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Evaluation of regional ecological security pattern in the Beiqinfang Urban Agglomeration based on an integrated ecological network

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Abstract

Ecological security patterns are essential for maintaining ecosystem biodiversity, and ecological network construction has become an important approach to evaluate and optimize regional ecological security patterns, thereby informing conservation strategies under rapid urbanization. However, ecological security pattern research in the Beihai–Qinzhou–Fangchenggang urban agglomeration, Guangxi province, China, remains limited. This study assessed habitat quality using the InVEST model and integrated MSPA, landscape connectivity analysis, and existing protected-area inventories to identify ecological sources. The MCR-gravity model and circuit theory were then integrated to assess the importance of ecological corridors, while hydrological analysis was used to identify potential ecological radiation pathways to optimize the network. The results identified 22 ecological sources and 231 potential corridors, including 32 Level I and 87 Level II corridors, supplemented by 21 hydrological radiation pathways. This study proposes an optimized ecological security pattern comprising "*Two Barriers–Three Zones–Four Corridors–Three Cores–Multiple Nodes*". These findings support prioritizing core ecological sources, controlling land-use changes along key corridors, and restoring ecological breakpoints to enhance regional connectivity. This integrated framework provides a scientific basis for territorial ecological restoration and conservation planning in the Beiqinfang Urban Agglomeration.

Keywords: green infrastructure; ecological network; landscape connectivity; biodiversity

1. Introduction

Ecological security patterns have attracted considerable attention across ecology, geography, landscape science, and urban planning. They are essential for maintaining ecosystem health and integrity while protecting human production and livelihoods from ecological degradation and environmental pollution (Dabelko et al., 1995; Liu et al., 2015), thereby supporting a green, healthy, and sustainable environment (Fu, 2010). Nowadays, ecological network has become an primarily approach to evaluate and optimize ecological security patterns. Ecological networks consist primarily of ecological patches, corridors, and nodes [1]. By connecting fragmented habitats and key ecological nodes, ecological corridors enhance landscape connectivity[2,3], facilitate species movement and gene flow [4–6], and contribute to regional ecological security, biodiversity conservation, and ecosystem services [7,8].

In existing studies, ecological network construction generally involves three key steps: ecological source identification, ecological corridor construction, and the identification of important corridors. As the primary ecological carriers within a network, ecological sources provide essential habitats and serve as core areas for maintaining ecological processes and landscape connectivity[9]. Their identification is therefore fundamental to the construction of an effective ecological network. Common approaches include direct selection, comprehensive evaluation, and Morphological Spatial Pattern Analysis (MSPA).

The direct selection method identifies ecological sources based on existing conservation areas, species habitats, and ecological protection planning [10,11], or urban green space and land-use patterns [12–14]. Although straightforward and highly applicable, this approach is relatively subjective and may not fully capture spatial heterogeneity in habitat quality and ecological connectivity. Comprehensive evaluation methods integrate multiple indicators, such as ecosystem services, habitat suitability, vegetation characteristics, hydrological conditions, and anthropogenic disturbance, to assess the ecological suitability of landscape units [15–18]. These methods provide a more comprehensive assessment of ecological value, but their effectiveness depends heavily on indicator selection, weighting schemes, and the availability of high-quality spatial data. In contrast, MSPA applies morphological principles to land-use raster data [19] and classifies ecological landscapes into spatially distinct categories more precisely, including core areas, bridge areas, and edge areas [20–22]. By explicitly characterizing the structural pattern and connectivity of ecological patches, MSPA provides a relatively objective and spatially explicit basis for identifying ecologically important source areas and potential connectivity structures.

Ecological corridor construction and the identification of important corridors commonly employ the Minimum Cumulative Resistance (MCR) model–gravity model framework, graph theory, circuit theory, or multi-criteria evaluation. The MCR model simulates ecological movement [23,24] by calculating the minimum cumulative resistance distance between ecological sources based on an integrated resistance surface[25], thereby identifying potential ecological corridors effectively [26]. However, it generally represents ecological movement as a relatively narrow optimal pathway and provides limited information on the spatial width and alternative routes of ecological corridors [27]. The gravity model complements the MCR model by quantifying the strength of ecological interactions between source patches [28,29], thereby facilitating the assessment and prioritization of potential corridors according to their relative importance [30]. Graph theory represents ecological sources as nodes and potential connections as edges, enabling the structural connectivity and topological characteristics of ecological networks to be quantitatively evaluated [31–33]. Circuit theory further extends this framework by simulating ecological movement as current flow across heterogeneous landscapes, allowing multiple dispersal pathways and areas of concentrated ecological flow to be identified [34–37]. In addition, multi-criteria evaluation methods integrate ecological importance, landscape characteristics, and anthropogenic disturbance to assess the relative importance and conservation priority of ecological corridors [38,39]. Overall, these approaches provide complementary perspectives on habitat quality, structural connectivity, ecological flows, and corridor importance, and their integrated application can improve the comprehensiveness and spatial reliability of regional ecological network construction.

With the rapid advancement of urbanization in China, population growth and land-use transformation have exerted significant impacts on ecosystem health, biodiversity, and regional ecological security [40–45]. In recent years, China has continuously promoted ecological civilization development and the delineation of ecological conservation redlines, emphasizing the establishment of ecological corridors and ecological networks to facilitate ecosystem conservation and restoration. The Beihai–Qinzhou–Fangchenggang Urban Agglomeration (hereafter referred to as the Beiqinfang Urban Agglomeration) is characterized by abundant forest resources and high ecological significance and located at an important free trade node between China and Association of Southeast Asian Nations. However, accelerating regional integration and urbanization have intensified conflicts between ecological conservation and economic development, highlighting the need to strengthen regional ecological security and promote sustainable urban development.

Given the spatial conflicts between ecological conservation and economic development in the Beiqinfang Urban Agglomeration, this study aims to: (1) assess regional ecological environmental quality under the influence of economic development and expanding human activities; (2) construct a potential regional ecological network by integrating established ecological network models; and (3) optimize the network structure and identify key ecological corridors and nodes, thereby constructing an ecological security pattern and providing a scientific basis for biodiversity conservation.

2. Materials and Methods

2.1. Study Area

The Beiqinfang Urban Agglomeration, located in southern Guangxi Zhuang Autonomous Region, China, borders the Beibu Gulf and comprises three cities: Beihai, Qinzhou, and Fangchenggang. In the early stages of development, the three cities exhibited similar functional orientations and spatial layouts, resulting in some degree of overlapping development and competition. To promote regional coordination, the Guangxi Zhuang Autonomous Region subsequently implemented a series of policies for the development of the Guangxi Beibu Gulf Economic Zone, providing an institutional foundation for the coordinated development of the three cities.

The Beiqinfang Urban Agglomeration is characterized by diverse natural conditions and abundant ecological resources. The region is surrounded by mountains and hills to the east, west, and north. The northwest is dominated by the Shiwandashan Mountains, while the central area consists mainly of low hills, terraces, alluvial basins, and river-valley plains with relatively gentle terrain; the remaining areas are characterized by moderate hills and low mountains. Located within the Southeast Asian monsoon zone, the region has a typical subtropical maritime monsoon climate, characterized by mild winters, hot summers, abundant sunshine, and high precipitation. The mean annual temperature ranges from approximately 22 to 23.4°C, while annual precipitation ranges from 1250 to 2755 mm. The continuous mountain and hill systems, together with rivers such as the Fangcheng and Beilun Rivers that flow into the Beibu Gulf, provide favorable conditions for maintaining high biodiversity and ecological connectivity.

Meanwhile, the Beiqinfang Urban Agglomeration has experienced rapid socioeconomic development. From 2000 to 2020, its GDP increased by more than 11-fold, accompanied by a declining share of the primary sector and increasing contributions from the secondary and tertiary sectors, indicating rapid industrialization and urbanization. Population distribution is characterized by concentrated development along major rivers and coastal areas, particularly in the southeastern coastal zone of the Beibu Gulf and along the Qin River. With continued urban development, new population growth centers have emerged in relatively flat areas and tourism-oriented zones, accompanied by an increasing number of small, high-density population clusters.

However, rapid urbanization driven by regional development policies has intensified the fragmentation of ecological spaces. Therefore, balancing social and economic development with ecological conservation is essential for maintaining regional ecological integrity. Accordingly, this study focuses on the terrestrial ecological space of the Beiqinfang Urban Agglomeration, excluding marine and island areas, with a total study area of approximately 20400 km² (see Figure 1).

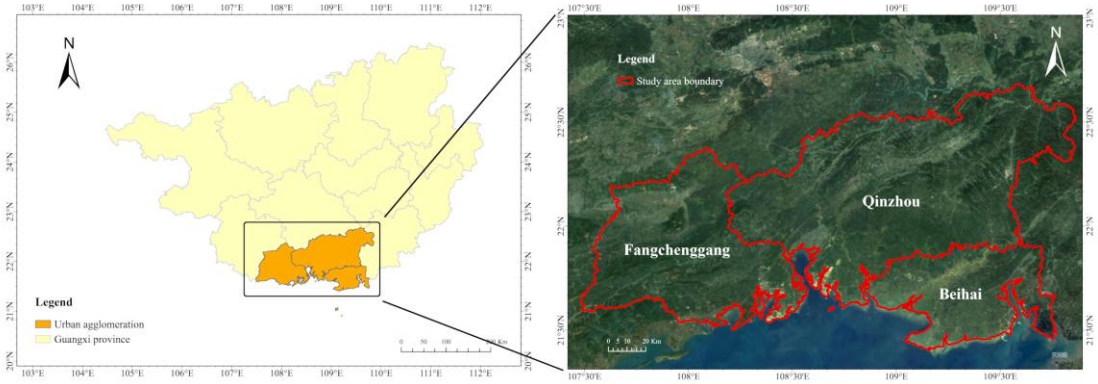


Figure 1. Overview of study area.

2.2. Data Sources

The datasets used in this study can be categorized into four main groups:

(1) Land use/land cover (LULC) data for Beihai City, Qinzhou City, and Fangchenggang City in 2020 were obtained from the Resource and Environmental Science and Data Center (RESDC) of the Chinese Academy of Sciences (http://www.resdc.cn). Following the national land-use classification standard and considering the objectives of this study, the LULC data were aggregated into six primary categories: cropland, forestland, grassland, water bodies, built-up land, and unused land (see Figure 2). Digital elevation model (DEM) data of study area were obtained from Geospatial Data Cloud (https://www.gscloud.cn/).

(2) Road vector network data were primarily obtained from OpenStreetMap (https://www.openstreetmap.net.cn/). Four types of transportation networks, namely railways, expressways, national and provincial roads, were extracted to characterize anthropogenic disturbance and support the construction of the ecological resistance surface.

(3) Data on national and autonomous-region-level nature reserves and forest parks, together with relevant planning and policy documents, were collected from the official websites of the governments and relevant administrative departments of Guangxi province and Beihai City, Qinzhou City, and Fangchenggang City. Major references included the "National Ecotourism Development Plan (2016–2025)", the "Integrated Development Plan for Beiqinfang Urban Agglomeration in the Guangxi Beibu Gulf Economic Zone (2019–2025)", and the "List of Nature Reserves in Guangxi province (November 2020)".

(4) Regional population and socioeconomic data were obtained comprehensively from the "2020 China Statistical Yearbook", national censuses, and the WorldPop high-resolution global population dataset (www.worldpop.org).

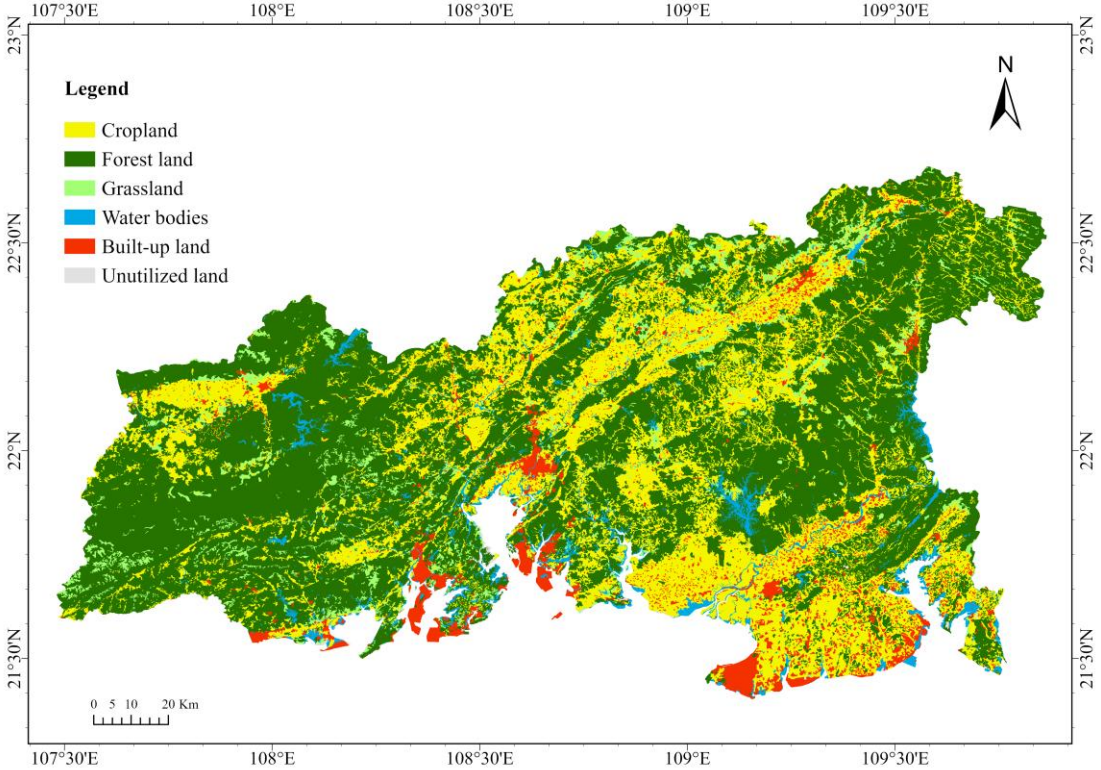


Figure 2. Spatial distribution of land-use/land cover of study area.

