2) Optimizing Ecological Networks: Optimizing the topological structure of ecological networks is a crucial means to enhance the stability and connectivity of regional ecological networks. Adding edges is a commonly used optimization method in the topological structure of complex networks [77]. Simultaneously, adding ecological stepping stones in the ecological network is an important means to optimize the ecological network [78]. Therefore, in this study, first, ecological stepping stones were added on the basis of the original ecological network. Second, since nodes with low degree values in the ecological topological network can affect the connectivity and stability of the network, ecological demand source nodes with an in-degree value of only 1 were selected for edge addition optimization. Finally, as larger betweenness centrality implies that nodes are more likely to become congested and form bottlenecks in the network, edge addition optimization was performed to reduce the shortest paths passing through these nodes.

3) Measuring Ecological Network Stability: The stability of an ecological network refers to the ability of an ecosystem to restore its structure and functionality to either the original state or a new equilibrium state within a certain period of time after being subjected to external disturbances or internal perturbations [18]. Assuming that the ecological supply sources and demand sources in the study area were not susceptible to attacks, this study employs a scenario of random attacks. Nodes in the network were randomly removed to simulate the changing trend of ecological network stability performance when facing sudden natural disaster scenarios. The changes in three indicators—global efficiency, largest subgraph size, and robustness—were used to represent the variations in ecological network stability performance before and after optimization.

IV. RESULTS

A. Results of Ecological Supply Sources and Demand Sources

1) Identification of Ecological Supply Sources: Candidate patches identified as ecological supply sources are larger habitats offering ample space and resources. Among these, patches

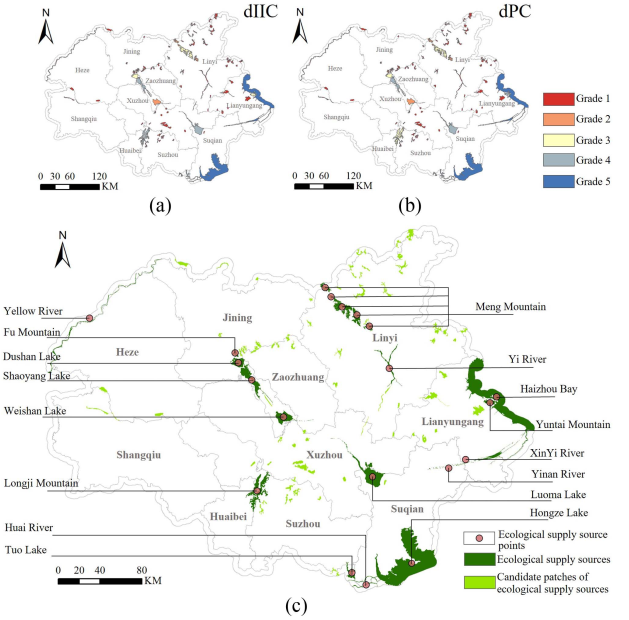


Fig. 3. Ecological supply sources in XMA. (a) dIIC grade of candidate patch for ecological supply sources. (b) dPC grade of candidate patch for ecological supply sources. (c) Spatial characteristics of ecological supply sources.

exhibiting superior landscape connectivity have been selected as the region's ecological supply sources. In this study, using the natural break method in ArcGIS 10.5, the dIIC and dPC of patches are classified into grades 1–5, representing a spectrum from the lowest to the highest levels. Fig. 3(a) and (b) represents the spatial characteristics of landscape connectivity for the candidate patches of ecological supply sources. The XMA contains 95 candidate patches for ecological supply sources, covering a total area of 4475.03 km^2. From the overall spatial distribution perspective, the candidate patches for ecological supply sources predominantly concentrate in the central and eastern regions, with few patches in the western region. Patches with smaller and more fragmented distributions exhibit lower connectivity. Consequently, upon excluding patches with dIIC and dPC levels of 1, the final ecological supply source areas for the study area were identified. Therefore, after removing patches with dIIC and dPC levels of 1, the ecological supply source areas for the study area were obtained.

Fig. 3(c) illustrates that both the number and total area of ecological supply sources in the XMA are relatively limited. We have identified 20 ecological supply sources, with a total area of 3534.23 km^2, accounting for 3.35% of the study area. Overall, ecological supply sources are densely distributed in the central and eastern regions of the XMA but are sparsely located in the western region. In the western region, only the segment of the Yellow River in Heze serves as an ecological supply source, which is related to the fact that there is more agricultural space and less ecological land in the eastern Henan region. Specifically, ecological supply sources are distributed in cities in the central and lower reaches of the Huai River plain and in the eastern coastal plain. However, there is a lack of ecological supply sources within the jurisdiction of Shangqiu. Ecological supply sources are mainly composed of oceans, rivers, lakes, and mountains. Notably, freshwater lakes are an important component, such as Dushan Lake, Shaoyang Lake, and Weishan Lake in the Nansihu Basin, as well as Luoma Lake in Xuzhou and Hongze Lake in Suqian.

