Identifying priority areas for conservation in the lower Yellow River basin from an ecological network perspective

Jieming Kang\textsuperscript{a,b,c}, Chunlin Li\textsuperscript{b,c}, Meirui Li\textsuperscript{a}, Teng Zhang\textsuperscript{b} and Baolei Zhang\textsuperscript{a}

\textsuperscript{a}College of Geography and Environment, Shandong Normal University, Jinan, Shandong, China; \textsuperscript{b}Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China; \textsuperscript{c}CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China

**ABSTRACT**

Taking the lower Yellow River basin as the study area, this study aims to construct ecological networks to mitigate the negative impacts of rapid urbanization on the ecosystem. Ecological sources were identified based on morphological spatial pattern analysis (MSPA), habitat quality and landscape connectivity. The ecological resistance surface was constructed and corrected by integrating natural and anthropogenic factors. The spatial range of ecological corridors and some of their key nodes were identified based on circuit theory. The ecological network (EN) was finally optimized using a similarity search and cost connectivity modules. The results show that the optimized ecological network structure is more stable than before. The EN includes 23 ecological sources with a total area of 5464.8 km\textsuperscript{2} and 30 ecological corridor clusters with a total area of 2205.92 km\textsuperscript{2}. Through the internal landscape heterogeneity of the corridor, 28 ecological node areas and 75 barrier areas were identified as key protection and restoration areas, with a total area of 78.44 km\textsuperscript{2} and 372.79 km\textsuperscript{2}, respectively. Through the construction and optimization of EN, this study identifies key areas for promoting ecological sustainability and provides a useful framework for coordinating regional ecological conservation and economic development.

**INTRODUCTION**

In the past few decades, the world’s population has proliferated and the accompanying dramatic urbanization has driven the rapid expansion of artificial land surfaces, which have encroached on large amounts of ecological land/natural habitats (L. He and Zhang 2022; L. Li et al. 2022). The loss of natural ecological space has led to changes in the structure and function of pristine ecosystems and a significant reduction in ecosystem services such as water containment, biodiversity, soil conservation (Faber et al. 2021; X. Li et al. 2021; Travers, Härdtle, and Matthies 2021), etc. The changes in natural landscape morphology and attributes have accelerated the fragmentation of landscape patches, forced the extension of species migration distances, and reduced the connectivity between landscapes, thus further affecting the stability of regional landscape patterns. Moreover, with the overexploitation of resources, a series of ecological and environmental problems, such as air pollution, water shortages, land desertification, and heat island effects, have been triggered, threatening the stability of regional landscape patterns and urban ecological security (Gittins, Hemingway, and Dajka 2021; Guo et al. 2022b; Liao et al. 2022).

Building an ecological network (EN) to improve the quality and stability of ecosystems has become a national policy for ecological conservation in China. The EN originated from the “patch-corridor-matrix” theory of landscape ecology (Jongman 1995; Noss 1983), which protects the ecological function of ecosystems by conserving ecological processes. Some scholars have applied ENs to conserve biodiversity (Cui et al. 2020), build urban green spaces (Hüse et al. 2016), regulate ecosystem services (L. Huang et al. 2021), and improve ecosystem sustainability (Wang, Li, and Huang 2021) with excellent results, which laterally proves that an EN is an important way to coordinate development and conservation.

An EN mainly consists of ecological sources and ecological corridors. (Cui et al. 2020). First, an ecological source is the patch with the highest level of regional ecological conservation (Kang et al. 2021). Many traditional methods directly select nature reserves as sources (Vergnes, Kerbiriou, and Clergeau 2013; Zhao and Xu 2015), ignoring the internal heterogeneity of patches. Other studies screened sources based on ecological importance and sensitivity evaluation (Jin et al. 2021). However, the selection of assessment factors tends to lack trade-offs in ecological spatial structure.
In recent years, many studies have identified sources using morphological spatial pattern analysis (MSPA) (Wang et al. 2021), which uses mathematical morphological principles to identify and classify raster data. MSPA can distinguish the spatial connectivity types of different patches but cannot reflect the differences between different land types. Habitat quality is the ability of the natural environment to provide suitable conditions for the sustainable survival and development of individuals and populations (Jackson et al. 2001). Sources, as large ecological spaces, should have high habitat quality (R. Zhang et al. 2021). Second, the construction of an ecological resistance surface is a prerequisite for ecological corridor identification, which responds to the ease of species migration (L. Huang et al. 2021). The ecological resistance surface simulated by the traditional method of allocating resistance based on land cover type usually fails to reflect the effects of natural and anthropogenic disturbances. Therefore, using night-light data to simulate human activities and correct for resistance has become a more scientific option (Peng et al. 2018). Finally, ecological corridors are the carriers of regional material circulation, energy flow and information transmission, which makes them an important channel for protecting ecological processes (Dong et al. 2020). The methods of identifying ecological corridors are mainly the minimum cumulative resistance (MCR) model (S. Li et al. 2021) and circuit theory (Peng et al. 2018; Yang, Bai, and Shi 2021). The MCR model assumes that species are "prophetic" and choose optimal paths during migration (Adriaensen et al. 2003). However, biological movements are largely stochastic, similar to the movement of electric charges in electric circuits. Circuit theory simulates species migration with the movement of electrons in a circuit, largely restoring the real ecological flow (Mcrae et al. 2008). It is not uncommon to combine MSPA and circuit theory to construct EN (An et al. 2020; Tianlin Zhai and Huang 2022), but these studies generally only scratch the surface and do not delve into aspects such as the scale of MSPA, the correction of ecological resistance surface, and the threshold change of circuit theory, and it is worth considering whether these factors affect the accuracy of EN.