3. Methodology

3.1. Research framework

This study aims to optimize the regional ecological network based on the identification of ecological sources, construction of comprehensive ecological resistance surface and potential ecological corridors (Figure 3). The technical workflow consists of three main stages: (1) Identification of ecological

source. Habitat quality was assessed using the InVEST model based on land use/land cover data, and key ecological sources were identified by integrating MSPA analysis, biodiversity conservation areas, and landscape connectivity assessments; (2) Construction of resistance surface. A comprehensive ecological resistance surface was constructed in ArcGIS 10.5 by integrating land use/land cover data, landscape pattern, DEM, and human activity data, including railway and road networks. (3) Construction and optimization of ecological network. Potential ecological corridors were extracted using the Minimum Cumulative Resistance (MCR) model. The gravity model was further applied to quantify the interaction strength between ecological sources and prioritize important ecological corridors, while circuit theory and hydrological analysis were incorporated to identify and optimize the ecological corridors. Ecological nodes and barrier points were then identified to establish a more comprehensive regional ecological network, providing a scientific basis for territorial ecological restoration, ecological conservation, and related spatial planning in the Beiqinfang Urban Agglomeration.

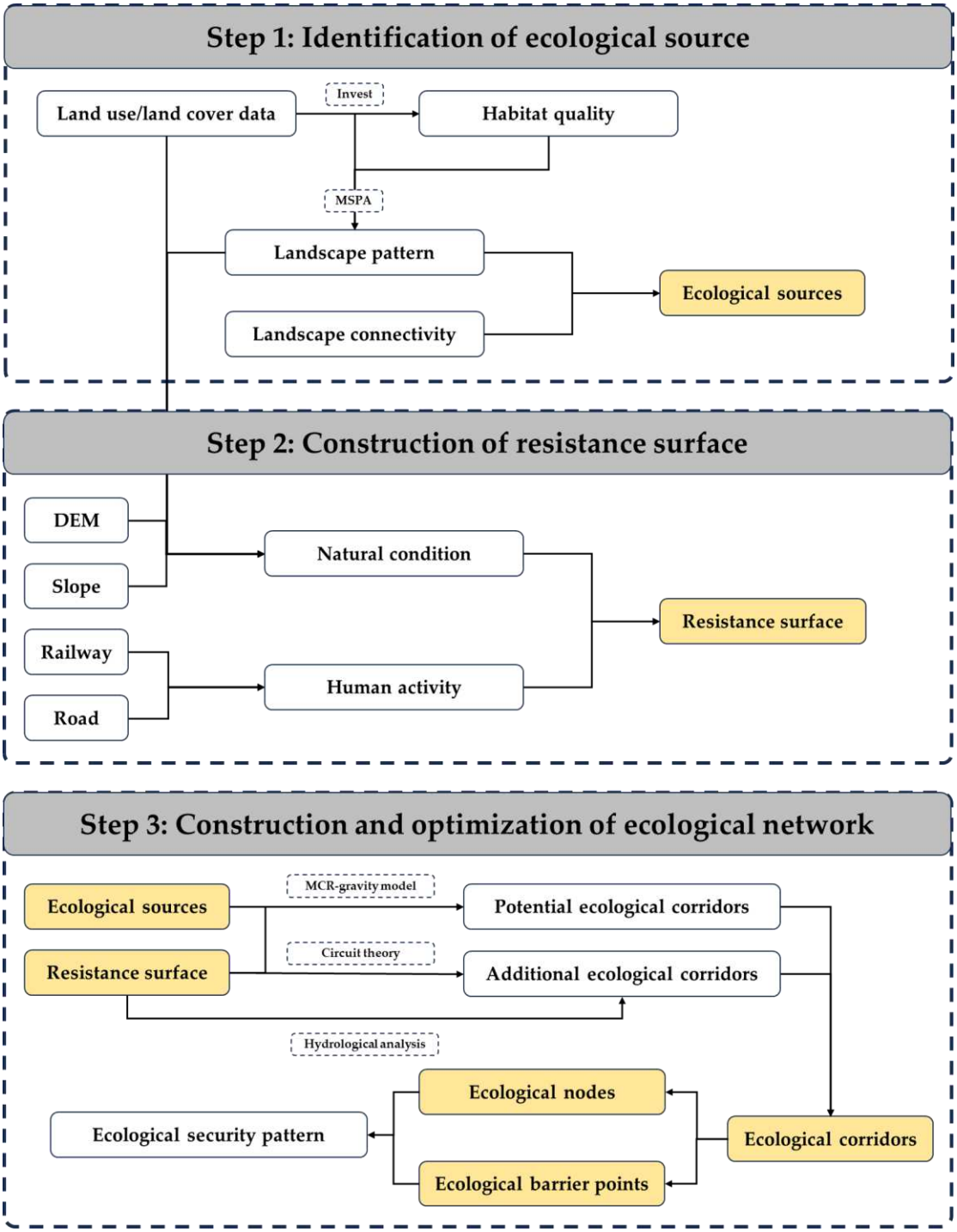


Figure 3. Research framework for ecological network construction and optimization.

3.2. Construction of the ecological network

3.2.1. InVEST model for ecological evaluation

Areas with high habitat quality generally provide more favorable conditions for species survival and reproduction, thereby supporting higher biodiversity. To quantify habitat quality in the Beiqinfang Urban Agglomeration, the Habitat Quality module of the InVEST model, which is widely used for habitat quality assessment , was employed.

The model quantifies habitat quality by considering the effects of threat sources on different land cover types. In this study, land cover types dominated by intensive human activities, including cropland,

urban areas, rural settlements, other built-up land, and unutilized land, were identified as threat sources, while the remaining land cover types were regarded as ecological sources. Habitat quality was assessed based on the sensitivity of different land cover types to threat sources and the spatial effects of these threat sources. The assessment primarily considers three factors: the distance to threat sources, the relative influence weights of threat sources, and the sensitivity of different land cover types. The Habitat Quality Index was calculated using Equation 1:

$$Q_{xj} = H_j \times \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z}\right) \quad (1)$$

where Q_{xj} represents the habitat quality of pixel x within land cover type j; H_j denotes the habitat suitability of land cover type j; z is a default model parameter, which is set to 2.5; k is the semi-saturation constant, which is typically set to half the maximum value of the D_{xj}; D_{xj} represents the habitat threat intensity of pixel x within land cover type j, which is obtained using Equation 2:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{W_r}{\sum_{r=1}^{R} W_r}\right) r_y i_{rxy} \beta_x S_{jr} \quad (2)$$

where R represents the number of threat sources; Y_r represents the total number of pixels in threat sources r; W_r represents the weight of the threat source r, with values ranging from 0 to 1, indicating the relative destructive impact of the threat sources on the habitats; r_y denotes the effect of the threat pixel y in threat sources r; β_x represents the accessibility level of pixel x, and S_{jr} represents the sensitivity of the land cover type j to threat sources r; i_{rxy} represents the effect of threat pixel y on pixel x, calculated by distance using Equation 3:

$$i_{rxy} = \begin{cases} 1 - \left(\frac{d_{xy}}{d_{r\,max}}\right) & \text{if linear} \\ \exp\left(-\left(\frac{2.99}{d_{r\,max}}\right) d_{xy}\right) & \text{if exponential} \end{cases} \quad (3)$$

where d_{xy} represents the Euclidean distance between pixel x and pixel y; $d_{r\,max}$ represents the maximum influence distance of the threat sources r.

Following the InVEST user manual and previous studies [46–52], the Chinese Academy of Sciences' secondary-level Land Use and Cover Classification (LUCC) dataset was used as the base data. Cropland, urban areas, rural settlements, other built-up land, and unutilized land, which are associated with intensive human activities and substantial habitat disturbance, were selected as threat sources (Table 1). Habitat suitability values for the remaining land cover types were assigned on a scale of 0–1, with higher values indicating greater sensitivity of the corresponding habitat to anthropogenic threats (Table 2).

Table 1. The influence weights and maximum influence distance of threat sources.

Threat sources	Weight (W_r)	Maximum distance ($d_{r\,max}$)	Decay
Cropland	0.5	3 km	Linear
Urban areas	1	10 km	Exponential
Rural settlements	0.6	5 km	Exponential
Other built-up land	0.7	4 km	Exponential
Unutilized land	0.5	1 km	Linear

Table 2. The sensitivity of different land cover types to threat sources.

Land cover type	Sensitivity to stress sources (S_{jr})

	Habitat Suitability (H_j)	Cropland	Urban areas	Rural set-tlements	Other built-up land	Unutilized land
Paddy field	0.4	0.3	0.7	0.6	0.5	0.3
Dry land	0.6	0.3	0.6	0.6	0.5	0.3
Forest land	0.8	0.5	0.7	0.6	0.5	0.5
Shrub land	0.9	0.6	0.8	0.7	0.5	0.5
Sparsely forest land	0.9	0.7	0.8	0.7	0.6	0.6
Other forest land	0.9	0.6	0.8	0.7	0.6	0.6
Grassland with high cover	0.9	0.7	0.8	0.7	0.6	0.6
Grassland with medium cover	0.8	0.6	0.8	0.7	0.6	0.6
River and canal	0.8	0.4	0.7	0.6	0.5	0.5
Lake and pond	0.9	0.4	0.7	0.6	0.5	0.4
Reservoirs	0.7	0.4	0.6	0.5	0.5	0.4
Tidal flats	0.8	0.6	0.8	0.7	0.5	0.5
Floodplains	0.7	0.5	0.7	0.6	0.5	0.5

3.2.2. MSPA for landscape pattern identification

Morphological Spatial Pattern Analysis (MSPA) is a raster-based image processing approach developed by Vogt et al. based on mathematical morphology to identify and quantify spatial patterns and structural connectivity in landscapes [19]. By analyzing the spatial structure and topological relationships of ecological patches, MSPA classifies landscape patterns into seven types: Core, Bridge, Islet, Perforation, Edge, Loop, and Branch [21,22,53]. Their ecological significance and statistical characteristics are presented in Table 3. This approach is particularly useful for identifying structurally important habitat patches and potential ecological connectivity within ecological networks.

Table 3. The ecological significance and statistics of MSPA landscape types.

Landscape types	Ecological significance
Core	It serves as the "source" of various ecological processes and plays a crucial role in species reproduction and biodiversity conservation, which consist primarily of forest parks and large-scale planted forests.
Bridge	It is a narrow strip of land connecting patches in different core areas. These are mostly green belts that facilitate the migration of local species and enhance landscape connectivity.
Loop	It is the internal pathway for the exchange of matter and energy within the same core area, and serve as shortcuts for such exchanges.
Branch	It primarily serves as an extension of green space and acts as a corridor for species dispersal and the exchange of energy with the surrounding landscape.
Edge	It serves as a transitional zone between the core area and the surrounding non-green landscape areas, helping to reduce the impact of the external environment and human disturbance. It typically consists of the outer forest belts surrounding forest parks and large-scale forest plantations.
Perforation	It serve as transition zones between the core area and the non-green space within int.

Islet	They usually are small, isolated patches with low connectivity and little potential for the exchange of matter and energy with other patches, which are primarily small green spaces in urban or rural areas.

In this study, MSPA was conducted using Guidos Toolbox 2.8 and ArcGIS 10.5. First, three land cover types—forest, grassland, and water bodies—were extracted from the LUCC dataset of the Beiqinfang Urban Agglomeration using the reclassification function in ArcGIS 10.5 and defined as the "foreground" due to their relatively low levels of human disturbance and important habitat functions. All other land cover types were defined as the "background". The resulting data were converted into a binary raster with a spatial resolution of 30 m × 30 m. The binary raster was then imported into Guidos Toolbox 2.8 using an 8-neighbour connectivity analysis and an edge width of 1 pixel.

3.2.3. Landscape connectivity significance evaluation

Ecological sources are key landscape components that provide essential ecological services and support ecosystem functioning. Landscape connectivity reflects the extent to which ecological patches facilitate or hinder material exchange, species movement, and ecological processes [54,55]. High landscape connectivity facilitates wildlife migration and material flows among ecological components, thereby enhancing biodiversity and contributing to the stability and sustainability of regional ecosystems[56–58]. Therefore, maintaining and improving the connectivity of ecological sources is essential for sustaining regional ecological processes and biodiversity.

To characterize the ease of energy and species movement among ecological patches, this study employed the **I**ntegral **I**ndex of **C**onnectivity (IIC) and the **P**robability of **C**onnectivity (PC) to assess overall landscape connectivity, and the **d**elta **P**robability of **C**onnectivity (dPC) to quantify the contribution of individual patches to ecological network connectivity [59–63]. IIC and PC range from 0 to 1, with higher values indicating greater overall and potential connectivity among ecological patches, which implies stronger landscape connectivity within the study area. Similarly, a higher dPC value indicates that the patch has greater ecological significance within the ecological network. They are calculated using Equation 4:

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

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^*}{A_L^2} \quad (4)$$

$$dPC_k = \frac{PC - PC_{remove,k}}{PC} \times 100\%$$

where n represents the number of patches in the study area; a_i and a_j represent the areas of patches i and j, respectively. nl_{ij} represents the connections between patches, and A_L is the total area of the habitat patches. p_{ij}^* denotes the probability of dispersal or migration of a species or other ecological process between patch i and j. $PC_{remove,k}$ represents the value of probability connectivity after removing patch k from the landscape.

In this study, Conefor 2.6 was used to evaluate landscape connectivity. Based on sensitivity tests, a distance threshold of 2500 m was selected, beyond which changes in patch fragmentation were negligible, while the connectivity probability was set to 0.5. Accordingly, the PC, IIC, and dPC values of core patches were calculated. Based on the characteristics of the study area and dPC values, ecological sources were classified into three levels: Class I (dPC > 10), Class II (1 ≤ dPC ≤ 10), and Class III (0.1 ≤ dPC < 1).

3.2.4. MCR model for resistance surface construction

The establishment of ecological corridors helps facilitate species movement and energy flow between habitat patches, making it a crucial step in ecological network construction. Species movement

and energy exchange between patches are constrained by environmental resistance associated with factors such as slope, elevation, and land-use type. Higher resistance values indicate greater environmental constraints and lower habitat suitability, whereas lower values represent more favorable conditions for species movement and ecological corridor development. To identify potential dispersal pathways and quantify movement resistance, the Minimum Cumulative Resistance (MCR) model has been widely applied in ecological studies. Based on the assumption that habitat loss and increasing distances between habitat patches may increase risks of population decline and extinction, the MCR model estimates the cumulative cost of species movement from ecological sources to target areas [64–67]. It identifies the least-cost path between ecological sources and target areas, thereby representing the minimum resistance that ecological flows must overcome during movement between source areas.