2) Identification of Ecological Demand Sources: As shown in Fig. 4(a), the total ESV in the XMA amounts to 174.115 billion yuan. The ESV per unit area ranges from a high of 22 460.5 million yuan/km^2 to a low of 0 yuan/km^2. The highest ESV areas are predominantly distributed in water bodies, such as Nansihu Lake, Luoma Lake, and Hongze Lake, and coastal areas, such as Haizhou Bay in the east. Areas with comparatively higher ESV values encompass the mountainous and hilly terrain of the northern and central regions. Areas with low values are primarily observed in construction lands and adjacent farmlands.

For assessing ecological scarcity, the study employs the quantile method, segmenting per capita ESV into five distinct grades. As shown in Fig. 4(b), areas with high and relatively high levels of per capita ESV are mainly concentrated in the central, southern, and eastern parts of the study area. More specifically, these areas encompass the southern part of Suqian, the southeastern part of Xuzhou, the eastern part of Lianyungang, the southern part of Suzhou, the southern part of Huaibei, the eastern part of Shangqiu, the southern part of Jining, the south-eastern part of Zaozhuang, and the eastern part of Linyi. Areas with low levels of per capita ESV are primarily located in urban construction land. In terms of EEH, the quantile method is again utilized to categorize the ESV to GDP ratio into five grades. Fig. 4(c) reveals that areas with high EEH values are predominantly found in the western, northern, and southern regions of the study area. In contrast to the spatial pattern of per capita ESV, the central part of Heze has a moderate per capita ESV but a higher grade of EEH. Conversely, the central area of Suqian displays a higher per capita ESV with a moderate EEH grade. This may be related to the spatial characteristics of local per capita GDP. The spatial distribution of areas with low values of EEH is similar to that of per capita ESV.

Following the normalization of per capita ESV and EEH values and their equal-weighted overlay, they are segmented into five grades using the quantile method to delineate the spatial pattern of ecological demand [see Fig. 4(d)]. Ecological demand sources were extracted from grades 4 and 5, which represent high and relatively high ecological demand grades. As shown in Fig. 4(f), a total of 21 ecological demand sources were identified, with a total area of 5049 km^2, accounting for 4.78% of the study area. The distribution of ecological demand sources is relatively even, with larger areas in the central and eastern regions, and smaller ones in the western region. Notably, Linyi features the largest ecological demand source, covering 1356 km^2. Each prefecture-level city has ecological demand sources. Xuzhou has the highest number of ecological demand source areas, with five, which is closely related to the positioning of Xuzhou as the central city of the XMA.

B. Results of Ecological Resistance Surfaces and Corridors

1) Construction of Ecological Resistance Surfaces: In this study, ecological resistance surfaces are represented by the

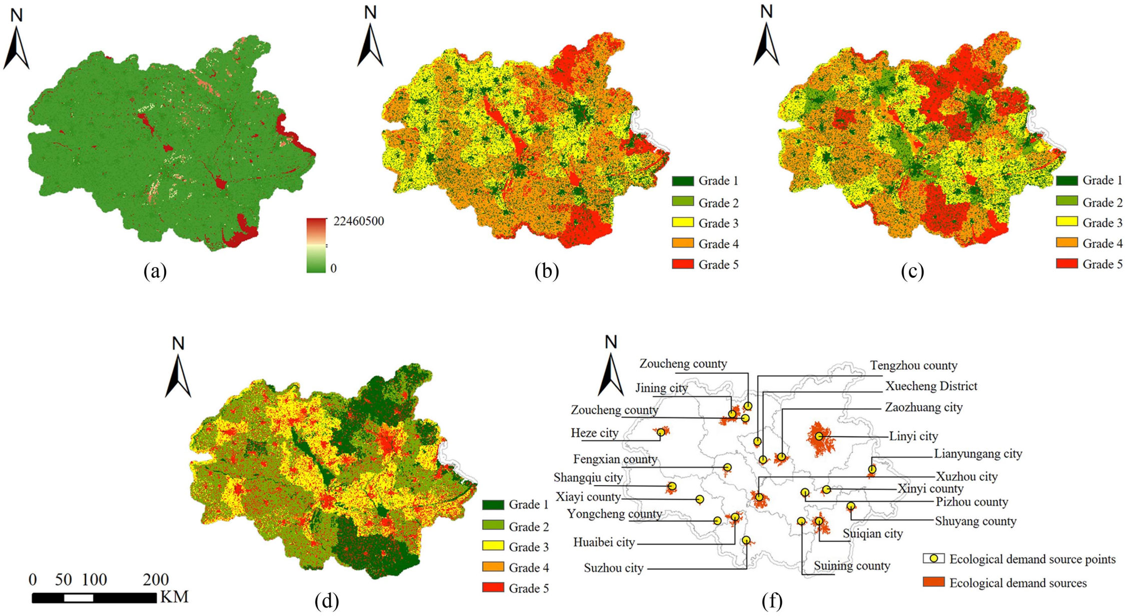


Fig. 4. Ecological demand sources in XMA. (a) Spatial characteristics of ESV. (b) Spatial characteristics of ESV per capita. (c) Spatial characteristics of EEH. (d) Spatial characteristics of superimposed EHH and ESV per capita. (f) Spatial characteristics of ecological demand sources.