Resource, environmental and ecological problems have become the key constraints in the development of many regions (Grimm et al. 2008). In the process of social civilization moving forward, the Yellow River Basin (YRB) has been "weak and sickly:" it has a poor ecological background, water shortages, severe soil erosion, and weak resource and environmental carrying capacity (Qu et al. 2021; T. Zhai, Zhang, and Zhao 2021). In 2019, China elevated YRB ecological protection to a national strategy. In 2020, the Shandong government decided to take the lead in YRB ecological protection. In this context, this study focuses on the YRB in Shandong and aims to construct an EN and address the following questions: (1) How can important ecological resources with intact natural attributes, excellent habitat quality and good connectivity be identified among large-scale human-land ecosystems? (2) How can the spatial range of ecological corridors be determined? (3) What do the key node areas in the ecological corridor that affect ecological flow mean in the landscape ecology?

Material and methods

Study area and data sources

The Yellow River, the fifth longest river in the world and the second longest river in China, is the main birthplace of Chinese civilization and is known as the "Mother River" of China. It originates from the Tibetan Plateau and flows through nine provinces before joining the Bohai Sea in Dongying, Shandong Province, with a total length of 5464 km. The study area considered in this paper is the lower Yellow River region (N34°58′-38°09′, E114°48′-119°19′) (Figure 1), the Shandong Yellow River basin (SYRB), with a total length of 628 km and a basin area of 18,300 km², mainly including the 9 cities Jinan, Zibo, Tai’an, Dongying, Liaocheng, Dezhou, Jinjing, Binzhou and Heze. These cities had a total area of 82,500 km², a resident population of 54,217,900 and a gross domestic product of 3.54 trillion in 2020. The topography is characterized by the eastern and central parts of the Taishan Mountains jutting out, with relatively gentle terrain to the north and south. The SYRB has a warm temperate monsoon climate with four distinct seasons, an average annual precipitation of 500–800 mm, and an average annual temperature of 12–14°C.

The data used in this study mainly include land use, digital elevation model (DEM), administrative boundary, precipitation, night light, socio-economic and nature reserve data. (1) The 2020 land use data were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences (https://www.resdc.cn), with a resolution of 30 m, 6 primary land classes and 25 secondary land classes; (2) the DEM data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn), with a resolution of 30 m; and (3) the precipitation data were obtained from the China Meteorological Data Network (http://data.cma.cn). (4) Night light data were obtained from the Google Earth Engine platform (https://earthengine.google.com), provided by the Earth Observation Group; they were monthly average data from
May 2020 with a resolution of approximately 500 m. (5) The administrative boundary data were provided by the China National Geographic Information Center (http://www.ngcc.cn); (6) the socio-economic data and demographic data were from the Shandong Province Statistical Yearbook 2020; and (7) the nature reserve data were collected by the Resource and Environment Science Data Center of the Academy of Sciences.

Methods

The research in this paper can be broadly divided into three parts (Figure 2). First, ecological sources were identified based on MSPA, habitat quality and landscape connectivity, and then sources were optimized using a similarity search. Second, the ecological resistance surface was constructed based on natural and anthropogenic factors, and then the resistance surface was corrected with night-light data. Finally, the spatial

![Figure 1](image1.png)

Figure 1. Location and elevation of the study area.

![Figure 2](image2.png)

Figure 2. The research framework of this paper.
range of the ecological corridor was determined based on circuit theory, and the key areas to be protected and restored in the area were analyzed in detail.

**Multi-perspective identification of ecological sources**

Ecological sources are important sites for realizing ecological processes, important ecological spaces for regional species, and key areas for realizing EN construction and ensuring regional ecological security. Ecological sources should be identified from multiple perspectives to compensate for the errors of single-target identification in ecological background identification and the imbalance in ecological structure and ecological process identification. Based on the comprehensive consideration of ecological structure systematicity and ecological process integrity, MSPA, habitat quality evaluation and landscape connectivity evaluation are innovatively combined to extract regional ecological sources.