Compared with previous studies [68,69], this study jointly considers natural environmental conditions and human activities in the Beiqinfang Urban Agglomeration. In addition to four commonly used resistance layers, namely slope, elevation, MSPA landscape pattern, and land cover type, the distances to railways, expressways, national and provincial roads were incorporated to characterize transportation-related anthropogenic disturbances. Based on expert knowledge and previous studies, resistance values and weights were assigned to the selected factors according to the characteristics of the study area (Table 4). The resistance layers were then integrated using the Raster Calculator in ArcGIS 10.5 according to Equation 5 to generate the comprehensive ecological resistance surface. The comprehensive ecological resistance surface was calculated as follows:

$$V_{CR} = \sum R_{ij} \times W_j \quad (5)$$

where V_{CR} is the comprehensive ecological resistance surface; R_{ij} is the resistance values of the jth resistance factors within the ith pixel; W_j is the weight of the jth resistance factors.

Table 4. The resistance values and weights of different resistance surfaces in study area.

Resistance surfaces	Weights	Resistance factors and their values
MSPA landscape pattern	0.3	Core (5), Bridge (10), Loop (20), Branch (30), Islet (50), Edge (60), Perforation (70), Background (100)
Land cover type	0.25	Forest land (10), Grassland (20), Cropland (30), Bare land (50), Water bodies (70), Built-up land (100)
Elevation (h) /m	0.17	h ≤ 300 (10), 300 < h ≤ 600 (30), 600 < h ≤ 900 (50), 900 < h ≤ 1200 (70), h > 1200 (90)
Slope (s) / °	0.13	s ≤ 8 (10), 8 < s ≤ 15 (30), 15 < s ≤ 25 (50), 25 < s ≤ 35 (70), s > 35 (90)
The distances to railways (d1) / km	0.06	d1 ≤ 1 (100), 1 < d1 ≤ 2 (80), 2 < d1 ≤ 3 (60), 3 < d1 ≤ 5 (20), d > 5 (10)
The distances to expressways (d2) /km	0.05	d2 ≤ 0.5 (100), 0.5 < d2 ≤ 1 (80), 1 < d2 ≤ 1.5 (60), 1.5 < d2 ≤ 3 (20), d2 > 3 (10)
The distances to national and provincial roads (d3) / km	0.04	d3 ≤ 0.5 (100), 0.5 < d3 ≤ 1 (80), 1 < d3 ≤ 1.5 (60), 1.5 < d3 ≤ 3 (20), d3 > 3 (10)

Based on the vector data of ecological sources and the ecological resistance surface raster images, the MCR model was applied to estimate the minimum cumulative resistance to species movement and identify least-cost paths as potential ecological corridors, thereby constructing the ecological network of the Beiqinfang Urban Agglomeration. The MCR model is expressed as Equation 6:

$$MCR = f_{min} \sum_{j=n}^{i=m} D_{ij} \times R_i \quad (6)$$

where MCR denotes the minimum cumulative resistance value from ecological source j to a given landscape unit i; D_{ij} represents the spatial distance from ecological source j to a given landscape unit i; R_i denotes the mean resistance value of source i; f_{min} represents the positive relationship between minimum cumulative resistance and ecological processes.

3.2.5. Gravity model for identifying the importance of corridors

The gravity model, originally developed to describe interactions between cities and countries, has been widely applied to transportation and trade analysis and subsequently introduced into ecological network research [70]. In this study, the gravity model was used to quantify the interaction strength between ecological sources and construct an interaction matrix, thereby evaluating the relative importance of potential ecological corridors. The model is expressed as Equation 7:

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{[\frac{1}{P} \times ln\, S_i][\frac{1}{P} \times ln\, S_j]}{\frac{L_{ij}}{L_{max}}^2} = \frac{L_{max}^2\, ln(S_i S_j)}{L_{ij}^2 P_i P_j} \quad (7)$$

where G_{ij} represents the interaction strength between patch i and j; N_i and N_j represent the weights of patch i and j; D_{ij}^2 represents the standardized resistance value of the potential corridor between patch i and j; S_i and S_j represent the areas of patch i and j, respectively; L_{ij} represents the cumulative resistance value of the corridor between patch i and j; and L_{max} represents the maximum cumulative resistance value of all potential corridors within the study area.

Based on the ecological characteristics of the study area and the requirements of regional ecological network construction, potential ecological corridors were classified into three levels according to their interaction strength: Level I ($G_{ij} \geq 50$), Level II ($10 \leq G_{ij} < 50$), and Level III ($G_{ij} < 10$).

3.2.6. Circuit theory and Hydrological analysis for network optimization

In addition to the MCR–gravity model, circuit theory has also been widely applied to ecological network construction. By assigning ecological meanings to electrical concepts such as resistance, current, and voltage, circuit theory simulates the random movement of species across heterogeneous landscapes. This theory was initially introduced into the field of ecological connectivity research by McRae et al. [34] and has since been used to identify potential ecological corridors and key ecological nodes.

Due to the random walk property, ecological sources can be represented as electrical 'current', while resistance surfaces can be represented as electrical 'resistance'. In this study, the Linkage Mapper toolbox (https://linkagemapper.org/) was used to calculating the 'resistance' or 'current', and thus to identify potential ecological corridors. Circuitscape software (https://circuitscape.org/) was then used to calculate corridor current density, which represents the relative probability of species movement through each raster pixel. Areas with high current density indicate concentrated movement flows and were identified as critical ecological nodes, whereas areas with low current density and high resistance were identified as potential ecological barriers requiring ecological restoration. Each ecological source was assigned a current of 1 A, the cost-weighted corridor width was set to 10000, and the "All-to-One" mode was used for iterative calculations.

Furthermore, based on hydrological analysis, low-resistance pathways radiating from ecological sources along the cumulative resistance surface can be identified as potential routes for the dispersal of biological and genetic flows. These pathways, referred to as "radiation pathways", can complement the ecological network by enhancing connections between ecological sources and surrounding habitat patches and ecological nodes.

These radiation pathways were extracted from the comprehensive ecological resistance surface using the hydrology tools in ArcGIS 10.5 to generate a flow-accumulation raster. The flow-accumulation threshold was iteratively adjusted by comparing the extracted pathways with ecological corridors identified by the MCR–gravity model and considering their spatial extension and connectivity. A threshold of 10000 was ultimately selected, and radiation pathways were extracted using the raster calculator and stream-ordering tools. First- and second-order streams were selected as hydrological radiation pathways

and incorporated as additional ecological corridors based on their potential ecological functions, thereby improving the structural integrity and connectivity of the regional ecological network.

3.2.7. Comprehensive identification of ecological nodes and barrier points

Ecological barrier points are generally defined as locations where ecological networks intersect with hard landscapes dominated by intensive human activities [71]. Urban roads and other artificial infrastructure can interfere with species movement, reduce survival rates, and consequently affect regional ecosystem functioning. Ecological nodes are typically located at intersections of ecological corridors or in areas with relatively weak ecological functions. They connect fragmented habitat patches, enhance ecological connectivity, and can provide temporary habitats for species movement, particularly along long-distance corridors [72].

In this study, intersections between ecological corridors and hydrological radiation pathways were identified as ecological nodes, while intersections between transportation routes and ecological corridors or radiation pathways were identified as ecological barrier points. Given the relatively low movement resistance and higher passage probability of Level 1 and Level 2 ecological corridors, their intersections were classified as Level 1 ecological nodes and prioritized for ecological green-space construction and conservation optimization. Intersections between Level 3 ecological corridors and hydrological radiation pathways were classified as Level 2 ecological nodes. In addition, circuit-theory-derived ecological pinch points, characterized by high current density and concentrated stochastic movement flows, were incorporated into the Level 1 ecological nodes because of their critical role in maintaining ecological connectivity.

Intersections between major transportation routes, including railways and national roads, and ecological corridors or radiation pathways were identified as Level 1 ecological barrier points. In addition, low-current-density ecological barriers identified by circuit theory were also incorporated into Level 1 ecological barrier points as a complementary category. Intersections between lower-grade national and provincial roads with ecological corridors or radiation pathways were classified as Level 2 ecological barrier points.

4. Results

4.1. Analysis of ecological habitat quality

Forestland, cropland, and built-up land are the dominant land-use types in the Beiqinfang Urban Agglomeration, accounting for 57.2%, 29.6%, and 5.4% of the total terrestrial area, respectively. The predominance of forestland, which covers more than half of the terrestrial area, indicates a relatively favorable ecological foundation.

As is shown in Figure 4, the spatial distribution of habitat quality exhibited a clear spatial gradient, with generally higher values inland and lower values along the coast. Areas with better habitat quality were mainly concentrated in the Shiwandashan in the west and the Liuwandashan in the central-east. These areas are characterized by relatively high terrain and extensive mountain and water bodies, forming an important ecological framework for the urban agglomeration. In contrast, areas with moderate or lower habitat quality were primarily distributed along the Qinjiang River plain in the central region and the coastal urban areas, which are characterized by relatively flat terrain and intensive population, port, and tourism development. Notably, with accelerating urbanization and tourism development, areas of high habitat quality have shown increasing fragmentation and invaded by other areas with moderate or lower quality. This pattern highlights the urgency to strengthen ecological conservation and connectivity in the context of continued regional development.

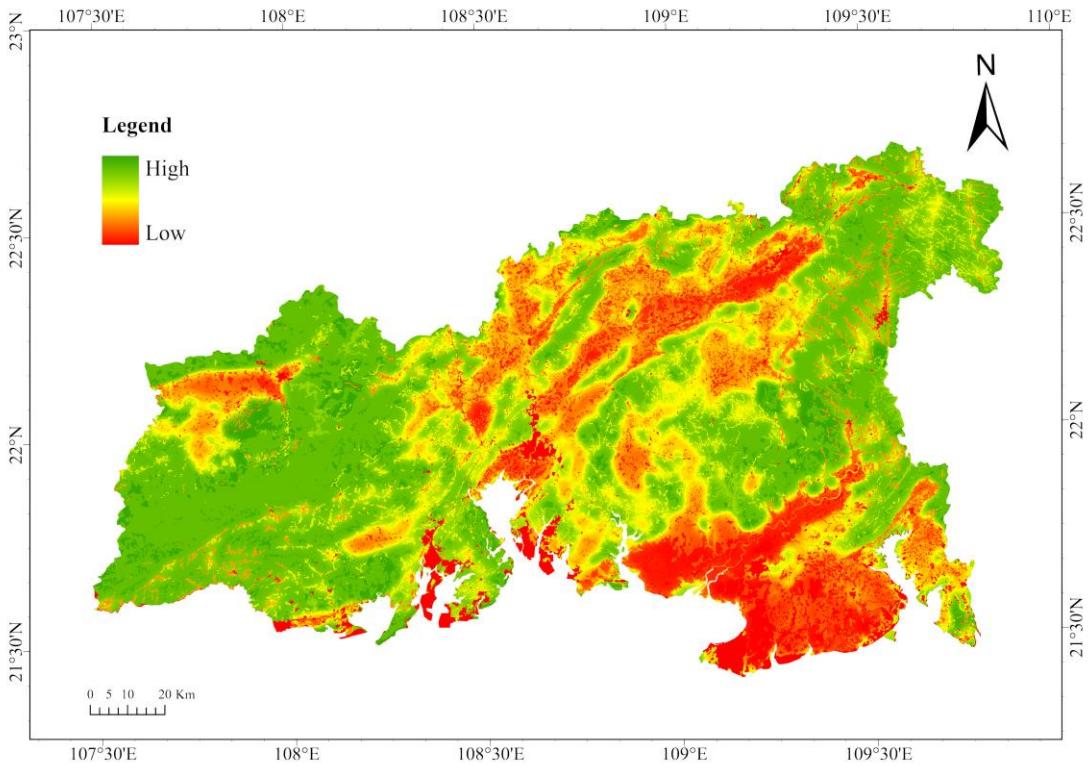


Figure 4. The spatial distribution of habitat quality within the study area.

4.2. Construction of ecological network

4.2.1. Identification of ecological sources

MSPA was conducted using forestland, grassland, and water bodies as the foreground, with the results presented in Table 5 and Figure 5 Core areas were the dominant MSPA landscape type, covering 11959.47 km² and accounting for 92.11% of the total foreground area. Forestland predominated within the core areas, covering 10602.33 km² (88.65%). These core areas were mainly distributed in the western region, including the Shiwandashan National Nature Reserve, Golden Camellia National Nature Reserve, and Beilun Estuary Nature Reserve, as well as Liuwandashan Forest Park, Linhu Forest Park, and Wuhuangshan Forest Park in the central and eastern region of Qinzhou City. Their extensive and relatively continuous distribution indicates a high degree of ecological patch integrity and connectivity, providing a stable ecological foundation for regional ecosystem functioning.

In contrast, islets areas were the smallest MSPA type, covering only 0.29 km² (<0.01% of the foreground area), of which water bodies accounted for 0.16 km² (57.44%). They were mainly distributed in Beihai City and around the Qinjiang River basin. As the only MSPA type spatially isolated from other foreground patches, the extremely small proportion of islets further indicates a strong tendency toward ecological patch aggregation and a relatively stable spatial configuration.

Edge and perforation areas ranked second and third in spatial extent, covering 643.88 and 327.91 km² and accounting for 4.96% and 2.53% of the foreground area, respectively. Their relatively large proportions indicate noticeable edge effects along ecological patch boundaries, which helps maintain stable ecological spaces and buffer core habitats against anthropogenic disturbance. The remaining bridge, branch, and loop areas covered 11.04, 38.99, and 2.67 km², respectively, representing relatively small proportions of the foreground area. Although these landscape types are important for species movement, energy exchange, and material flows among ecological patches, their limited extent suggests that ecological connections between major ecological patches remain insufficient.

Overall, the Beiqinfang Urban Agglomeration exhibits highly aggregated core patches and relatively good overall ecological connectivity, but limited key linkage structures among major core areas.

Therefore, subsequent ecological conservation and spatial optimization should prioritize strengthening ecological corridors and connectivity pathways between major core patches.

Table 5. The statistics of landscape type based on MSPA.