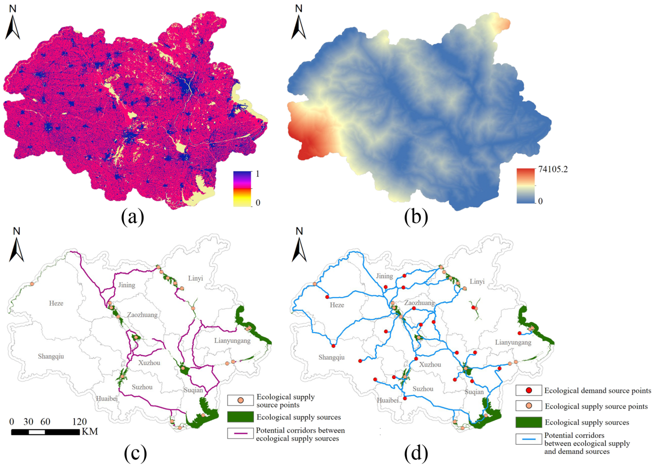
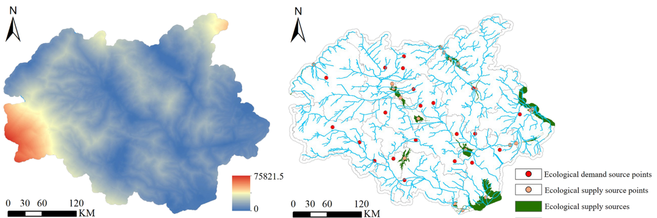


Fig. 5. Spatial characteristics of ecological resistance surfaces and potential ecological corridors. (a) Spatial characteristics of ecological resistance surfaces. (b) Spatial characteristics of CWD. (c) Spatial characteristics of potential ecological corridors between ecological supply sources. (d) Spatial characteristics of potential ecological corridors between ecological supply sources and demand sources.

reciprocal of habitat quality. As shown in Fig. 5(a), the maximum value of the ecological resistance surface in the study area ranges from a maximum of 1 to a minimum of 0. Areas with low values are mainly distributed in the central and eastern parts, which is similar to the spatial pattern of candidate ecological supply source patches. This suggests a relatively smooth flow of ecosystem services across ecological lands, characterized by lower resistance. High ecological resistance values are primarily found in areas with intense human activities, such as urban construction lands and rural residential areas.

2) Identification of Potential Corridors Between Ecological Supply Sources: Based on the identified ecological supply sources and ecological resistance surfaces, the study employed the linkage pathway tool in linkage mapper 3.0 to extract potential ecological corridors between ecological supply sources. The linkage pathway tool can calculate the CWD between multiple pairs of source areas [see Fig. 5(b)], generate a CWD surface to ascertain the LCP, and define the position and shape of corridors. Fig. 5(c) shows that 31 potential ecological corridors between ecological supply sources have been identified, spanning lengths from 0.07 to 254.64 km, cumulatively measuring 1863.86 km. The corridors in the study area's central part exhibit a circular spatial pattern. Corridors are dense in the central and eastern parts, while corridors are missing in the western part, which is related to the lack of ecological supply sources in the west. Shorter corridors are distributed in the southern part of Nansi Lake Basin in Jining and the Meng mountains area in the northern part of Linyi, connecting ecological supply sources with relatively close spatial distances.

3) Identification of Potential Corridors Between Ecological Supply Sources and Demand Sources: Based on the identified ecological supply sources and demand sources, as well as the ecological resistance surface, the study employed the MCR model to identify potential corridors linking ecological supply sources with demand sources, thus bridging ecological and urban spaces. As shown in Fig. 5(d), there are a total of 48 corridors between ecological supply sources and demand sources in the study area, with lengths ranging from 1.57 to 261.02 km, totaling 3647 km. In terms of the overall spatial distribution, the corridors in the central and western parts of the study area form a network-like pattern, while those in the eastern part are more isolated and shorter in length. The longer corridors are primarily located in the western part, which is closely related to



(a) (b)

Fig. 6. Spatial characteristics of cumulative cost distance surfaces and ecological radiation corridors. (a) Spatial characteristics of cumulative cost distance surfaces. (b) Spatial characteristics of ecological radiation corridors.

the density of ecological supply sources and the positioning of demand sources.

4) Identification of Ecological Radiation Corridors: Utilizing the existing ecological supply sources and employing the cost distance tool in ArcGIS, we derived the cumulative cost distance surface [see Fig. 6(a)]. The cost distance values range from a minimum of 0 to a maximum of 75 821.5. Applying hydrological analysis principles to extract well connected and relatively complete "valley lines," as shown in Fig. 6(b), a total of 1112 ecological radiation corridors were extracted. These corridors radiate outward from the ecological supply sources, which is basically consistent with the spatial distribution of resistance values in cumulative cost distance. Many of these ecological radiation corridors overlap with the previously identified corridors between ecological supply sources and between ecological supply and demand sources. Therefore, it is necessary to remove duplicate corridors and obtain the final ecological radiation corridors to form the ecological network.