Morphological spatial pattern analysis (MSPA) is an image processing method based on mathematical morphological operators (Soille and Vogt 2009; Vogt et al. 2007a). It measures, identifies and segments the corresponding raster image data of the study area via erosion, dilation and corresponding opening and closing operations and determines the overall spatial pattern, landscape type and landscape structure (Lin et al. 2021; P. Vogt et al. 2007b). MSPA is performed using binary data (1 for the foreground and 0 for the background), with woodlands, grasslands and water bodies, which are more ecologically efficient and less disturbed by humans, as the foreground, and other land types as the background. Then, Gudios Toolbox software (Version 3.0) was used to identify the topological relationships among the image elements, the study area was classified into seven landscape elements according to the morphological structures of different image elements and graphic processing methods (Vogt and Ritters 2017) (Table 51), and the core area was screened as the ecological source alternative patches.

Habitat quality refers to the ability of an ecosystem to provide a suitable living environment and sustainable living conditions for organisms. The submodules of the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) model are widely used in the evaluation of natural habitat quality (Mengist, Soromessa, and Feyisa 2021). The InVEST model facilitates the quantification of habitat quality based on four factors: the relative sensitivity of habitat types to threat factors, the relative influence between threat factors, the distance between habitats and threat factors, and the level at which the land is legally protected. The formula is as follows:

$$Q_{xy} = H_j \left[ 1 - \left( \frac{D_{xy}}{D_{xy} + k} \right)^{\frac{1}{r}} \right] \quad (1)$$

where $Q_{xy}$ is the habitat quality corresponding to raster $x$ in habitat $j$; $H_j$ is the habitat suitability corresponding to habitat $j$; $z$ is a constant with a fixed value of 2.5; $D_{xy}$ is the degree of habitat degradation of raster image $x$ in habitat $j$; and $k$ is the half-saturation constant, which is half of the highest habitat degradation raster value.

The data required for the InVEST model are mainly land use, threat factors and their weights and impact distances, the sensitivity of land use to each threat source, etc. We set the relevant parameters by referring to the user manual of the model and a large number of related studies (Gong et al. 2019; J. He, Huang, and Li 2017; Sallustio et al. 2017) (Table 1, Table 2). The habitat quality score is dimensionless, and the score indicates the fragmentation status of regional habitat patches and the strength of resistance to habitat degradation by anthropogenic disturbance. In ArcGIS 10.8, the raster of habitat results calculated by InVEST are classified into three classes using the natural breakpoint method: low quality (0–0.6), medium quality (0.6–0.8), and high quality (0.8–1) (Tang et al. 2022).

**Table 1.** The weights and maximum influence distances of threat sources.

| Threats          | Maximum influence distance (km) | Weight | Decay type  |
|------------------|---------------------------------|--------|-------------|
| Urban land       | 10                              | 1      | Exponential |
| Rural land       | 8                               | 0.8    | Exponential |
| Traffic land     | 9                               | 0.9    | Exponential |
| Cultivated land  | 6                               | 0.6    | Linear      |
| Unutilized land  | 4                               | 0.4    | Linear      |

**Table 2.** Sensitivity of different habitats types to different threat factors.

| Habitat type       | Habitat suitability | Urban land | Rural land | Traffic land | Cultivated land | Unutilized land |
|--------------------|---------------------|------------|------------|--------------|-----------------|-----------------|
| Cultivated land    | 0.3                 | 0.8        | 0.6        | 0.7          | 0               | 0.4             |
| Forestland         | 1.0                 | 0.8        | 0.7        | 0.7          | 0.6             | 0.2             |
| Grassland          | 0.9                 | 0.7        | 0.6        | 0.7          | 0.4             | 0.4             |
| Water              | 0.8                 | 0.7        | 0.6        | 0.7          | 0.4             | 0.4             |
| Construction land  | 0.0                 | 0          | 0          | 0            | 0               | 0               |
| Unutilized land    | 0.5                 | 0.4        | 0.4        | 0.4          | 0               | 0               |

Landscape connectivity is a measure of the continuity of landscape units, and good landscape connectivity is important for maintaining the stability of ecosystems and ecological processes (Sahraoui et al. 2021). We selected the probability of connectivity (PC)
and the importance value of patches (dPC) to measure the level of connectivity between core patches in the study area. We used ArcGIS 10.8 and the Conefor 2.6 plug-in to calculate the connectivity between MSPA core areas and high-quality habitat areas. After repeated experiments, the distance threshold required for the Conefor 2.6 plug-in was set to 2.5 km, and the connectivity probability between patches was set to 0.5. The results were classified into three types using the natural breakpoint method: ecological source, important core and general core. The calculation formula was as follows:

\[
PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij} \times a_{i} \times a_{j}}{A_{t}^{2}}
\]  

(2)

\[
dPC = \frac{PC_{\text{remove}} - PC}{PC} \times 100\%
\]  

(3)

where \(n\) denotes the total number of patches in the study area; \(a_{i}\) and \(a_{j}\) denote the areas of patches \(i\) and \(j\), respectively; \(p_{ij}\) denotes the maximum possibility of organisms spreading in patches \(i\) and \(j\); \(A_{t}^{2}\) denotes the total area of patches; \(PC_{\text{remove}}\) denotes the connectivity index of the landscape after removing a random patch; and \(dPC\) denotes the patch importance.