Landscape type	Area / km²	Percentage of the fore-ground area / %	Percentage of the landscape type / %		
			Forestland	Grassland	Water bodies
Core	11959.47	92.11	88.65	6.63	4.71
Bridge	11.04	0.09	43.41	5.57	51.01
Loop	2.67	0.02	68.24	6.30	25.46
Branch	38.99	0.30	48.48	6.53	44.99
Edge	643.88	4.96	72.12	8.69	19.19
Perforation	327.91	2.53	79.22	6.76	14.02
Islet	0.29	0.01	42.08	0.48	57.44

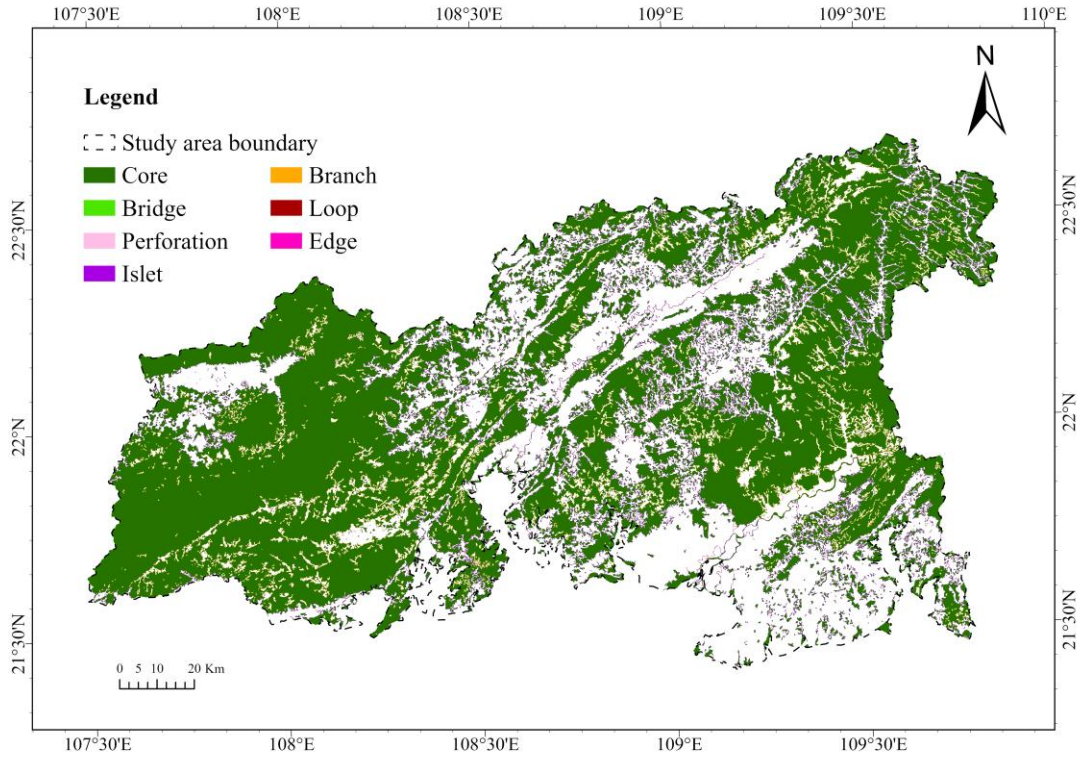


Figure 5. Landscape type classification based on MSPA.

4.2.2. Landscape connectivity analysis

Based on the MSPA results, ecological core areas were first extracted and integrated with the habitat quality assessment from the InVEST model. Areas with better habitat quality were considered highly suitable habitats. By jointly considering patch morphology, structural aggregation, and habitat suitability, approximately 6000 candidate ecological source patches were initially identified. Considering scale effects and the representativeness of ecological sources, patches larger than 1 km² were retained, yielding 97 candidate ecological sources. These patches covered approximately 85% of the ecological space in the study area and broadly overlapped with ecological protection areas delineated by different levels of territorial spatial planning.

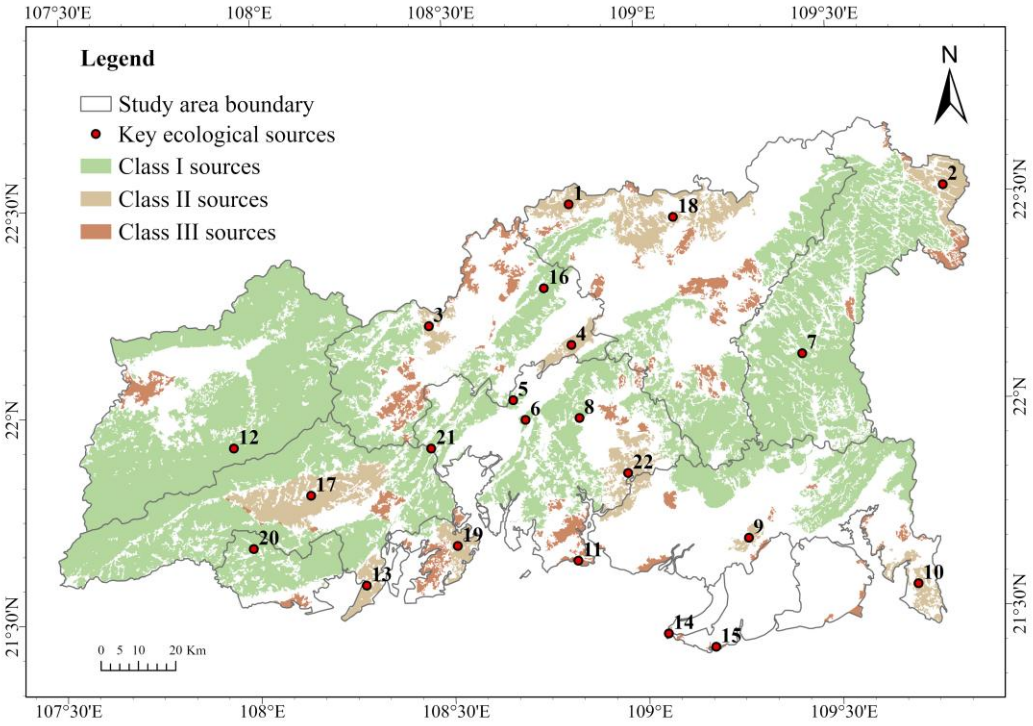
As shown in Table 6, the candidate ecological sources were further classified into three levels according to the ecological characteristics of the study area. Seven Class I ecological sources, twelve Class II ecological sources, and seventy-five Class III ecological sources were finally identified.

Class I sources were generally large and ecologically important, and frequently encompassed nature reserves, scenic areas, and forest parks. Among them, Source 12 had the highest dPC and IIC values (52.94 and 51.88, respectively) and covered 3197.91 km², encompassing the Shiwandashan National Nature Reserve, Wanggangshan Autonomous Regional Nature Reserve, Fentinghe Reservoir, and Naban Reservoir. Its high connectivity indices indicate both substantial habitat capacity and a strong contribution to regional landscape connectivity.

Class II sources were generally smaller and located near major ecological sources or along the edges of the study area. Despite their relatively lower connectivity contributions, these sources retained important ecological functions and included nature reserves, geological parks, and reservoirs. For example, Source 22 covered 154.08 km² and had dPC and IIC values of 4.82 and 2.07, respectively, encompassing Hongchaojiang Reservoir and Nawushan Autonomous Regional Geopark. Class II sources therefore provide important supplementary and connecting functions within the ecological network, helping maintain ecological continuity and structural integrity.

Class III sources were much smaller and more spatially dispersed, with limited contributions to overall landscape connectivity, but they retained localized ecological functions. These sources can therefore serve as "stepping stones" in subsequent ecological network optimization to enhance connectivity among major ecological sources.

Considering the patch size, connectivity contribution, spatial distribution, and existing conservation conditions, nineteen Class I and Class II sources were initially identified as key ecological sources. In addition, three Class III sources (Source 11, 14, and 15) with distinctive ecological significance were selected as supplementary key sources. These Class III sources provide important habitats and support energy and material exchange between terrestrial and coastal ecosystems, making them particularly valuable for establishing and strengthening regional land–sea ecological corridors. Consequently, 22 key ecological source patches were identified, with their spatial distribution and characteristics shown in Figure 6 and Table 7.



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Figure 6. Spatial distribution of key ecological sources.

Table 6. Landscape connectivity index and area of key ecological sources.

Source number	Level	IIC	dPC	Area / km²
1	Class II	1.12	1.79	97.02
2	Class II	1.61	2.23	131.23
3	Class II	1.00	1.52	57.43
4	Class II	0.71	1.16	63.49
5	Class I	20.18	33.52	18.71
6	Class I	20.08	33.37	10.32
7	Class I	42.01	44.88	2948.15
8	Class I	27.04	40.77	701.01
9	Class II	0.58	1.06	26.34
10	Class II	0.64	1.40	81.93
11	Class III	0.40	0.56	11.39
12	Class I	51.88	52.94	3197.91
13	Class II	0.75	1.18	62.99
14	Class III	0.37	0.43	3.06
15	Class III	0.37	0.48	3.35
16	Class I	9.18	13.53	305.62
17	Class II	4.70	5.95	302.59
18	Class II	3.27	5.49	266.19
19	Class II	0.90	1.45	72.97
20	Class I	14.81	18.35	901.25
21	Class I	28.35	43.60	563.50
22	Class II	2.07	4.82	154.08

4.2.3. Construction of resistance surfaces

As is shown in Figure 7, the ecological resistance surface was constructed by integrating multiple ecological and anthropogenic factors. Areas with relatively low resistance were mainly concentrated in the Shiwandashan Mountains and the Liuwandashan Mountains. These areas contain several national and regional nature reserves and are characterized by high ecological quality and relatively limited anthropogenic disturbance. Human activities are mainly related to tourism development and conservation infrastructure and are generally subject to ecological management measures. Thus, anthropogenic disturbance imposes relatively limited constraints on ecological processes in these areas, with natural factors such as elevation playing a more prominent role.

In contrast, high-resistance areas were primarily concentrated along the southern coast, particularly in Beihai City, where cropland, built-up areas, and port facilities are densely distributed. Intensive port-related activities, tourism, and service industries have resulted in substantial anthropogenic disturbance, forming ecological barriers across coastal and terrestrial areas. Relatively high resistance was also observed along the Qinjiang and Maolingjiang river basins in Qinzhou City, where resistance increased with the expansion and concentration of urban and rural settlements. These high-resistance areas may hinder the exchange of material, energy, and biological flows between ecological sources in the eastern and western parts of the urban agglomeration, thereby constraining regional ecological connectivity.

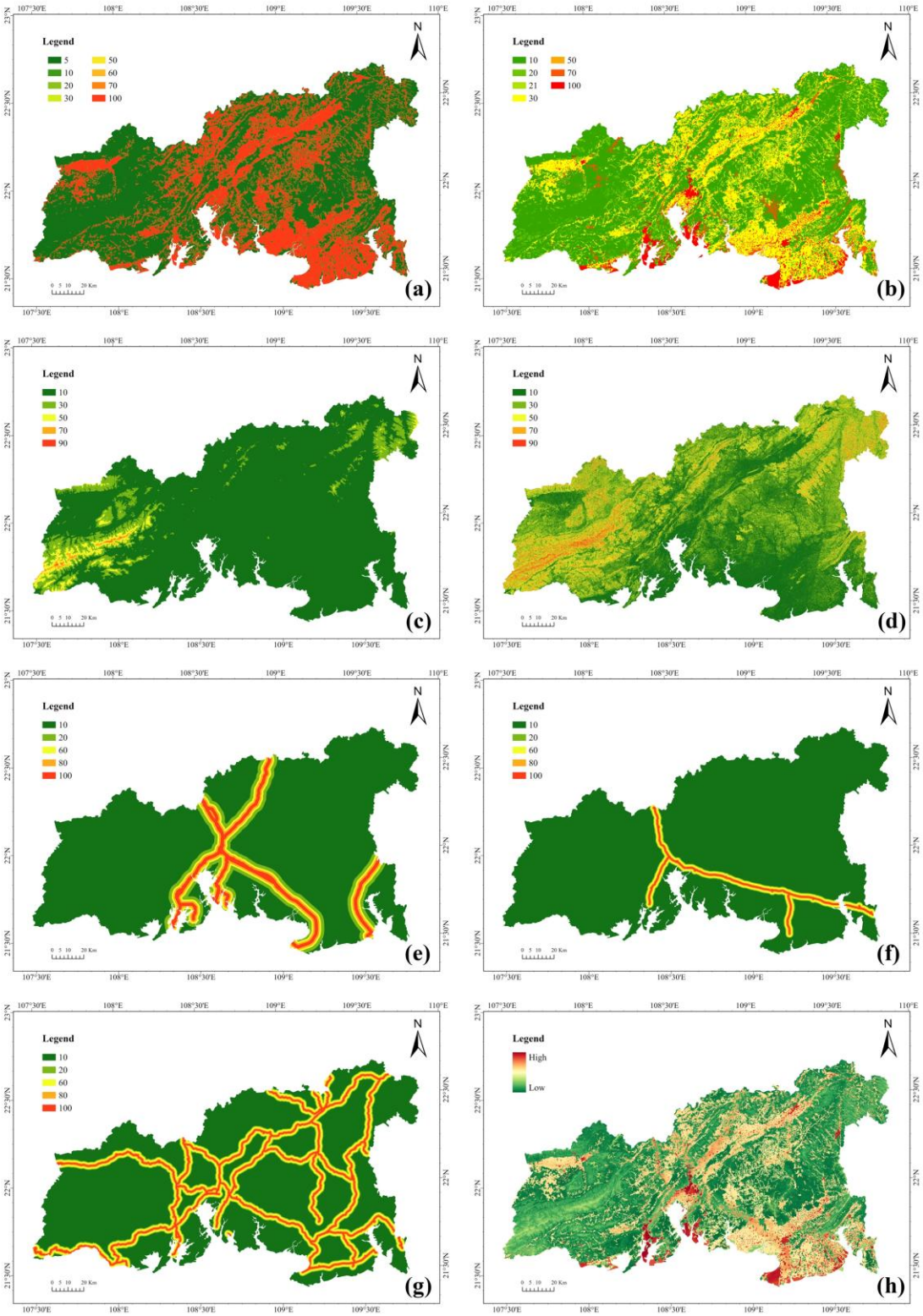


Figure 7. Construction of comprehensive resistance surface in the region. (a) MSPA landscape type; (b) land use classification; (c) elevation; (d) slope; (e) railways; (f) expressways; (g) national and provincial roads; (h) comprehensive resistance surface.

4.2.4. Construction of ecological corridors

A total of 231 potential ecological corridors were finally identified, with a total length of 9004.08 km. Forestland was the dominant type within the corridors, covering 144.41 km² and accounting for

88.83% of the total corridor area. Its predominance indicates relatively high ecological suitability and lower restoration costs for corridor construction. Cropland was the second-largest land-use type, covering 6.63 km² (4.08%), indicating that agricultural activities may constrain ecological continuity and the movement of materials, energy, and biota. These areas therefore require targeted ecological protection and restoration.