C. Results of Ecological Network

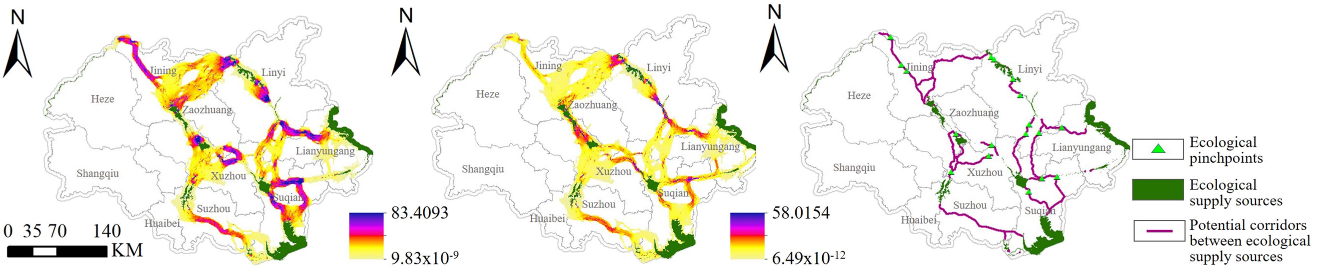
1) Results of Ecological Nodes:

a) Ecological pinchpoints: Fig. 7(a) and (b) displays the current density maps of the study area under all-to-one and pairwise modes, respectively, with darker colors denoting the areas of higher current densities. In the all-to-one mode, areas exhibiting high current density are broadly dispersed across the study area. The spatial distribution predominantly features higher current density in the central, northern, and eastern parts, with lower density in the southern regions [seeing Fig. 7(a)]. Areas with elevated current densities are primarily associated with shorter corridors, whereas longer corridors tend to exhibit relatively lower current densities. Significantly, the extended ecological corridor connecting the Heze section of the Yellow River with the Nansihu Basin, despite its length, maintains a high current density, suggesting a frequent exchange of ecological energy between these areas. Contrasting with the all-to-one mode, the pairwise mode reveals less distinct areas of high current density within the study area. The distribution of areas with high current density values in the pairwise mode is analogous to that observed in the all-to-one mode [see Fig. 7(b)]. Finally, integrating the high current density areas identified in both modes enabled the identification of ecological pinchpoints within the study area.

b) Ecological corridor intersections: The selection of corridor intersections as nodes in the ecological network is grounded in their vital role in facilitating ecological flow and species migration. These intersections effectively link diverse ecosystems, thereby aiding in the maintenance and restoration of biodiversity. As shown in Fig. 8(a), we identified 24 intersections of corridors between ecological supply sources and demand sources, which are predominantly concentrated in the central and northern parts of the study area. Furthermore, as shown in Fig. 8(b), we identified 17 intersections between corridors linking supply sources and those connecting supply and demand sources. Compared with the former, these intersections are less concentrated in the central part of the study area but are more clustered in the south and north. Finally, we identified 39 intersections of ecological radiation corridors and other corridors [see Fig. 8(c)]. The number of intersections is relatively higher than the former due to the widespread distribution of ecological radiation corridors. These intersections are mainly distributed in the western and central parts of the study area, with some concentrated on the longer potential corridors.

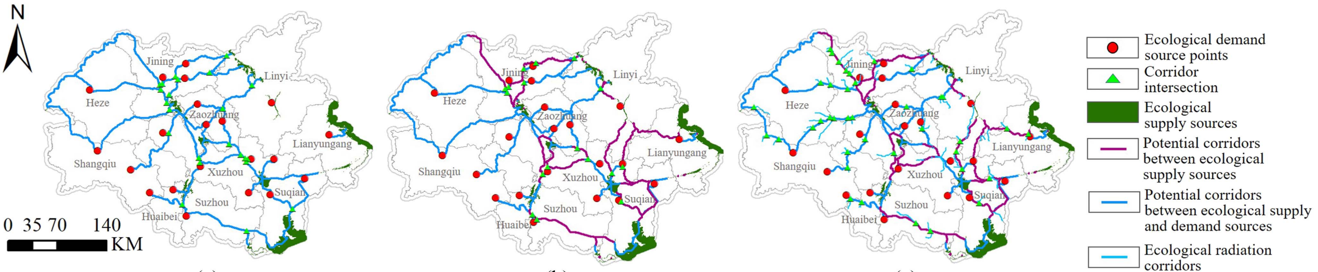
2) Construction of Ecological Network: Following the identification of ecological sources, potential ecological corridors, and ecological nodes, and subsequent removal of duplicate corridors and nodes, the ecological network of the XMA was established. As shown in Fig. 9, it includes 20 ecological supply sources, 21 ecological demand sources, 31 potential ecological corridors between supply sources, 48 corridors between ecological supply and demand sources, 87 ecological radiation corridors, and 75 ecological nodes. The total length of the ecological corridors between sources is 5511.17 km, and the total length of ecological radiation corridors is 1082.50 km. From the perspective of overall spatial distribution, this is a complex ecological network with the overall characteristic of "dense in the central region and sparse in the outer region," presenting a spider-web-like distribution. Notably, the ecological corridors in the western and southern parts of the study area have a large span, while the corridors in the central region are dense and structurally complex. This pattern arises primarily due to the concentrated distribution of ecological supply sources in the central region, compared with their scarcity in the western region. In addition, the ecological nodes in the western part of the study area are densely distributed and concentrated on long-span corridors. This indicates that the ecological energy flow in these areas is frequent and relatively fragile. If these areas are damaged, it may affect the overall stability of the ecological network. Therefore, further analysis of the structure and function of the ecological network is needed, and optimization should be carried out for its shortcomings.