**Construction and correction of resistance surfaces**

Species landscape use is seen as a process of competitive control and coverage of space, where ecological processes are achieved by overcoming resistance; ecological resistance characterizes the degree of difficulty in the migration, transfer and flow of species and energy between heterogeneous landscapes. The MCR model can be used to effectively calculate the resistance needed to overcome the flow of ecological energy between different landscape surfaces (Dai, Liu, and Luo 2021). The greater the resistance of the landscape surface is, the more difficult the flow of ecological energy will be, and the principle of the model is as follows:

\[
MCR = f_{\text{min}} \sum_{j=n}^{m} D_{ij} \times R_{i}
\]  

(4)

where \(MCR\) denotes the minimum cumulative resistance value, \(D_{ij}\) denotes the spatial distance from source \(j\) to destination \(i\), \(R_{i}\) denotes the resistance to be overcome to cross space \(i\), and \(f\) is a positive correlation coefficient.

Ecological resistance come from the influence of natural landscape features such as topography and slope on the one hand and the interference of human activities and other factors on the other hand. The accurate construction of ecological resistance surfaces is related to the extraction of ecological corridors, and such surfaces cannot be constructed considering only a single source of resistance. Currently, there is no standard for constructing ecological resistance surfaces at home or abroad, so we can simulate resistance only from various aspects to a certain degree. Some researchers (Balbi et al. 2019; Gurrutxaga et al. 2010) have chosen to construct ecological resistance surfaces by assigning uniform values to different landscape types, but this approach ignores the differences in ecological resistance coefficients under the same land cover types and does not consider the effects of human disturbances on ecological resistance. In this study, we quantified the resistance of the natural environment from five factors, land type, elevation, slope and distance (L. Huang et al. 2021; Yu et al. 2017; R. Zhang et al. 2021) (Table S2). Landscape type is the decisive influencing factor, and human activity is an important disturbing factor. Some studies have shown that night light can reflect human activity factors such as population density (Peng et al. 2018), economic development status and urbanization level to a certain extent, so the ecological resistance surface was corrected using night-light data, which, in theory, can better represent the actual ecological processes. The formula is as follows:

\[
R_{x} = \frac{N_{L_{x}}}{N_{L_{a}}} \times R
\]  

(5)

where \(R_{x}\) denotes the corrected resistance value, \(N_{L_{x}}\) denotes the nighttime lighting index of raster \(x\), \(N_{L_{a}}\) denotes the average lighting index of raster \(x\) corresponding to landscape type \(a\), and \(R\) denotes the initial resistance value of raster \(x\).

**Identification of the spatial range of ecological corridors**

Ecological corridors are linear or banded elements in the landscape that are clearly different from the substrate on both sides and are channels for material, energy and information exchange between ecological patches. Moreover, the maintenance or loss of biodiversity is closely related to corridors (Dong et al. 2020), which are an important part of the regional EN.

This study uses circuit theory to identify the direction and boundaries of ecological corridors in heterogeneous landscapes. According to this theory, species are considered random wanderers in the landscape, and the landscape is considered a conductive surface (corresponding to the ecological resistance surface) with different resistance values for different landscape types, wherein landscape types favorable for species migration and dispersal correspond to low resistance and vice versa. Each ecological source is considered a circuit node, and the cumulative resistance between each pair of nodes is calculated, corresponding to the effective resistance of the link (L. Huang et al. 2021). By connecting one of the paired circuit nodes to a 1 A current and the other to the ground, the cumulative current is calculated iteratively between all paired
circuit nodes. The magnitude of the cumulative current refers to the magnitude of the probability of species dispersal along a certain path such that the cumulative current value threshold can determine the extent of the ecological corridor (Peng et al. 2018). We used the Linkage Mapper toolbox (https://linkagemapper.org/) to identify ecological corridors, which operates on the principle of Ohm’s law (Kipnis 2009), with the following formula:

\[ I = \frac{V}{R_{\text{eff}}} \]  

(6)

where \( I \) is the current through the conductor, \( V \) is the voltage across the conductor, and \( R_{\text{eff}} \) is the effective resistance of the conductor. Noticeably, \( R_{\text{eff}} \) is closely related to the way the circuit is connected, and in parallel circuits (with multiple branches and constant branch resistance), \( R_{\text{eff}} \) decreases as the branches increase.

**Identification of priority areas for ecological protection and restoration**

Ecological corridors typically contain some key locations (ecological node areas and barrier areas), and we identified these areas as the priority areas for ecological protection and restoration. Ecological nodes are located in the most vulnerable parts of the ecological corridor and are the areas with the highest density of migration of ecological services, i.e., the places necessary for biological migration and diffusion (Yu et al. 2018). Ecological nodes play a key role in regional ecological processes and influence the landscape connectivity of the entire EN. They are the most vulnerable components to external disturbances in the landscape and need to be protected in a focused manner. In the circuit, the areas with the highest current values, i.e., the locations where all currents must pass, correspond to the ecological node areas. We used the pinch point module of Linkage Mapper to identify these areas.