As shown in Figure 8, the potential ecological corridors exhibit pronounced spatial heterogeneity, with a higher concentration in the central region and relatively sparse distributions in the west, east, and southeast. This pattern is closely related to the spatial distribution and fragmentation of ecological sources. The western and eastern regions contain large and relatively continuous ecological sources with strong inherent connectivity, resulting in a lower dependence on additional corridors. In contrast, intensive urban expansion and rural settlement development have fragmented ecological sources in the central region into smaller and more isolated patches, creating a greater need for connectivity enhancement. Accordingly, central corridors primarily connect fragmented sources and improve local connectivity, while also linking relatively distant ecological sources in the western and eastern regions and contributing to the stability of the regional ecological network.

While in the southeast, intensive anthropogenic disturbance has resulted in fewer and more dispersed ecological sources, leading to a relatively low density of potential corridors and pronounced connectivity deficiencies. This region should therefore be prioritized in subsequent ecological network optimization through measures such as strengthening source protection, restoring critical ecological nodes, and establishing key ecological corridors to improve network integrity, connectivity, and resilience.

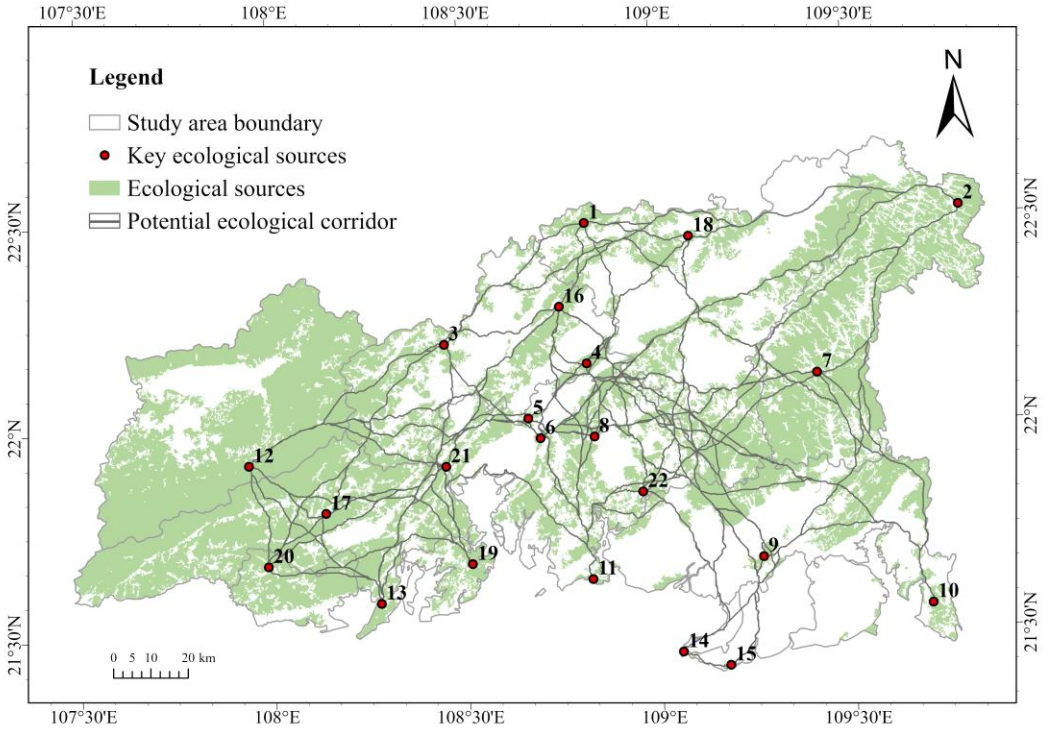


Figure 8. Construction of potential ecological corridor.

4.3. Evaluation and optimization of ecological security pattern

4.3.1. Importance evaluation of ecological corridors

As shown in Figure 9, a total of 32 Level I ecological corridors were identified, with a total length of 1106.11 km. These corridors were mainly concentrated in the central and eastern parts of the study area. They primarily connect major ecological sources in Fangchenggang City and Qinzhou City, linking important ecological areas such as the Shiwandashan National Nature Reserve, Bazhaigou Scenic Area,

Wanggangshan Autonomous Regional Nature Reserve, and Nawushan Autonomous Regional Geological Park. These corridors form the backbone of the regional ecological network, supporting species migration and key ecological processes. Therefore, priority should be given to the protection and restoration of these corridors to reduce anthropogenic ecological fragmentation and maintain continuous migration pathways.

In contrast to Level I ecological corridors, a total of 87 Level II ecological corridors were identified, generally connecting more spatially dispersed ecological sources. They were mainly distributed around the Shiwandashan Mountains in the northwest and the Nawushan Autonomous Regional Geological Park, where complex terrain, elongated mountainous landscapes, and dispersed ecological sources resulted in relatively low corridor density and longer inter-corridor distances. However, it is important to note that although ecological sources were relatively small, these important conservation areas can be connected by Level II corridors. This indicated that these corridors play an important supplementary role in connecting fragmented ecological sources, facilitating species movement, and compensating for the relatively limited ecological connectivity in the southeastern region.

Level 3 ecological corridors were primarily distributed along the periphery of the study area, where the intensity of interaction between ecological sources is relatively low. However, it should be noted that although their direct contribution to the ecological network is limited, they connect peripheral ecological patches and provide an outer ecological buffer zone, thereby contributing to network integrity and enhancing resistance to external anthropogenic disturbance.

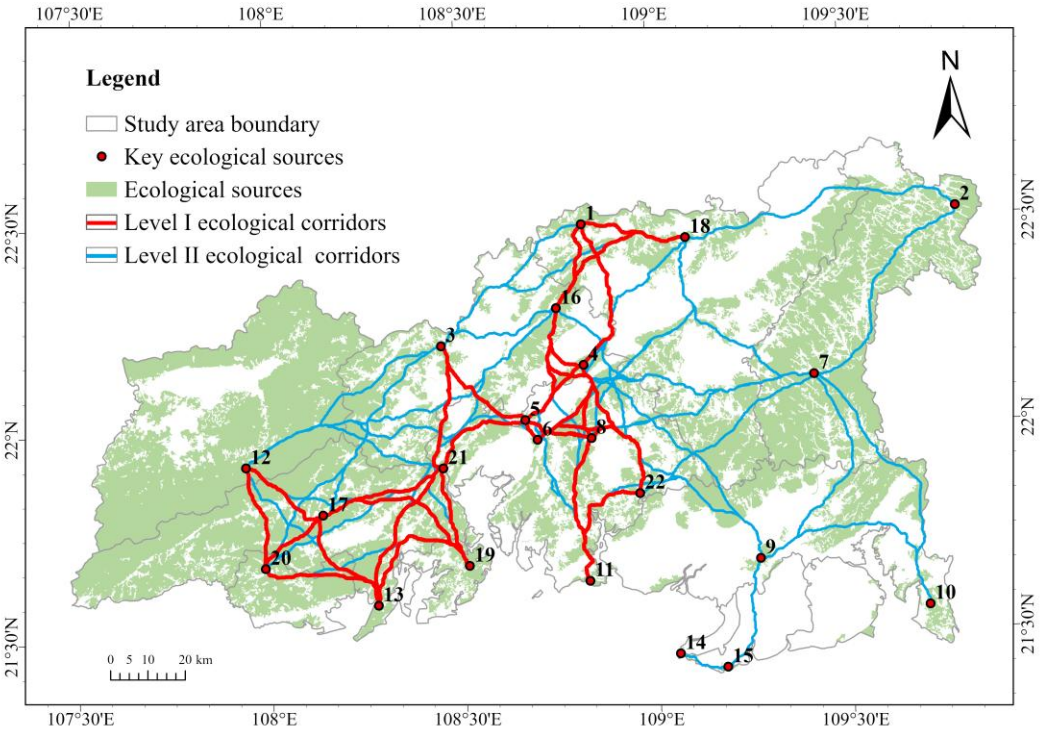


Figure 9. Identification of important ecological corridor.

In terms of land-use composition (Table 7), ecological corridors exhibit a clear land-use gradient across different levels: as corridor level decreases, the proportion of ecological land generally declines, while the proportions of cropland and built-up land increase. Forestland dominates Level I ecological corridors, accounting for 91.01%, followed by grassland at 4.53%, whereas built-up land and cropland account for only 0.18% and 2.87%, respectively. This indicates that Level I corridors have a favorable ecological foundation, allowing for direct ecological restoration and land-use adjustment. While in Level

II and Level III corridors, the proportions of forestland and grassland gradually decrease, while those of cropland and built-up land increase. Notably, cropland accounts for 5.24% of Level III corridors, exceeding its overall proportion across all potential ecological corridors (4.08%). This indicates that human-dominated land may constrain species movement, while converting Level III corridors into continuous ecological corridors may face constraints related to land-use adjustment, construction costs, and policy coordination.

Table 7. The resistance values and weights of different resistance surfaces in study area.

Corridor level	Length / km	Area / km²	Proportion / %				
			Forest land	Grassland	Water bodies	Built-up land	Cropland
Level I	1106.11	32.93	91.01	4.53	1.36	0.18	2.87
Level II	3955.79	97.91	90.45	4.11	1.77	0.35	3.27
Level III	3942.94	91.72	86.59	3.47	3.93	0.70	5.24
Overall	9004.84	222.56	88.83	3.89	2.66	0.48	4.08

4.3.2. Identification of additional potential ecological corridors

As is shown in Figure 10, a total of 10 potential ecological corridors were identified using circuit theory. The major corridors were primarily distributed between Source 1 and Source 3, Source 18 and Source 4, Source 9 and Source 14, and Source 9 and Source 15. These source pairs are characterized by relatively large spatial distances and high ecological resistance, indicating that circuit theory can identify potential species movement corridors in large-scale, high-resistance environments. Further comparison between the corridors identified by circuit theory and those derived from the MCR-gravity model revealed a high degree of spatial correspondence between the two approaches, suggesting that major ecological corridors exhibit relatively stable spatial patterns and providing complementary evidence for the identification of key ecological connections within the study area.

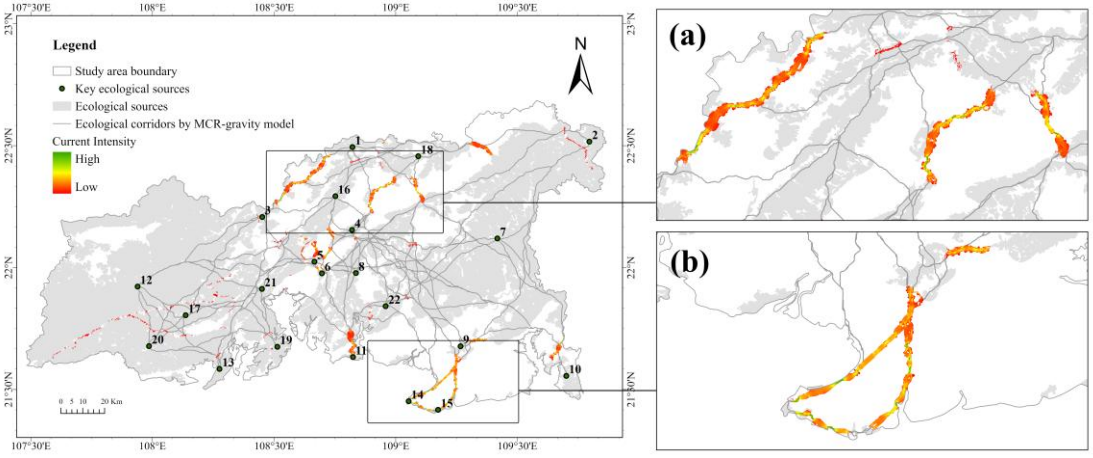


Figure 10. Spatial distribution of potential corridors and current intensity generated by circuit theory. (a) and (b) are zoom-in views of current intensity.

Furthermore, based on the landscape ecological resistance surface, potential hydrological radiation pathways were extracted by using hydrological analysis. 21 major supplementary radiation pathways with relatively concentrated distributions and high spatial continuity were consequently retained, with a total length of approximately 462.32 km (Figure 11). The results showed that these additional radiation pathways were primarily distributed in the western, eastern, and southeastern parts of the Beiqinfang Urban Agglomeration. These pathways mainly bridged ecological connectivity gaps within the western part of Shiwandashan Nature Reserve, the northeastern part of the Liuwandashan region, and ecological

sources in the Beihai City, thereby further optimizing the spatial structure of the existing ecological corridor network.

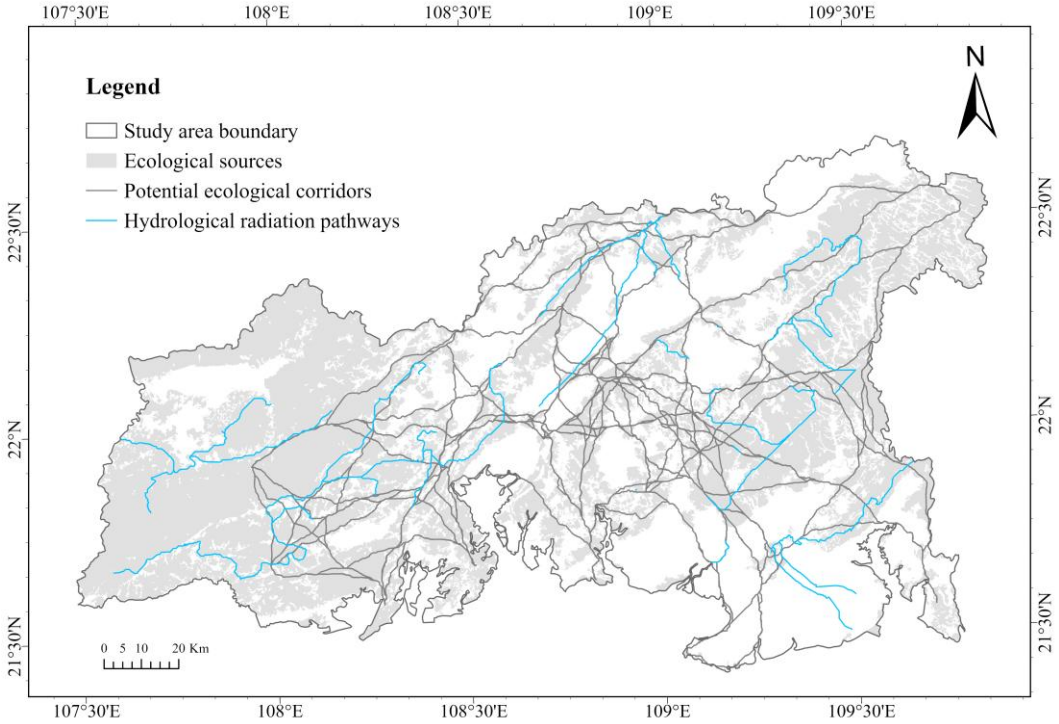


Fig. 11. Spatial distribution of additional radiation pathways based on hydrological analysis.