3) Analysis of Ecological Topological Network: Based on the complex network model, we abstracted the ecological network of the study area into a topological network for further analysis of its structure and function. Fig. 10 shows the spatial structure of the ecological topological network. We selected metrics, including average degree, average clustering coefficient, average path length, number of triangles, and number of communities, to represent the overall topological characteristics of the ecological network.



(a) (b) (c)

Fig. 7. Ecological pinichpoints in XMA. (a) Spatial characteristics of currents in all-to-one mode. (b) Spatial characteristics of currents in pairwise mode. (c) Spatial characteristics of ecological pinchpoints.



(a) (b) (c)

Fig. 8. Spatial characteristics of ecological corridor intersections. (a) Spatial characteristics of corridors' intersections between ecological supply sources and demand sources. (b) Spatial characteristics of corridors' intersections between supply sources and corridors between supply and demand sources. (c) Spatial characteristics of intersections of ecological radiation corridors and other corridors.

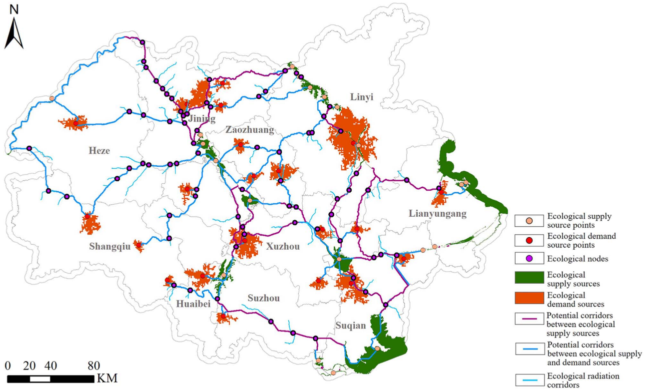


Fig. 9. Spatial pattern of ecological network in the XMA.

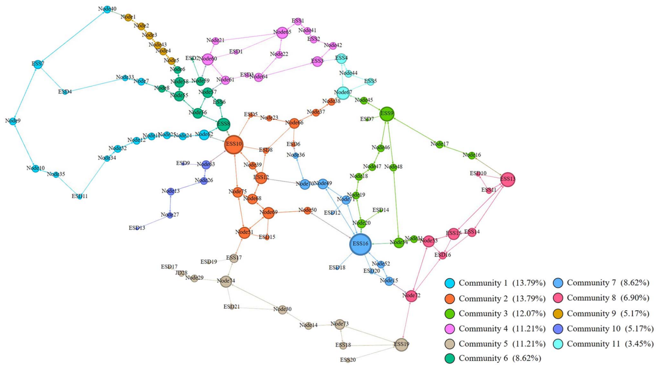


Fig. 10. Spatial pattern of the ecological topological network in XMA (ESS means the ecological supply sources; ESD means the ecological demand sources; and node means the ecological node).

Ecological network communities refer to a group of ecological nodes with similar characteristics and close connections. Species are more likely to interact frequently between closely related communities rather than loosely related ones [79]. As shown in Fig. 10, the ecological network of the study area, abstracted into a topological network, is divided into 11 communities, where nodes within the same community are densely connected. In terms of community structure, the number of nodes in each community is relatively even, and the distinction between communities is not significant. Communities 1 and 2, 4 and 5, 6 and 7, as well as 9 and 10 have the same number of internal nodes. In addition, some communities have a rather simple composition, resulting in a relatively larger total number of communities. For example, both communities 9 and 10 contain only 6 nodes and community 11 has only 4 nodes. Excessive refinement of communities may lead to the overall instability and difficulties in the maintenance of the ecological network. Therefore, optimizing the community structure should be emphasized in the subsequent ecological network optimization.

The average degree refers to the average number of edges on all nodes. The average clustering coefficient represents the average clustering degree of nodes. The average path length is

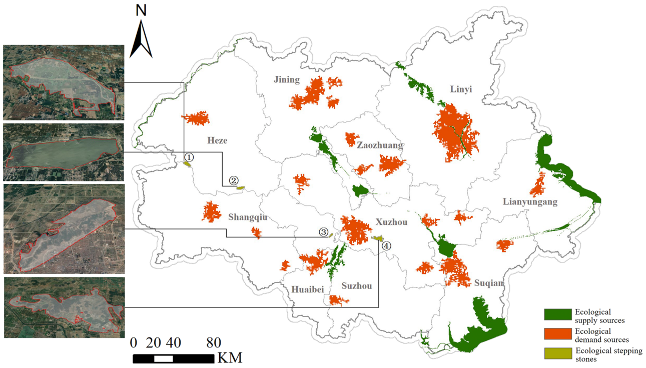


Fig. 11. Spatial characteristics of the new ecological stepping stones.