Barrier areas impede the exchange of information between species and are usually located between landscapes where resistance is high. Improving or removing these locations can greatly reduce resistance to ecological processes and effectively improve landscape connectivity. We used the Barrier Mapper module of Linkage Mapper to search the barrier area based on a moving window and calculated the magnitude of the cumulative current recovery value after removing the barrier area, with a larger recovery value indicating a more significant improvement in landscape connectivity after removal or repair.

**Ecological network optimization and evaluation**

The similarity search module (ArcGIS 10.8) can identify the candidate elements most similar to the input elements to be matched (Wang et al. 2021). In this model, ecological sources are considered as target elements and other core patches as candidate elements. Landscape connectivity and patch area and mean ecological resistance were regarded as “attributes of interest” and given equal weights (de la Barrera, Reyes-Paecke, and Banzhaf 2016), and the ecological source and core patches were normalized by Z transformation (H. Zhang, Zha, and Yao 2004). The weighted average similarity index of each candidate element and the target element was calculated. Candidate elements were ranked from the smallest (most similar) index to the largest (least similar) index.

A network is generally composed of nodes and edges, and the degree of network connectivity is expressed as the connection relationship between nodes and edges. Based on graph theory (Ruiz-Frau et al. 2020) and using the cost connectivity module, ecological sources and corridors are transformed into topological models corresponding to nodes and edges (Kong et al. 2010), and the main indexes of network analysis, including closure (\( \alpha \)), the line-point rate (\( \beta \)) and connectivity (\( \gamma \)), are used to evaluate the connectivity of EN (Cui et al. 2020). The network structure analysis is calculated as follows:

\[ \alpha = \frac{L - V + 1}{2V - 5} \]  

(7)

\[ \beta = \frac{L}{V} \]  

(8)

\[ \gamma = \frac{L}{3(V - 2)} \]  

(9)

where \( L \) is the total number of all corridors; \( V \) is the number of nodes in the network.

**Results**

**Ecological sources**

The results of MSPA are shown in Figure 3a. On the basis of MSPA, a foreground area of 11,598.61 km², accounting for 14.06% of the total area of the SYRB, was identified. The core area is an important component of the regional ecosystem structure and the largest region in the landscape, accounting for 87.90% of the landscape elements. The area is mainly concentrated in the central, southeastern and northeastern parts of the SYRB, with high density, and may contain potential ecological sources, while the southwestern and northwestern parts are more fragmented in distribution, and may become secondary sources. The bridge and loop areas play a certain connecting role, representing key features for achieving connectivity in the regional ecosystem and a pathway for energy flow between internal and external patches. These features account for only 0.32% and 0.02% of the total area, indicating that the core patches are more independent and that the connection between core landscapes needs
to be further optimized. The island was originally part of the core, but it was too small to be adjacent to the core and was separated from it. Therefore, the island can reflect the fragmentation degree of the core and only accounts for 0.02% of the landscape elements, which indicates that the core is more integral. In addition, perforation, edge and branch features accounted for 0.80%, 10.16% and 0.78% of the ecological landscape area, respectively.

The results of habitat quality evaluation based on the InVEST model are shown in Figure 3b, where the total areas of high, medium and low habitat quality are 17,282.20 km², 48,142.35 km² and 16,884.74 km², respectively, accounting for 21.00%, 58.49% and 20.51%, respectively. In terms of spatial distribution, the area of the SYRB with high habitat quality is basically the same as that revealed by MSPA, concentrated in the central, southeastern and northeastern parts.
These areas are densely wooded and biologically diverse, with rich ecological resources and high ecological value, making them an excellent choice for ecological sources.

We used ArcGIS 10.8 software to extract the core area identified by MSPA and then removed the small fragmented patches and some areas with human activity/conflict within the landscape, intersected the remaining area with high-quality habitat areas, and merged the patches with spatial aggregation and similar habitats within the patches into relatively complete patches according to the distribution density. We assessed the landscape connectivity of these areas and identified 43 ecologically important patches (Figure 4a), totaling 5754.07 km², i.e., 6.98% of the total area of the SYRB. The natural breakpoint method was used to classify the important ecological patches into three levels according to the degree of connectivity, including 15 ecological source patches totaling 5044.94 km², 13 important core patches totaling 522.67 km², and 15 general core patches totaling 191.33 km².

Ecological sources were mainly distributed in the central and southeastern parts of the SYRB. When overlaying ecological sources with land use data, forestland was the most dominant habitat for ecological sources, accounting for 86.14% of the total area, followed by water, accounting for 8.29%. These areas are rich in species, have a good ecological environment and high ecological service value, and should be treated as core areas for regional ecological protection, with development and construction activities within them prohibited and the strictest control measures implemented. In the western part of the SYRB, ecological resources are scarce, landscape connectivity is poor, and species migration and material flow barriers are serious. It is necessary to increase appropriate ecological resources and strengthen ecological construction in this region.