4.3.3. Comprehensive identification of ecological nodes and barrier points

As shown in Figure 12, a total of 89 Level 1 and 105 Level 2 ecological nodes were identified by integrating the ecological corridors and radiation pathways. Level 1 ecological nodes were mainly distributed within and around major ecological conservation areas, such as Shiwandashan Nature Reserve and the Maolingjiang River Basin, as well as along terrestrial–coastal transition zones, highlighting their importance for maintaining species movement and regional ecological connectivity. Level 2 ecological nodes were primarily concentrated in northeastern Qinzhou City, parts of the Liuwandashan region, and the urban area of Beihai City. Although relatively few protected areas are distributed in Liuwandashan, its favorable ecological foundation and ecological advantages warrant enhanced protection of species movement pathways. While in the urban area of Beihai City, where human activities and urbanization exert relatively strong disturbances, increasing urban green spaces and preserving space for species movement could strengthen material exchange between terrestrial and coastal ecological spaces.

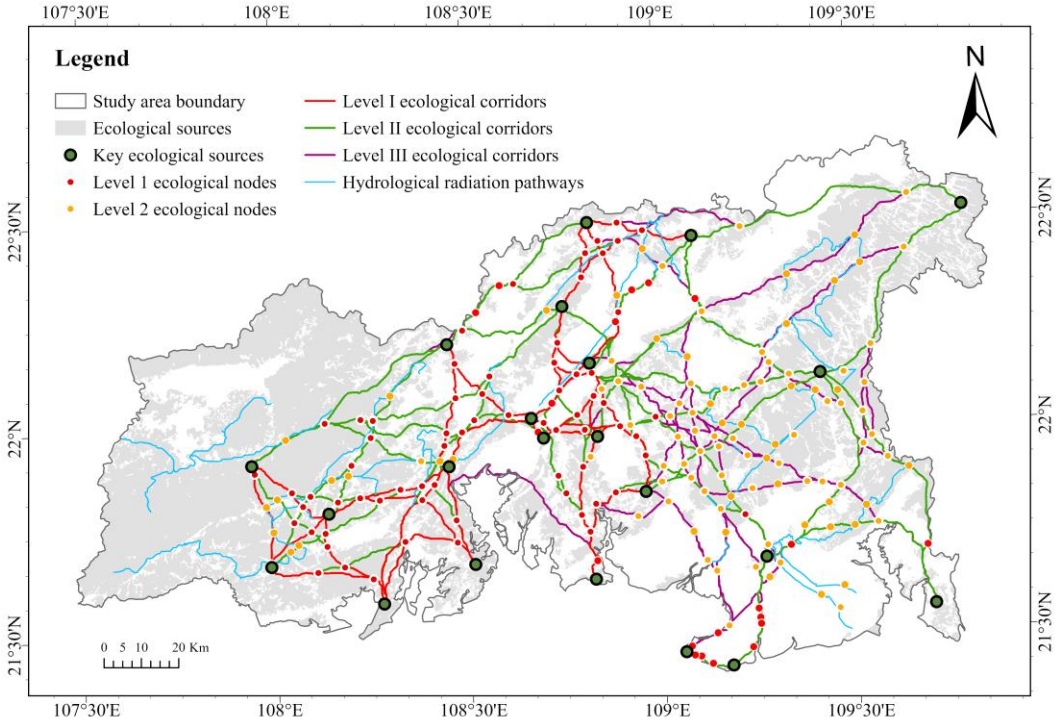


Figure 12. Spatial distribution of ecological nodes in the urban agglomeration

As shown in Figure 13, based on the regional road data and the ecological corridors and radiation pathways, 39 Level 1 and 70 Level 2 ecological barrier points were identified. These barrier points were mainly concentrated along the boundary between Fangchenggang City and Qinzhou City, the Maolingjiang River in central Qinzhou, and the urban area of Beihai City, and mostly occurred at intersections between ecological corridors and major transportation infrastructure, including the Guangnan Railway, Lanhai Expressway, and Liuqin Expressway.

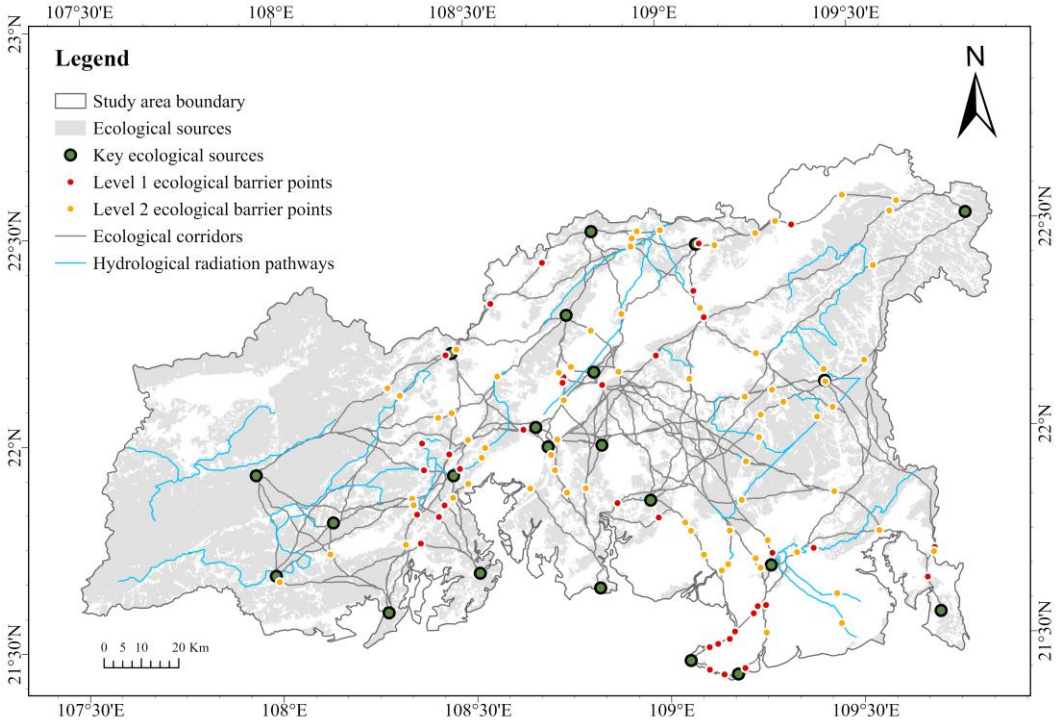


Figure 13. Spatial distribution of ecological barrier points in the urban agglomeration

4.3.4. Evaluation and optimization of ecological security pattern

Based on the spatial distribution of ecological sources and other key ecological nodes identified through the ecological security pattern of the Beiqinfang urban agglomeration, and considering its overall territorial spatial development pattern and ecological conservation objectives. As is shown in Figure 14, we propose an optimized ecological security pattern comprising "*Two Barriers–Three Zones–Four Corridors–Three Cores–Multiple Nodes*" (Fig. 14).

Two Barriers: (1) The northern mountainous barrier, characterized by abundant ecological sources, high forest coverage, rich biodiversity, and strong water conservation capacity, is primarily anchored by the Shiwandashan and Liuwandashan Mountains and serves as a major ecological defense for the urban agglomeration. (2) The southern coastal barrier encompasses extensive coastal wetlands and mangroves in Qinzhou. Although a sound foundation has been established for coastal shelterbelt development, urban expansion and port construction have reduced corridor availability, impeded wildlife movement, and increased ecological degradation risks along certain coastlines.

Three Zones: (1) The integrated land–sea zone, located along the transition from the Shiwandashan to the western coastal areas, requires coordinated management of terrestrial and marine ecosystems, restoration of forests and coastal wetlands, and mitigation of habitat fragmentation associated with mountain development and the marine-oriented economy. (2) The central zone, affected by urban expansion and transportation infrastructure development, faces increasing fragmentation of urban and rural ecological spaces. Landscape restoration, reconstruction of rural and natural environments, and improved corridor connectivity are therefore needed. (3) The eastern two-bay zone, located between the Beibu Gulf and the Guangdong–Hong Kong–Macao Greater Bay Area, is characterized by Level II ecological corridors and ecological barrier points. Poor corridor connectivity and anthropogenic pressures on wetlands and coastal ecosystems necessitate strengthened cross-regional ecological restoration.

Four Corridors: These comprise the ecological corridor around Shiwandashan, tourist attractions, eastern mountain, and Liuwandashan. Together, they form a network of species dispersal pathways connecting primarily Class I and Class II ecological sources, thereby facilitating material and energy flows among ecological sources. Specifically, (1) the ecological corridor around Shiwandashan connects the mountainous areas of Fangchenggang and western Qinzhou, supporting biodiversity conservation. (2) The ecological corridor around tourist attractions

links natural and cultural landscapes and enhancing ecological network integrity. (3) The ecological corridor along eastern mountains follows the eastern mountains. (4) The ecological corridor around the Liuwandashan should prioritize ecological conservation, restrict development of land for construction in the areas surrounding the corridor, and facilitate species migration.

Three Cores: These refer to the urban green cores of Beihai, Qinzhou, and Fangchenggang. These core areas consist primarily of downtown green spaces designated in regional spatial plans and farmland within city limits; they serve as key nodes in the urban agglomeration's ecological network. They fulfill both ecological and landscape functions, and efforts are needed to enhance urban resilience and green space connectivity.

Multiple Nodes: These include ecological nodes and barrier points. Located in critical areas for ecological conservation and restoration, these nodes are essential to maintaining corridor connectivity and overall network stability. Ecological nodes are key locations along the corridor that maintain connectivity between ecological sources, while ecological barriers represent areas that impede species migration. Therefore, priority should be given to protecting ecological nodes and restoring ecological barriers points.

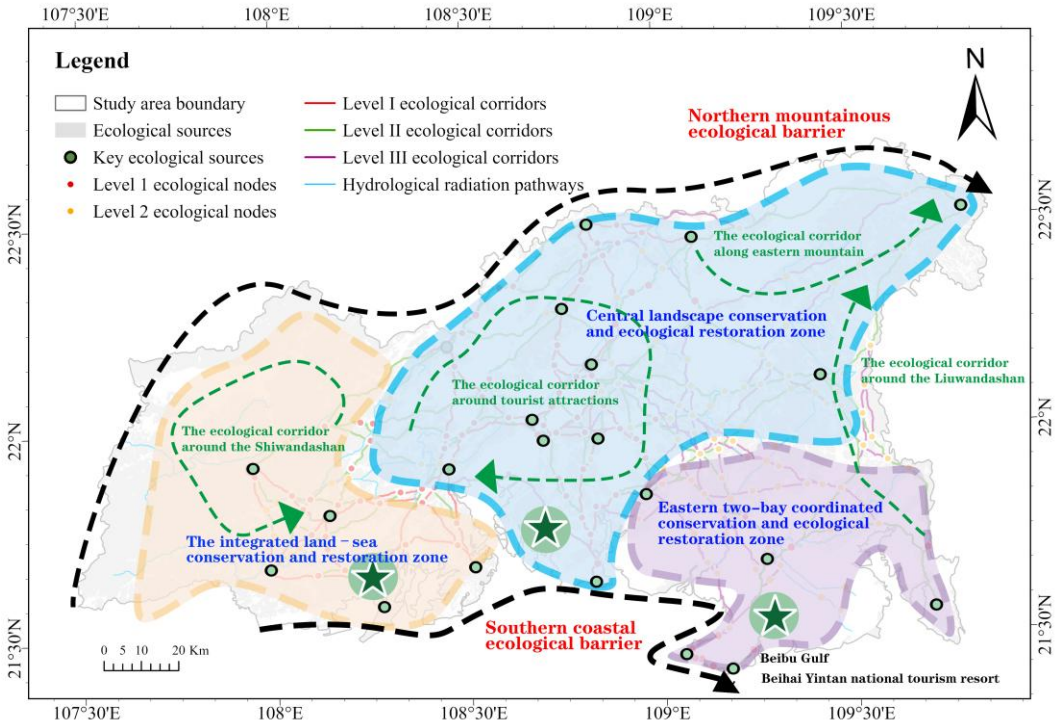


Figure 14. Ecological security pattern in the study area.

5. Discussion

5.1. Optimization of construction framework

After decades of development, ecological network construction has established a general framework consisting of ecological source identification, ecological resistance surface construction, and ecological corridor extraction [73,74]. However, several limitations remain in existing studies:

(1) Ecological sources are commonly identified based on protected areas, POI data, or MSPA–landscape connectivity analysis [75–77]. Directly selecting protected areas may overlook other important ecological spaces and introduce subjective biases, while MSPA-based approaches mainly characterize patch morphology and structural importance without fully evaluating habitat suitability.

(2) Ecological resistance surfaces are often constructed by assigning resistance values to land-use types; however, this approach is relatively subjective and may fail to capture ecological heterogeneity within the same land-use category [78,79].

(3) Traditional MCR models can identify least-cost migration pathways but have limited capacity to characterize corridor widths and critical connectivity areas [80].

To address these limitations, this study integrates MSPA, the InVEST model, landscape connectivity indices, and policy-designated ecological protected areas to identify ecological sources from multiple perspectives, including landscape structure, ecological function, and conservation value. This approach ensures that identified ecological sources possess both strong structural connectivity and high habitat suitability. For ecological corridor construction, the MCR–gravity model and circuit theory were jointly applied to exploit their complementary advantages in identifying optimal pathways, potential movement routes, and key connectivity nodes, thereby establishing a more comprehensive regional ecological network.

Furthermore, considering the limited ecological planning studies associated with the integrated development of the Beiqinfang Urban Agglomeration, this study incorporated hydrological analysis based on the ecological resistance surface to generate radiation pathways and further optimize the ecological network. The proposed ecological conservation and optimization strategies provide scientific support for territorial ecological restoration, conservation planning, and sustainable regional development in the Beiqinfang Urban Agglomeration.

5.2. Implication for ecosystem management

Comparison with the regional ecological planning framework shows that the ecological security pattern centered on Shiwandashan Nature Reserve and the Beibu Gulf coastal ecological barrier is broadly consistent with the concentration of major ecological corridors identified in this study, particularly in the Shiwandashan region. Meanwhile, areas with poor or very poor habitat quality identified in this study are mainly distributed along the southern coast and the Qinjiang River, which generally consistent with the ecological vulnerable zones identified by the planning framework. As the existing planning framework addresses ecological security pattern at the whole province scale and provides only a broad framework for the Beiqinfang Urban Agglomeration, the ecological corridors, nodes, and barrier points identified in this study provide a more spatially explicit basis for regional ecological conservation and restoration.