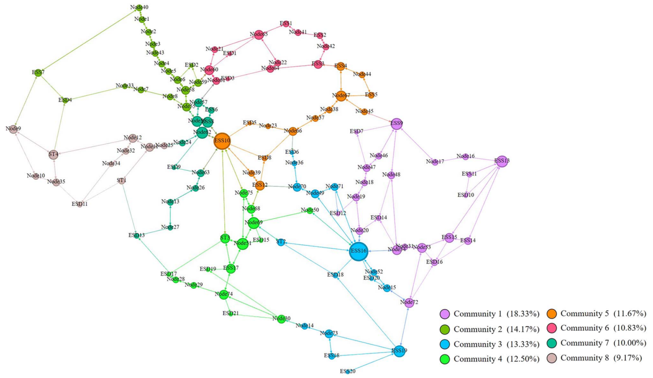


Fig. 12. Spatial characteristics of the optimized ecological topological network (ESS means the ecological supply sources; ESD means the ecological demand sources; and node means the ecological node).

the average distance between any two nodes. The number of triangles can be used to measure the stability of the network. Using Gephi software for calculation, the values of these indicators were obtained. Specifically, the average degree of the ecological topological network is 2.207, the average clustering coefficient is 0.072, the average path length is 9.272, and the number of triangles is 10. These indicators comprehensively measure the overall structure of the ecological topological network, providing a more intuitive reflection of the performance of the ecological network's structure and function. Therefore, this sets the stage for comparing the ecological network before and after optimization.

D. Optimization of Ecological Network

1) Ecological Stepping Stones Supplement: An analysis of the current spatial characteristics of the ecological network reveals a scarcity of ecological supply sources in the western part of the study area, along with extensive ecological corridors in the western and southern regions. Consequently, the supplementation of ecological stepping stones is crucial. Ecological stepping stones enhance the integrity and resilience of regional ecological networks by restoring connectivity in heterogeneous landscapes. In this study, after considering the importance and spatial location of ecological patches, four candidate patches from ecological supply sources were selected as stepping stones for ecological network optimization, with a total area of 84.60 km^2 (see Fig. 11). Positioned mainly in the western and central–southern regions of the study area and occupying central roles in the ecological network, these stepping stones act as effective transit stations for the flow of ecological energy and species migration.

2) Network Edge-Increasing Optimization Based on Complex Network Models: Through the analysis of the spatial characteristics of the ecological network, it was found that there are some shortcomings in the current network. Therefore, optimization of the ecological network was carried out from the perspective of topological features (see Fig. 12). First, there are some nodes in the current ecological network with low degrees, especially the ecological demand sources, which have a connectivity degree of only 1. When the edges of these nodes are damaged, it will lead to changes in the overall structure of the ecological network, and the connection between urban space and ecological space will be disrupted. Therefore, we selected nodes with a connectivity degree of 1 for edge addition optimization to ensure the stability of the ecological network. Specifically, corridors were added to ecological demand sites ESD9, ESD12, ESD13, ESD14, ESD17, ESD18, and ESD19, and the newly added ecological stepping stones were integrated into the ecological network.

Furthermore, betweenness centrality reflects the number of times a node serves as a "bridge" on the shortest paths between the other two nodes. A higher betweenness centrality implies that the node is more likely to become congested and form a bottleneck in the network. Therefore, for nodes with high betweenness centrality values, the optimization approach needed is to increase ecological corridors and reduce the shortest paths passing through these nodes. This, in turn, lowers the betweenness centrality of the nodes, enhancing the stability of the ecological network. For the current ecological topological network, nodes ESS10 and ESS16, as well as Node56, 75, 62, and 51, have relatively high betweenness centrality, indicating that they serve as "bridges" more frequently. Hence, edges should be added around them to reduce their betweenness centrality. Finally, we obtained the optimized ecological topological network.

3) Analysis of the Ecological Network Characterization After Optimization: Based on the above optimization measures, we have obtained a new ecological network. As shown in Fig. 13, compared with the unoptimized ecological network, we have added 4 new ecological stepping stones and 29 ecological corridors, with a total length of 1826.75 km. From a spatial distribution perspective, it exhibits a more complete and complex spider-web structure, filling the previous external structure's sparsity. The addition of ecological stepping stones has improved the network in the western part of the research area. In terms of ecological network communities, as shown in Fig. 12, the optimized ecological topological network has eight communities. The number of communities has been reduced compared to before, and the community structure is more reasonable. Among them, Community 8, which contains the fewest nodes, has 11

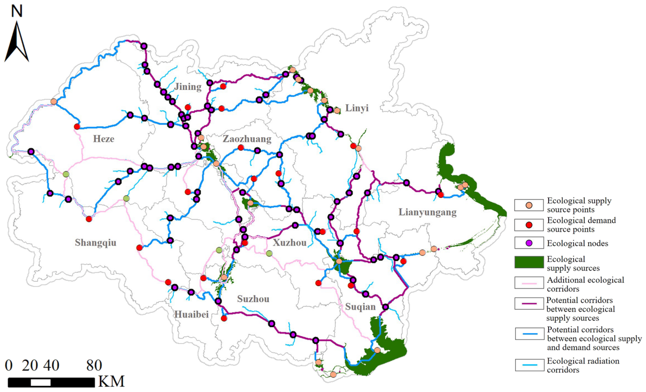


Fig. 13. Spatial characteristics of the optimized ecological network.