**Ecological resistance surface**

The five types of resistance factors were superimposed and then corrected using nighttime light data to obtain the SYRB ecological resistance surface (Figure 4b). The high values of resistance were mainly located in the central and south-central parts of the SYRB. These areas are the urban centers of Jinan, Zibo, Dongying, Binzhou and Jining, which are mostly construction sites with a high intensity of human activities, development and utilization. The low values of resistance were mainly distributed in the north–south part of the SYRB and at the boundary, and the land types were mainly forestland and water. With the lowest resistance values in the north of the study area at the locations of Jining and Heze, where the largest freshwater lake in northern China, Weishan Lake, is located, with very high habitat quality. A small number of low resistance areas also exist at the border of Binzhou and Jinan, which are far from urban centers and less affected by human activities, making them suitable for species growth and dispersal. In general, the ecological resistance values in the central part of the study area were significantly higher than those in other areas, with the highest average ecological resistance value of 39.20 observed in Zibo, followed by 35.68 in Jinan, and the lowest average ecological resistance value of 30.19 observed in Heze.

**Optimized ecological network**

In the analysis in section 3.1, we found that the ecological sources of the SYRB are mainly concentrated in the central region, with a large extension area and good interconnection. The lack of ecological resources in other areas is not conducive to the spread and diffusion of ecological flows. Moreover, after the EN was constructed, the ecological corridors spatially spanned a large area and were easily obstructed by other external landscapes, which is not conducive to the ecological function of the landscape (Figure 5a). From the perspective of improving EN structure, some new ecological sources should be planned for these areas. Based on the similarity search module, we selected the core patches most similar to the ecological source as the planning source, with a total area of 419.86 km². This value is 8.32% larger than the pre-planning ecological sources (Figure 5b).

Ecological corridors are the core components of an EN. After optimizing the ecological sources, 30 ecological corridor clusters were identified based on circuit theory (Figure 5b). The land types within the corridors are mainly woodland, grassland and arable land, with an average length of 30,832 m (1592–165,542 m) and a total area of 2205.92 km². Notably, the corridors differ in spatial morphology, with the northern region showing more influence of human activities, ecological flow compression in terms of direction and space, high crossing resistance, and narrow and linear corridors, while the central and southern areas are reticulated and radial and have concentrated ecological resources or adjacent areas, low crossing resistance, and free species or energy flow.

We used network analysis to evaluate the structure of the constructed ecological network. The results were as follows: before optimization, the α, β, and γ indexes were 0.31, 1.64, and 0.62, respectively; after optimization, the α, β, and γ indexes were 0.46, 1.89, and 0.74, respectively. All three indexes have increased to different degrees, and the regional ecological network structure is also more stable in terms of ecological network structure, indicating that various ecological flow cycles have increased, facilitating ecosystem species migration and information transfer.
Ecological protection and restoration priority areas

Ecological node areas are necessary pathways for biological migration and energy transfer. A total of 28 landscape ecological node areas with an average width of 296 m and a total area of 78.44 km$^2$ were identified in this study (Figure 6). Superimposition of these areas with the ecological resistance surface shows that the ecological node areas are all located in places with low resistance values, but the landscapes with high resistance, such as cultivated land...
and artificial land, are distributed within a certain range around them. These high resistance landscapes are mostly located at corridor intersections, and some ecological processes are compressed, so they are narrower. Ecological node areas often face strong human activity interference while performing important connectivity functions, and the protection of ecological nodes is of strategic importance in maintaining the continuity of landscape ecological structures and the integrity of system functions. Thus, ecological node areas need to be prioritized for maintenance and management.

Ecological barriers are locations where organisms are hindered by various factors in their migration between ecological sources. Based on the moving window method, 75 ecological barrier areas with an area of more than 1 km² were screened out, for a total area of 372.79 km² (Figure 6). The comparison with Google Earth in Figure 6 shows that most of the barriers are located in areas where natural and artificial ecosystems intermingled, where the larger areas are under urban construction (No. 1, No. 2, and No. 3), a few barriers are at the edges of mountain ranges (No. 4), and relatively small barriers are located in rural land (No. 5), where the ecological corridors are short and narrow. The resistance values rise due to topography or human factors, which may directly cut off the ecological corridors and block information transfer in the ecosystem. Therefore, these areas are key areas for future EN construction improvement.