Considering differences in ecological characteristics and sensitivity to human disturbance, differentiated conservation and restoration measures should be implemented across ecological spaces:

(1) In core ecological areas such as Shiwandashan and Liuwandashan, ecological protection should be strictly enforced, and human disturbance should be controlled, while agricultural and tourism activities should be appropriately regulated without compromising ecological functions.

(2) For Level I and Level II ecological corridors dominated by forest land and grassland, land-use conversion should be strictly controlled to maintain ecological functions and network connectivity. In highly developed areas, Level III corridors can be restored through ecological greening and wildlife crossings to improve connectivity.

(3) Existing ecological barrier points can be mitigated by maintaining and widening ecological shelterbelts and establishing wildlife movement passages, while major planned infrastructure should incorporate ecological crossing spaces to reduce barrier effects. Level 1 ecological nodes should receive priority protection of their existing habitats. For part of Level 2 nodes in urban areas, where human disturbance is relatively intensive, expanding urban green spaces and preserving movement corridors can promote material exchange and potential gene flow between terrestrial and coastal ecosystems.

5.3. Limitations and future research

(1) This study primarily constructed the terrestrial ecological network based on land-use data and did not fully account for the distinctive terrestrial–coastal characteristics of the Beiqinfang Urban Agglomeration. The study area contains important coastal mangrove ecosystems, which, although smaller in extent than terrestrial forests, play a critical role in terrestrial–marine species movement and ecological

connectivity. In addition, Weizhou Island in Beihai City is an important protected area, while the surrounding marine environment was not incorporated into the ecological network. Compared with terrestrial landscape ecology, marine landscape ecology remains relatively underdeveloped. Future research should therefore further explore the theory and methods of integrated terrestrial–marine ecological network construction.

(2) Ecological network construction is subject to significant scale effects, and coarse spatial resolutions may overlook small ecological patches with relatively high connectivity. Considering data accuracy and the extent of the study area, a 30-m spatial resolution was adopted in this study. However, models such as InVEST and MSPA may produce different habitat quality and landscape connectivity results at different raster scales. Future studies could therefore compare ecological networks constructed at multiple spatial resolutions to evaluate their structural characteristics and stability across scales.

(3) This study focused primarily on the spatial patterns of the ecological network, while the width and effectiveness of ecological corridors were not directly validated through field surveys. Corridors identified by the MCR model were delineated using a minimum width of 30 m, representing the assumed minimum corridor width required for species movement. Although circuit theory further delineates potential corridor areas and improves spatial identification, it does not fully account for landscape characteristics, spatial heterogeneity, and functional effectiveness within and around corridors. Thus, the appropriateness and ecological effectiveness of corridor width require further validation through species-specific behavioral data and field-based monitoring.

6. Conclusion

Under continued urbanization and regional integration, the BeiqinFang Urban Agglomeration faces increasing pressure on ecological space and biodiversity conservation. Constructing and optimizing regional ecological networks is therefore essential for maintaining ecosystem stability and connectivity. The results show that forestland and cropland account for more than 80%, indicating a generally favorable ecological baseline. By integrating InVEST model, MSPA, landscape connectivity, and protected-area data, 22 ecological sources were identified, mainly concentrated in the western Shiwandashan and eastern Liuwandashan regions. The MCR model identified 231 potential ecological corridors with a total length of 9004.08 km. Further integration of the gravity model, circuit theory, and hydrological analysis identified 32 Level I corridors, 87 Level II corridors, and 21 hydrological radiation pathways, together with 89 Level 1 and 105 Level 2 ecological nodes and 39 Level 1 and 70 Level 2 ecological barrier points. This study finally proposes an optimized ecological security pattern comprising "*Two Barriers–Three Zones–Four Corridors–Three Cores–Multiple Nodes*". The results demonstrate that an integrated framework can effectively identify critical ecological areas and network vulnerabilities. Strengthening source protection, controlling land-use changes along key corridors, restoring ecological barrier points caused by road crossings, and improving stepping-stone habitats around ecological nodes can enhance regional connectivity. This framework provides a scientific basis for ecological restoration and conservation planning in the Beiqinfang Urban Agglomeration and offers a transferable approach for ecological network planning in rapidly urbanizing regions.

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Data availability statement:

1. Land use/land cover (LULC) data that support the research are available from the Resource and Environmental Science and Data Center (RESDC) of the Chinese Academy of Sciences (http://www.resdc.cn), but the data are available upon purchase.

2. Digital elevation model (DEM) data that support the research are available free from Geospatial Data Cloud (https://www.gscloud.cn/).

3. Road vector network data that support the research are available free from OpenStreetMap (https://www.openstreetmap.net.cn/).

4. Regional population and socioeconomic that support the research are available upon request from National Bureau of Statistics of China and available free from the WorldPop high-resolution global population dataset (www.worldpop.org).

Declarations

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References

1. Nor, A.N.M.; Corstanje, R.; Harris, J.A.; Grafius, D.R.; Siriwardena, G.M. Ecological Connectivity Networks in Rapidly Expanding Cities. *Heliyon* **2017**, *3*, e00325, doi:10.1016/j.heliyon.2017.e00325.
2. Closset-Kopp, D.; Wasof, S.; Decocq, G. Using Process-Based Indicator Species to Evaluate Ecological Corridors in Fragmented Landscapes. *Biological Conservation* **2016**, *201*, 152–159, doi:10.1016/j.biocon.2016.06.030.
3. Yu, Q.; Yue, D.; Wang, Y.; Kai, S.; Fang, M.; Ma, H.; Zhang, Q.; Huang, Y. Optimization of Ecological Node Layout and Stability Analysis of Ecological Network in Desert Oasis：a Typical Case Study of Ecological Fragile Zone Located at Deng Kou County(Inner Mongolia). *Ecological Indicators* **2018**, *84*, 304–318, doi:10.1016/j.ecolind.2017.09.002.
4. Jongman, R.H.G.; Külvik, M.; Kristiansen, I. European Ecological Networks and Greenways. *Landscape and Urban Planning* **2004**, *68*, 305–319, doi:10.1016/S0169-2046(03)00163-4.
5. Ignatieva, M.; Stewart, G.H.; Meurk, C. Planning and Design of Ecological Networks in Urban Areas. *Landscape Ecol Eng* **2011**, *7*, 17–25, doi:10.1007/s11355-010-0143-y.
6. Richter, B.; Behnisch, M. Integrated Evaluation Framework for Environmental Planning in the Context of Compact Green Cities. *Ecological Indicators* **2019**, *96*, 38–53, doi:10.1016/j.ecolind.2018.05.025.
7. Li, X.; Zhou, W.; Ouyang, Z.; Xu, W.; Zheng, H. Spatial Pattern of Greenspace Affects Land Surface Temperature: Evidence from the Heavily Urbanized Beijing Metropolitan Area, China. *Landscape Ecol* **2012**, *27*, 887–898, doi:10.1007/s10980-012-9731-6.
8. Bascompte, J. Structure and Dynamics of Ecological Networks. *Science* **2010**, *329*, 765–766, doi:10.1126/science.1194255.
9. Williamson, J.C.; Bestelmeyer, B.T.; McClaran, M.P.; Robinett, D.; Briske, D.D.; Wu, X.B.; Fernández-Giménez, M.E. Can Ecological Land Classification Increase the Utility of Vegetation Monitoring Data? *Ecological Indicators* **2016**, *69*, 657–666, doi:10.1016/j.ecolind.2016.05.030.

10. Yan, L.; Yu, L.; An, M.; Su, H.; Li, H.; Yuan, C. Explanation of the Patterns, Spatial Relationships, and Node Functions of Biodiversity and Island: An Example of Nature Reserves in Guizhou, Southwest China. *Sustainability* **2019**, *11*, 6197, doi:10.3390/su11226197.
11. Xu, J.; Fan, F.; Liu, Y.; Dong, J.; Chen, J. Construction of Ecological Security Patterns in Nature Reserves Based on Ecosystem Services and Circuit Theory: A Case Study in Wenchuan, China. *International Journal of Environmental Research and Public Health* **2019**, *16*, 3220, doi:10.3390/ijerph16173220.
12. Li, H.; Chen, W.; He, W. Planning of Green Space Ecological Network in Urban Areas: An Example of Nanchang, China. *International Journal of Environmental Research and Public Health* **2015**, *12*, 12889–12904, doi:10.3390/ijerph121012889.
13. Cui, L.; Wang, J.; Sun, L.; Lv, C. Construction and Optimization of Green Space Ecological Networks in Urban Fringe Areas: A Case Study with the Urban Fringe Area of Tongzhou District in Beijing. *Journal of Cleaner Production* **2020**, *276*, 124266, doi:10.1016/j.jclepro.2020.124266.
14. Yao, H. Characterizing Landuse Changes in 1990–2010 in the Coastal Zone of Nantong, Jiangsu Province, China. *Ocean & Coastal Management* **2013**, *71*, 108–115, doi:10.1016/j.ocecoaman.2012.09.007.
15. Shi, X.; Qin, M. Research on the Optimization of Regional Green Infrastructure Network. *Sustainability* **2018**, *10*, 4649, doi:10.3390/su10124649.
16. Chen, C.; Shi, L.; Lu, Y.; Yang, S.; Liu, S. The Optimization of Urban Ecological Network Planning Based on the Minimum Cumulative Resistance Model and Granularity Reverse Method: A Case Study of Haikou, China. *IEEE Access* **2020**, *8*, 43592–43605, doi:10.1109/ACCESS.2020.2976548.
17. Kong, F.; Yin, H.; Nakagoshi, N.; Zong, Y. Urban Green Space Network Development for Biodiversity Conservation: Identification Based on Graph Theory and Gravity Modeling. *Landscape and Urban Planning* **2010**, *95*, 16–27, doi:10.1016/j.landurbplan.2009.11.001.
18. Pereira, M.; Segurado, P.; Neves, N. Using Spatial Network Structure in Landscape Management and Planning: A Case Study with Pond Turtles. *Landscape and Urban Planning* **2011**, *100*, 67–76, doi:10.1016/j.landurbplan.2010.11.009.
19. Vogt, P.; Riitters, K.H.; Estreguil, C.; Kozak, J.; Wade, T.G.; Wickham, J.D. Mapping Spatial Patterns with Morphological Image Processing. *Landscape Ecol* **2007**, *22*, 171–177, doi:10.1007/s10980-006-9013-2.
20. Carlier, J.; Moran, J. Landscape Typology and Ecological Connectivity Assessment to Inform Greenway Design. *Science of The Total Environment* **2019**, *651*, 3241–3252, doi:10.1016/j.scitotenv.2018.10.077.
21. Saura, S.; Vogt, P.; Velázquez, J.; Hernando, A.; Tejera, R. Key Structural Forest Connectors Can Be Identified by Combining Landscape Spatial Pattern and Network Analyses. *Forest Ecology and Management* **2011**, *262*, 150–160, doi:10.1016/j.foreco.2011.03.017.
22. Soille, P.; Vogt, P. Morphological Segmentation of Binary Patterns. *Pattern Recognition Letters* **2009**, *30*, 456–459, doi:10.1016/j.patrec.2008.10.015.

23. Wang, Y.-H.; Yang, K.-C.; Bridgman, C.L.; Lin, L.-K. Habitat Suitability Modelling to Correlate Gene Flow with Landscape Connectivity. *Landscape Ecol* **2008**, *23*, 989–1000, doi:10.1007/s10980-008-9262-3.
24. Hepcan, Ç.C.; Özkan, M.B. Establishing Ecological Networks for Habitat Conservation in the Case of Çeşme–Urla Peninsula, Turkey. *Environ Monit Assess* **2011**, *174*, 157–170, doi:10.1007/s10661-010-1447-y.
25. Ye, H.; Yang, Z.; Xu, X. Ecological Corridors Analysis Based on MSPA and MCR Model—A Case Study of the Tomur World Natural Heritage Region. *Sustainability* **2020**, *12*, 959, doi:10.3390/su12030959.
26. Santos, J.S.; Leite, C.C.C.; Viana, J.C.C.; dos Santos, A.R.; Fernandes, M.M.; de Souza Abreu, V.; do Nascimento, T.P.; dos Santos, L.S.; de Moura Fernandes, M.R.; da Silva, G.F.; et al. Delimitation of Ecological Corridors in the Brazilian Atlantic Forest. *Ecological Indicators* **2018**, *88*, 414–424, doi:10.1016/j.ecolind.2018.01.011.
27. Zhang, L.; Peng, J.; Liu, Y.; Wu, J. Coupling Ecosystem Services Supply and Human Ecological Demand to Identify Landscape Ecological Security Pattern: A Case Study in Beijing–Tianjin–Hebei Region, China. *Urban Ecosyst* **2017**, *20*, 701–714, doi:10.1007/s11252-016-0629-y.
28. Lu, Y.; Cheng, Q.; Wang, M. Construction and Evaluation of the Panjin Wetland Ecological Network Based on the Minimum Cumulative Resistance Model. *Ecological Modelling* **2025**, *505*, 111118, doi:10.1016/j.ecolmodel.2025.111118.
29. Wang, H.; Li, H.; Lin, C.; Feng, Q.; Chen, Z.; Bi, P. Identifying and Prioritizing Potential Ecological Corridors That Integrate Structural Connectivity and Efficiency: An Integrated Framework Combining Infomap, the Gravity Model, and Robustness Analysis. *Ecological Informatics* **2026**, *99*, 104041, doi:10.1016/j.ecoinf.2026.104041.
30. Zhang, Z.; Meerow, S.; Newell, J.P.; Lindquist, M. Enhancing Landscape Connectivity through Multifunctional Green Infrastructure Corridor Modeling and Design. *Urban Forestry & Urban Greening* **2019**, *38*, 305–317, doi:10.1016/j.ufug.2018.10.014.
31. Hashemi, R.; Darabi, H.; Hashemi, M.; Wang, J. Graph Theory in Ecological Network Analysis: A Systematic Review for Connectivity Assessment. *Journal of Cleaner Production* **2024**, *472*, 143504, doi:10.1016/j.jclepro.2024.143504.
32. Lumia, G.; Praticò, S.; Di Fazio, S.; Cushman, S.; Modica, G. Combined Use of Urban Atlas and Corine Land Cover Datasets for the Implementation of an Ecological Network Using Graph Theory within a Multi-Species Approach. *Ecological Indicators* **2023**, *148*, 110150, doi:10.1016/j.ecolind.2023.110150.
33. Shen, J.; Wang, J.; Wu, T.; Wang, Y. Building Landscape Ecological Network with Multi-Scenario Connectivity Based on Network Fault Tolerance Index and Networking Technology in Graph Theory. *Ecological Indicators* **2024**, *166*, 112417, doi:10.1016/j.ecolind.2024.112417.
34. McRae, B.H.; Beier, P. Circuit Theory Predicts Gene Flow in Plant and Animal Populations. *Proceedings of the National Academy of Sciences* **2007**, *104*, 19885–19890, doi:10.1073/pnas.0706568104.