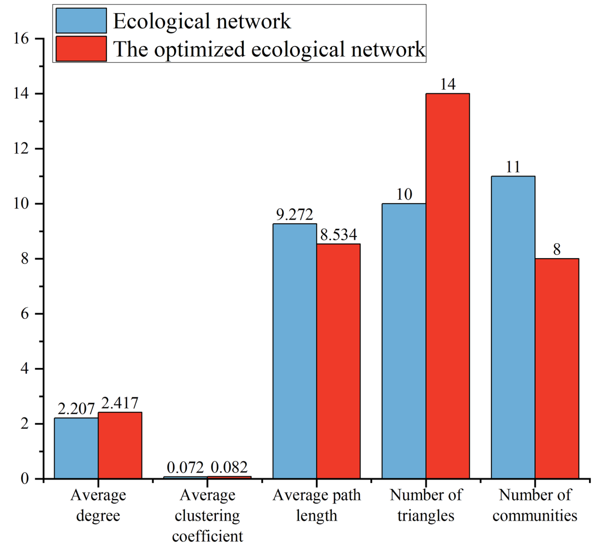


Fig. 14. Comparison of ecological network topology characteristic metrics before and after optimization.

nodes, and the internal structure of the community has improved. The connections between communities are also closer.

In terms of other indicators measuring the overall structure of the ecological topological network, there is also a significant improvement compared with the unoptimized ecological network. As shown in Fig. 14, the optimized ecological network has an average degree of 2.417, an average clustering coefficient of 0.082, and 14 triangles. These indicators have improved compared with the unoptimized ecological network, indicating that the ecological network has become more tightly structured and stable, with a wider radiation. The average path length is 8.534, which has decreased compared to before, indicating an enhanced overall connectivity of the ecological network. Overall, after optimization, the interactivity between nodes in the ecological network has improved, and the overall energy flow and species migration in the network have become more efficient and the structure more stable.

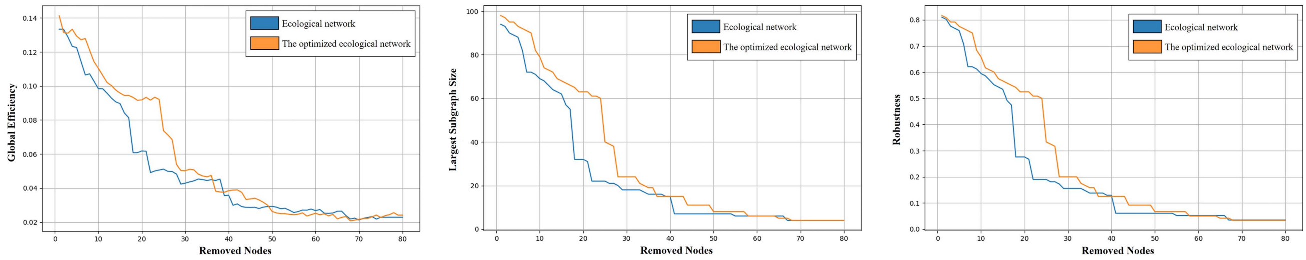
V. DISCUSSION

A. *Measurement of the Stability of Ecological Networks*

The optimization of the ecological network involves a critical objective of enhancing the stability and resilience of the ecosystem. The evaluation of ecological network stability and the comparison of stability indicators pre- and postoptimization can provide insights into the extent to which optimization strategies have improved the resilience of the network [80]. Therefore, the stability of the ecological network may be completely assessed through the examination of global efficiency, largest subgraph size, and robustness [81]. As shown in Fig. 15, in the context of random network attacks, there is a negative correlation between the proportion of attacked nodes and the stability of the network. In general, the optimized network demonstrates enhanced stability in comparison with the unoptimized network. Specifically, prior to the point at which 50% of nodes are attacked, the optimized ecological network exhibits superior values in terms of global efficiency, largest subgraph size, and robustness when compared with the unoptimized network. This observation suggests a comparative enhancement in the quality and reliability of network connectivity, accompanied by a discernible augmentation in its resilience against malicious attacks. This approach is more favorable for the preservation of a stable regional ecological energy flow and the assurance of regional ecological security.

B. *Methodological Advantages*

This study's method, which emphasizes the ecological supply and demand perspective, offers several methodological advantages that set it apart from traditional methods. First, the ecological supply and demand perspective provides a more holistic view of the ecosystem, ensuring that both the sources of ecological services and the areas that demand these services are considered. This approach recognizes that ecosystems are not just providers of services but also have areas that require these services for proper functioning. By considering both supply and demand, the constructed ecological networks are more aligned with the actual needs and provisions of the ecosystem, ensuring a more balanced and sustainable network [22], [28]. Furthermore, the use of complex network models for optimization offers a robust method to enhance the structure and function of the ecological network. Complex network models, with their ability to capture intricate relationships and dependencies, provide a more nuanced understanding of the ecosystem's dynamics [12]. This allows for the identification of key nodes and corridors that are crucial for the network's stability and resilience. By optimizing these critical components, the ecological network becomes more resistant to disturbances and can maintain its function even under adverse conditions [82]. Moreover, the integration of remote sensing data adds another layer of precision to the study. Remote sensing offers high-resolution spatial data that can capture the nuances of the landscape, ensuring that the constructed and optimized ecological network is grounded in real-world conditions [42].