Discussion

Reflections on the process of identifying ecological sources

Ecological sources are the basis for building an EN, and some studies directly consider natural landscapes as ecological sources. Yu considers large shrublands and water bodies as ecological sources in western central Inner Mongolia (Yu et al. 2017), and this approach may still be useful for desert oasis landscapes with few people, but for areas with high levels of urbanization and severe human interference such as the SYRB, ecological sources cannot be identified simply by considering unilateral ecological benefits. Establishing a multi-perspective source identification system by organically combining ecological structure systematics and ecological process integrity is an appropriate choice at the moment. It is important to note in particular that in relevant studies there were interconnected corridors between every two sources, but this is not always the case. When developing ecological conservation strategies, more attention should be given to the connections between regions; otherwise, many ecological patches will become isolated “islands,” and a large amount of biodiversity will be lost as a result (Berger-Tal and Saltz 2019). The spatial overlay of sources and nature reserves shows that 83.26% of the source area comprises nature reserves, and the remaining part is non-nature reserves with excellent ecological and environmental quality. In the future, relevant authorities can look for ideas from our novel multi-perspective ecological source evaluation in the planning of nature reserves.

Notably, MSPA is very sensitive to the pixel value of the data. Considering the degree of urbanization and landscape fragmentation in the SYRB, larger pixels may lack some smaller landscape patches or force the identification of landscapes such as islands; therefore, a pixel scale of 30 m x 30 m was chosen. In addition, edge width also affects MSPA results. In this study, the edge width was set to 1, the raster accuracy was 30 m, and the edge effect was 30 m. The edge effects in some studies corresponded to 60 or 90 m (Lin et al. 2021; S. Wang et al. 2021). Edge effects can lead to changes in the landscape attributes of some small patches, affecting the overall results. For example, some narrow or very small landscapes are correctly identified as core areas when the edge effect is 30 m (Figure 7), while at 60 m or 90 m, they are judged by MSPA as other landscapes, such as bridge, branch and islet, because of the influence of scale. As a result, many core landscapes are not identified, and subtle quantitative changes may cause qualitative changes in the results (Table S3). In addition, we use all land cover that is less affected by humans as the foreground of MSPA, which ignores the adaptation of different species. This is because there may be certain species whose habitats are in urbanized environments. A scholar’s discussion of modeling the taxonomy of 66 priority species in Calabria based on landscape connectivity gives us an important insight (Modica et al. 2021). In future studies, more accurate results may be obtained by modeling refinement of focal species or some specific species in the study area.

Importance of resistance thresholds for ecological corridor identification

Ecological corridors are important sites for ecological factors and processes such as habitat, reproduction, migration and dispersal of species, and some studies treat the corridor based on the MCR model as a line with no actual width (X. Guo et al. 2020; Hou et al. 2021), which not only fails to apply the research results to practical planning, but also ignores that landscape corridors are areas with edge effects, and the size of this area is closely related to the ecological functions it includes. The application of circuit theory to identify ecological corridors is a hot research topic nowadays, however, most of such research applications do not consider the effect of the change of current threshold
on the spatial range of ecological corridors (An et al. 2020; Tianlin Zhai and Huang 2022), and the simple application of default parameters is not rigorous. To this end, we discussed in detail the spatial range of ecological corridors based on the differences in landscape heterogeneity reflected by different cumulative resistance thresholds. The range of resistance thresholds we discussed is 1000–12,000 in increments of 1000, as shown in Figure 8 (due to image size, only the first 9 images are shown). During the experiment, it was found that the area of the ecological corridor increased with the resistance threshold, but the spatial layout of the ecological corridor did not change from the beginning to the end. The growth trend of ecological corridor area and the trend of decreasing cumulative current gradually decelerated beginning at a resistance threshold value of 6000, which indicates that it is more difficult to overcome external resistance and expand the ecological corridor at this time. Furthermore, if we continue to increase the threshold value, there will be increasingly high resistance values in the ecological corridor, and the landscape heterogeneity of the corridor will increase, which is not conducive to various ecological processes inside the corridor. Therefore, we used the resistance threshold 6000 to determine the spatial extent of the corridor. In addition, the maximum cumulative current value of the ecological node decreased with an increasing threshold, which can be well explained by knowledge of electrical circuits: as the width of the corridor increases, the number of branches in the circuit increases, leading to a shunt in the current, i.e., a decrease in the current. Notably, the locations of the ecological nodes did not change significantly as the cumulative current values decreased, proving that there are some critical areas in the landscape with fixed locations, and it is important to guarantee the integrity of these areas for the ecological security of the natural ecosystem.

**Differences between ecological networks and other ecological policies**

Ecological civilization has become China’s long-term strategy for building a sustainable, harmonious and eco-friendly society (Mu et al. 2022). A good ecological strategy should support social development while considering ecological conservation (Spencer 2021). The most commonly applied ecological protection strategies are the “ecological control line” (Chen et al. 2021), “green infrastructure” (Washbourne 2022) and “ecological security pattern” (Guo et al. 2022a) strategies, among others. Essentially, EN and these concepts are spatial regulation schemes to mitigate the negative impacts of urbanization on ecosystems. The difference is that the EN approach reduces important ecological spaces to flat point and line...
structures that can be better positioned and optimized. Thus, the EN approach is also considered a spatial implementation of the concept of “planetary boundaries” (Steffen et al. 2015). Its advantage is that it can identify critical ecological elements and vulnerable areas by measuring the importance of landscape patches for ecological processes and functions and determine the paths connecting critical areas according to the continuity between landscapes (X. Huang et al. 2021; Wu et al. 2021). These areas are also the minimum ecological needs for meeting socio-economic development. As our research reveals, the construction of EN not only assesses large-scale habitat quality and enhances landscape connectivity, but also identifies priority areas for regional conservation and restoration. Promoting the construction of EN supports mitigation and adaptation strategies for combating future various ecological risks while mitigating ecosystem disturbances from intense human activities.