35. Ling, X.; Liu, M.; Tian, D.; Wang, Y.; Lu, C.; Zhang, Y.; Li, F.; Miao, Z.; Man, W. Scenario-Based Ecological Network Dynamics in Coastal Wetlands: An Integrated FLUS-MSPA-Circuit Theory Framework for the Western Bohai Bay. *Ecological Indicators* **2026**, *187*, 114921, doi:10.1016/j.ecolind.2026.114921.
36. Baohua, H.; Xiangqiao, K.; Jinlong, L.; ZhangYe Research on the Ecological Network and Resilience of Yantai Based on Circuit Theory and Robustness Modeling. *Ecological Indicators* **2026**, *189*, 115084, doi:10.1016/j.ecolind.2026.115084.
37. McRae, B.H. Isolation by Resistance. *Evolution* **2006**, *60*, 1551–1561, doi:10.1111/j.0014-3820.2006.tb00500.x.
38. Liao, L.; Sun, L.; Lu, J.; Tang, X.; Li, J.; An, R. Three-Dimensional Habitat Suitability Index as an Ecological Indicator for Diagnosing Dam-Regulated Fish Migration Corridor Disruption and Guiding Turbine-Level Flow Management. *Ecological Indicators* **2026**, *190*, 115420, doi:10.1016/j.ecolind.2026.115420.
39. Weber, T.; Sloan, A.; Wolf, J. Maryland's Green Infrastructure Assessment: Development of a Comprehensive Approach to Land Conservation. *Landscape and Urban Planning* **2006**, *77*, 94–110, doi:10.1016/j.landurbplan.2005.02.002.
40. Kim, K.-H.; Pauleit, S. Landscape Character, Biodiversity and Land Use Planning: The Case of Kwangju City Region, South Korea. *Land Use Policy* **2007**, *24*, 264–274, doi:10.1016/j.landusepol.2005.12.001.
41. Tan, P.Y.; Abdul Hamid, A.R. bin Urban Ecological Research in Singapore and Its Relevance to the Advancement of Urban Ecology and Sustainability. *Landscape and Urban Planning* **2014**, *125*, 271–289, doi:10.1016/j.landurbplan.2014.01.019.
42. Martellozzo, F.; Ramankutty, N.; Hall, R.J.; Price, D.T.; Purdy, B.; Friedl, M.A. Urbanization and the Loss of Prime Farmland: A Case Study in the Calgary–Edmonton Corridor of Alberta. *Reg Environ Change* **2015**, *15*, 881–893, doi:10.1007/s10113-014-0658-0.
43. Jiang, P.; Cheng, L.; Li, M.; Zhao, R.; Huang, Q. Analysis of Landscape Fragmentation Processes and Driving Forces in Wetlands in Arid Areas: A Case Study of the Middle Reaches of the Heihe River, China. *Ecological Indicators* **2014**, *46*, 240–252, doi:10.1016/j.ecolind.2014.06.026.
44. Peng, J.; Liu, Y.; Liu, Z.; Yang, Y. Mapping Spatial Non-Stationarity of Human-Natural Factors Associated with Agricultural Landscape Multifunctionality in Beijing–Tianjin–Hebei Region, China. *Agriculture, Ecosystems & Environment* **2017**, *246*, 221–233, doi:10.1016/j.agee.2017.06.007.
45. Lemos, M.C.; Morehouse, B.J. The Co-Production of Science and Policy in Integrated Climate Assessments. *Global Environmental Change* **2005**, *15*, 57–68, doi:10.1016/j.gloenvcha.2004.09.004.
46. Riitters, K.H.; Vogt, P.; Soille, P.; Kozak, J.; Estreguil, C. Neutral Model Analysis of Landscape Patterns from Mathematical Morphology. *Landscape Ecol* **2007**, *22*, 1033–1043, doi:10.1007/s10980-007-9089-3.
47. Sun, H.; Liu, C.; Wei, J. Identifying Key Sites of Green Infrastructure to Support Ecological Restoration in the Urban Agglomeration. *Land* **2021**, *10*, 1196, doi:10.3390/land10111196.

48. Wang L.; Feng X.; Chang Q.; Liu H.; Wang J. Pattern Construction of Habitat Network for Urban Green Space Based on the Compound Model of InVEST and MCR. *Chinese Landscape Architecture* **2020**, *36*, 113–118, doi:10.19775/j.cla.2020.06.0113.
49. Zhang X.; Zhou J.; Li M. Analysis on spatial and temporal changes of regional habitat quality based on the spatial pattern reconstruction of land use. *ACTA GEOGRAPHICA SINICA* **2020**, *75*, 160–178.
50. Hao Y.; Zhang N.; Du Y.; Wang Y.; Zheng Y.; Zhang C. Construction of ecological security pattern based on habitat quality in Tang County,Hebei, China. *Chinese Journal of Applied Ecology* **2019**, *30*, 1015–1024, doi:10.13287/j.1001-9332.201903.007.
51. Cotter, M.; Häuser, I.; Harich, F.K.; He, P.; Sauerborn, J.; Treydte, A.C.; Martin, K.; Cadisch, G. Biodiversity and Ecosystem services−A Case Study for the Assessment of Multiple Species and Functional Diversity Levels in a Cultural Landscape. *Ecological Indicators* **2017**, *75*, 111–117, doi:10.1016/j.ecolind.2016.11.038.
52. Lin, Y.; Lin, W.; Wang, Y.; Lien, W.; Huang, T.; Hsu, C.; Schmeller, D.S.; Crossman, N.D. Systematically Designating Conservation Areas for Protecting Habitat Quality and Multiple Ecosystem Services. *Environmental Modelling & Software* **2017**, *90*, 126–146, doi:10.1016/j.envsoft.2017.01.003.
53. An, Y.; Liu, S.; Sun, Y.; Shi, F.; Beazley, R. Construction and Optimization of an Ecological Network Based on Morphological Spatial Pattern Analysis and Circuit Theory. *Landscape Ecol* **2021**, *36*, 2059–2076, doi:10.1007/s10980-020-01027-3.
54. Taylor, P.D.; Fahrig, L.; Henein, K.; Merriam, G. Connectivity Is a Vital Element of Landscape Structure. *Oikos* **1993**, *68*, 571, doi:10.2307/3544927.
55. Liccari, F.; Boscutti, F.; Bacaro, G.; Sigura, M. Connectivity, Landscape Structure, and Plant Diversity across Agricultural Landscapes: Novel Insight into Effective Ecological Network Planning. *Journal of Environmental Management* **2022**, *317*, 115358, doi:10.1016/j.jenvman.2022.115358.
56. Chen L.; Fu B. The Ecological Significance and Application of Landscape Connectivity. *Chinese Journal of Ecology* **1996**, 37–42, doi:10.13292/j.1000-4890.1996.0065.
57. Luo, Y.; Wang, H.; Wang, Y.; Zeng, M.; Zhang, S.; Hu, T.; Wu, J. Assessing the Role of Wildlife Ecological Corridors in Restoring Functional Connectivity of Road-Fragmented Habitats Using a Stochastic Movement Model and Scenario Simulation. *Ecological Engineering* **2026**, *232*, 108074, doi:10.1016/j.ecoleng.2026.108074.
58. Makwati, J.J.; Temu, S.; Simon, O.; Mwanukuzi, P.K.; Ndangalasi, H.J. Impacts of Land Use and Land Cover Change on Habitat Connectivity: A Case Study of the Igando Igawa Wildlife Corridor, Southern Tanzania. *Global Ecology and Conservation* **2026**, *66*, e04057, doi:10.1016/j.gecco.2026.e04057.
59. Zhang, C.; Chen, W.; Huang, F.; He, L.; Li, H. Dynamic Simulation of Functional Connectivity and Identification of Conservation Priorities for Grassland in China's Poyang Lake Considering Ecological Processes. *Ecological Indicators* **2023**, *149*, 110163, doi:10.1016/j.ecolind.2023.110163.
60. Guo, Z.; Zhu, C.; Fan, X.; Li, M.; Xu, N.; Yuan, Y.; Guan, Y.; Lyu, C.; Bai, Z. Analysis of Ecological Network Evolution in an Ecological Restoration Area with the MSPA-MCR

Model: A Case Study from Ningwu County, China. *Ecological Indicators* **2025**, *170*, 113067, doi:10.1016/j.ecolind.2024.113067.

61. Saura, S.; Pascual-Hortal, L. A New Habitat Availability Index to Integrate Connectivity in Landscape Conservation Planning: Comparison with Existing Indices and Application to a Case Study. *Landscape and Urban Planning* **2007**, *83*, 91–103, doi:10.1016/j.landurbplan.2007.03.005.
62. Men, D.; Pan, J. Ecological Network Identification and Connectivity Robustness Evaluation in the Yellow River Basin under a Multi-Scenario Simulation. *Ecological Modelling* **2023**, *482*, 110384, doi:10.1016/j.ecolmodel.2023.110384.
63. Pascual-Hortal, L.; Saura, S. Comparison and Development of New Graph-Based Landscape Connectivity Indices: Towards the Priorization of Habitat Patches and Corridors for Conservation. *Landscape Ecol* **2006**, *21*, 959–967, doi:10.1007/s10980-006-0013-z.
64. Knaapen, J.P.; Scheffer, M.; Harms, B. Estimating Habitat Isolation in Landscape Planning. *Landscape and Urban Planning* **1992**, *23*, 1–16, doi:10.1016/0169-2046(92)90060-D.
65. Song, S.; Wang, S.; Du, J.; Zhang, X. Karst Restoration Zoning Based on Fracture-Modified Minimum Cumulative Resistance Model and Ecological Network Resilience Assessment: A Case Study in Guizhou, China. *Ecological Engineering* **2026**, *223*, 107842, doi:10.1016/j.ecoleng.2025.107842.
66. Lu, Y.; Cheng, Q.; Wang, M. Construction and Evaluation of the Panjin Wetland Ecological Network Based on the Minimum Cumulative Resistance Model. *Ecological Modelling* **2025**, *505*, 111118, doi:10.1016/j.ecolmodel.2025.111118.
67. Zhou, L.; Zhao, Y.; Zhu, C.; Shi, C. Route Selection for Scenic Byways in Karst Areas Based on the Minimum Cumulative Resistance Model: A Case Study of the Nanpan–Beipan River Basin, China. *Ecological Indicators* **2024**, *163*, 112093, doi:10.1016/j.ecolind.2024.112093.
68. Liu C.; Liu D.; Feng R.; Tang Q.; Guo C. Construction of ecological security pattern in Northeast China based on MCR model. *Acta Ecologica Sinica* **2021**, *41*, 290–301.
69. Xu W.; Huang S.; Geng J.; Wang X.; Fu W.; Lin S.; Dong J. Construction of Ecological Space Network in Xiamen City Based on MCR and Gravity Model. *Journal of Northwest Forestry University* **2022**, *37*, 264–272.
70. Sklar, F.H.; Costanza, R. The Development of Dynamic Spatial Models for Landscape Ecology: A Review and Prognosis. **1991**, *82*, 239–288, doi:10.1007/978-1-4757-4244-2_10.
71. Blaschke, T. The Role of the Spatial Dimension within the Framework of Sustainable Landscapes and Natural Capital. *Landscape and Urban Planning* **2006**, *75*, 198–226, doi:10.1016/j.landurbplan.2005.02.013.
72. Zhou, D.; Song, W. Identifying Ecological Corridors and Networks in Mountainous Areas. *International Journal of Environmental Research and Public Health* **2021**, *18*, 4797, doi:10.3390/ijerph18094797.
73. Zhang, F.; Liu, X.; Jia, Y. Construction and Evolution of River Basin Ecological Network Based on Circuit Theory and MSPA: A Case Study of Dawen River Basin. *Ecological Modelling* **2025**, *510*, 111364, doi:10.1016/j.ecolmodel.2025.111364.

74. Li, J.; Wang, Y.; Shi, G.; Pei, X.; Zhang, C.; Zhou, L.; Yang, G. Ecological Security Pattern Construction Using Landscape Ecological Quality: A Case Study of Yanchi County, Northern China. *J. Arid Land* **2025**, *17*, 19–42, doi:10.1007/s40333-025-0093-8.
75. Huang, X.; Wang, H.; Shan, L.; Xiao, F. Constructing and Optimizing Urban Ecological Network in the Context of Rapid Urbanization for Improving Landscape Connectivity. *Ecological Indicators* **2021**, *132*, 108319, doi:10.1016/j.ecolind.2021.108319.
76. Sun, B.; Chen, Z.; Ji, H.; Cheng, D.; Yan, Y.; Tang, J. From Ecological Source Classification to Conservation: Constructing a Spatial-Temporal Ecological Security Pattern for the Yellow River Basin, China. *Ecological Frontiers* **2026**, *46*, 2663–2676, doi:10.1016/j.ecofro.2026.08.007.
77. Wei, J.; Tao, C.; Li, C.; Yue, X.; Wang, M.; Li, D.; Wu, Y. Integrating Ecosystem Services and Avian Biodiversity for the Construction of Ecological Security Patterns: A Case Study of the Central Yunnan Urban Agglomeration. *Journal of Cleaner Production* **2026**, *580*, 149647, doi:10.1016/j.jclepro.2026.149647.
78. Li, S.; Xiao, W.; Zhao, Y.; Lv, X. Incorporating Ecological Risk Index in the Multi-Process MCRE Model to Optimize the Ecological Security Pattern in a Semi-Arid Area with Intensive Coal Mining: A Case Study in Northern China. *Journal of Cleaner Production* **2020**, *247*, 119143, doi:10.1016/j.jclepro.2019.119143.
79. Huang, L.; Liu, S.; Fang, Y.; Zou, L. Construction of Wuhan's Ecological Security Pattern under the "Quality-Risk-Requirement" Framework. *Chinese Journal of Applied Ecology* **2019**, *30*, 615, doi:10.13287/j.1001-9332.201902.014.
80. Dai, L.; Liu, Y.; Luo, X. Integrating the MCR and DOI Models to Construct an Ecological Security Network for the Urban Agglomeration around Poyang Lake, China. *Science of The Total Environment* **2021**, *754*, 141868, doi:10.1016/j.scitotenv.2020.141868.

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