(a) (b) (c)

Fig. 15. Comparison of ecological network stability before and after optimization.

In conclusion, the methodological approach adopted in this study, which combines the ecological supply and demand perspective with complex network models and integrates remote sensing data, offers a comprehensive and robust method for the construction and optimization of ecological networks. This approach not only ensures the creation of a resilient and sustainable network but also provides valuable insights that can guide future research and conservation efforts.

C. Limitations and Future Works

This research endeavor is not without its inherent constraints. To begin with, in the process of selecting ecological supply sources, we utilized the MSPA and conducted an analysis of landscape connectivity. This comprehensive approach allowed us to identify and extract the ultimate ecological supply sources. Certain scholars opt to compute numerous functions of ecosystem services in order to completely identify and extract ecological supply sources [44], [83]. In further investigations, it is recommended to conduct a comparative analysis of various selection strategies in order to objectively ascertain the spatial distribution of ecological supply sources. Furthermore, with respect to the establishment of ecological resistance surfaces, certain researchers propose the utilization of the study area's characteristics as a means to adapt and adjust the ecological resistance surface [19], [84]. In future investigations, it is imperative to conduct a more comprehensive examination of the distinctiveness of the research domain. Moreover, the creation and optimization of the ecological network in this study did not incorporate temporal considerations, as it just relied on data from a singular year. The dynamics of ecosystem services' supply and demand exhibit temporal and spatial variability [85]. Hence, it is recommended that future research endeavors employ long-term time-series data and more advanced remote sensing processing in order to gain a precise comprehension of the underlying mechanisms that drive ecosystem evolution [86]. This would afterward provide more efficient guidance for ecological restoration and protection initiatives. Finally, this study primarily examined the entire XMA as the designated research region. However, it did not incorporate a comprehensive multiscale nested analysis. Scale is a key element in landscape ecology, and different scales can reveal different ecological processes and patterns [87], [88], [89]. Several scientists have observed that the establishment of an ecological security pattern at a singular size may result in a lack of synchronization in ecological structure across other scales [24], [90]. Therefore, it is imperative for future studies to examine the composition and structure of the ecological network across various geographical scales in order to attain the integrated linkage among landscape ecological structure, process, and function.

VI. CONCLUSION

Urbanization and industrialization have profoundly changed human living and production patterns, especially in economically developed urban agglomerations. Although the coordinated urban development of the XMA has promoted economic growth, it has overlooked the health and stability of the ecological environment. This region faces an imbalance in ecological supply and demand, resulting in a significant shift in the socioecological structure. To safeguard regional security and enhance human well-being, this study constructed and optimized the ecological network of the XMA, focusing on ecological supply and demand. The optimization, implemented through complex network models, aims to refine the network's structure and augment its stability. The research results are given as follows.

1) *Construction of the ecological network*: From the supply–demand perspective, the ecological network of the XMA includes 20 ecological supply sources, 21 ecological demand sources, 31 potential ecological corridors between supply sources, 48 corridors between supply and demand sources, 87 ecological radiation corridors, and 75 ecological nodes. It has an overall characteristic of "dense in the center, sparse on the outside," resembling a spider-web distribution.
2) *Optimization of the ecological network*: After optimization, the ecological network added 4 ecological stepping stones and 29 ecological corridors, forming a more complete and complex spider-web structure, effectively compensating for the previous sparsity of the external structure.
3) *Comparison of ecological topological network structures*: Compared to before optimization, the optimized ecological network structure is tighter and more stable, with a broader radiation range and enhanced overall connectivity.
4) *Stability analysis of the ecological network*: Under random attack scenarios, the optimized ecological network's global efficiency value, the largest subgraph size, and

robustness are all superior to the unoptimized network, showing better stability, which is conducive to maintaining the stable flow of regional ecological energy.

In summary, the contributions of this study are summarized as follows: Methodologically, the study establishes a regional ecological network, framing it within the context of ecological supply and demand. Furthermore, this study employs complex network theory to model the ecological network, conducts a comprehensive analysis of its structure, and suggests specific optimization strategies; In addition, the study assesses the stability of the ecological topological network under random perturbations, enabling a comparison of the network's state pre- and postoptimization. Theoretically, this study initially enhances the construction framework for regional ecological networks. Second, this study advances the balance between supply and demand in regional ecosystem services. Finally, this study offers practical guidance for ecosystem management and spatial planning in highly urbanized areas, contributing to the region's sustainable development.

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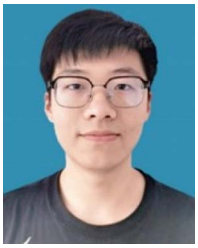

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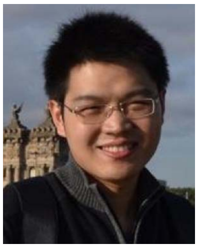

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