**Implications and the limitations of the study**

In a few developed countries with high levels of urbanization, abundant natural resources and low population density, spatial conservation focuses primarily on...
the uniqueness and fragility of natural ecosystems. However, in most developing countries, such as China, natural habitats are under tremendous pressure from the unbridled expansion of artificial surfaces in the process of rapid urbanization, and the landscape pattern is gradually fragmented, affecting the connectivity between patches, which in turn directly affects ecosystem energy flow and material circulation. Therefore, connecting fragile ecological patches and constructing an ecological corridor network that can effectively improve the quality of biological living environments and ecosystems is of great significance for maintaining regional ecological security and promoting sustainable development.

Ecological corridors are the theoretical basis for maintaining the originality of ecosystems and protecting species diversity. This paper applies circuit theory to briefly discuss corridor ranges, and other studies have simulated corridor ranges by applying ant colony algorithms (Peng et al. 2019). Overall, ecological corridor widths are less studied, and the methods are worth discussing. The habitat suitability of species and their migration and dispersal abilities are to some extent influenced by the width of ecological corridors. Should corridors of different scales be constructed for species with different migration and dispersal abilities to reflect regional habitat characteristics and landscape differences? How can the optimal corridor width be determined for different species? In addition, the spatial distribution of ecological nodes and barrier areas is a key node affecting the connectivity of EN. Current studies focus on determining ecological corridor trajectories and node locations, ignoring the spatial volumes of both and failing to integrate them with the required widths for species migration, which is not conducive to determining the specific extent of ecological restoration areas. All these scientific issues deserve more in-depth research.

Conclusions
Currently, the framework of EN based on circuit theory has become mature, yet many studies have overlooked what certain key nodes in EN mean in reality, and appropriate optimization of networks is equally critical for enhancing ecological information flow and exchange. It is worthwhile to ponder beyond discussing the refinement of research methods to bring about variability in research results, such as the setting of scales and thresholds. How to better take into account the habitat suitability of key protected species and specific species in the region affected by anthropogenic and natural landscapes is also a major part of future research.

This paper constructs and optimizes the EN in the lower Yellow River. Firstly, ecological sources were identified based on MSPA, habitat quality and landscape connectivity. Secondly, the ecological resistance surface was constructed by integrating five natural factors and modified by simulating human factors with night-light data. Thirdly, based on the circuit theory, the landscape was modeled as a “conductive surface,” where “currents” simulated the ecological processes in heterogeneous landscapes, and the range of ecological corridors and the key nodes in them were identified. Finally, the ecological sources were optimized using similarity search, while the spatial distribution of the corridors was changed; and the network structure before and after optimization was evaluated using graph theory. The main results are as follows.

(1) The optimized EN has more ecological sources and multiple ecological circulation channels than before the optimization, while the structure is more stable. The optimized EN contains 23 ecological sources with a total area of 5464.8 km², dominated by woodlands and water bodies, mainly concentrated in the central part of the study area; 30 ecological corridor clusters with a total area of 2205.92 km², dominated by woodlands, grasslands and arable land with a spatially reticulated and radial arrangement; 28 ecological node areas with a total area of 78.44 km², spatially compressed due to the interference of human activities in a narrow range; and 75 major barrier areas, with a total area of 372.79 km², mostly distributed in natural and artificial mixed ecosystems, hindering the transmission of ecological flows, which may cut off ecological corridors at any time.

(2) Implications for ecological conservation include optimizing EN as an important strategy to enhance landscape connectivity and habitat continuity. A stable EN is conducive to the ecological processes of species habitat, migration, dispersal and reproduction, thus achieving the purpose of securing regional ecological security with a small amount of ecological land. The assessment method of ecological sources in this study can provide ideas for future planning of nature reserves. Ecological corridors are the link between ecological sources, and in reality, it is easy to neglect the information exchange between adjacent sources; the construction or planning of ecological corridors is crucial for biodiversity conservation. Ecological nodes and barrier areas should be the focus of attention in future ecological conservation and restoration efforts. Policy makers may be able to explore the balance between economic and social development and ecological protection in the construction of EN.
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Author contributions

J.K.: Conceptualization, Methodology, Investigation, Validation, Visualization, Writing – original draft. T.Z., M.L.: Data curation. C.L., B.Z.: Conceptualization, Funding acquisition, Project administration, Supervision.

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