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Identification of Ecological Security Pattern and Ecological Restoration Zoning Strategy in the Shandong Section of the Beijing-Hangzhou Grand Canal

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Abstract: (1) Background: Identifying ecological security patterns and restoring the Beijing-Hangzhou Grand Canal in Shandong is vital for future ecological conservation and maintaining ecosystem sustainability. (2) Methods: The study area was selected, and the InVEST3.9.0 model was used to assess natural-environment ecosystem services. An optimal evaluation approach based on the Minimum Cumulative Resistance model was developed to define the ecological security pattern. (3) Results: There were 20 ecological source areas in the lower and east portions of the study area, mainly grasslands, forests, and water areas. Additionally, 40 ecological corridors, 48 ecological pinch points, and 75 ecological barrier points were generated, densely distributed in the east. The area was divided into five core functional zones. (4) Conclusions: Establishing ecological function zones and considering landscape changes from high-frequency human activities in spatial planning can lead to a more reasonable division of ecological restoration areas. Ecological function zone construction can enhance understanding of implementing ecological security patterns in national land planning and support national ecological security goals.

Keywords: ecological security pattern; ecological restoration; circuit theory; Beijing-Hangzhou Grand Canal in Shandong section

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1. Introduction

The intensifying conflicts between resources and the environment have sharply reduced high-quality habitats across the territory [1]. High-intensity development further diminishes the connectivity of landscape patches between regions, exacerbating the difficulties of species migration and accelerating the process of species extinction [2]. Therefore, strengthening research on ecological restoration zoning and spatial patterns and establishing a comprehensive ecological safety framework are crucial for mitigating these issues [3]. The studies of ecological restoration zoning (ERZ) strategies contribute to the protection [4] and enhancement of regional ecosystem services. Similar to protecting water and biodiversity, they are essential for maintaining ecological balance and human well-being. By identifying ecologically sensitive areas and ecological risk points, these strategies facilitate more effective management of ecological risks and decrease the adverse effects of human activities on ecosystems. Furthermore, the ESP optimizes land use and land cover (LULC) planning, ensuring harmonious coexistence between ecological protection and

economic development while providing scientific guidance for biodiversity conservation. Furthermore, Ecological Pinch Point (EPP) refers to areas that are crucial for ecological protection [5]. Ecological Barrier Points (EBPs) are regions where the movement of species between habitat patches is obstructed. These points can be identified by calculating the current recovery value after removing the obstacles. Eliminating these barriers can enhance connectivity between ecological sources [6], making ecological restoration necessary.

Research on constructing ecological security patterns (ESPs) has gradually developed a fundamental paradigm characterized by "ecological source identification, resistance surface construction, and corridor extraction". This universal framework has been widely applied in various contexts, including urban areas [7], mineral resource regions [6], watersheds [8], and arid regions [9], effectively regulating and maintaining regional ecological safety. Despite its critical role in ecological protection and resource management, this fundamental paradigm often remains limited to optimizing ecological structures and processes, overlooking the practical application of ERZ strategies [10]. Similarly, in the identification of ecological source areas (ESAs), one method involved the selection of highly beneficial regions based on a qualitative evaluation of the structural characteristics of the region, while another relied on comprehensive quantitative evaluations based on ecological connectivity [11], ecological sensitivity [12], and ecological relevance indicators [13]. However, these methods overlooked the adaptability of ERZ strategies in dynamic contexts [14]. Due to the synergistic effects of natural environmental changes and anthropogenic activities, the extent, connectivity, and ecological functions of ecological source areas, along with the survival and distribution patterns of species, are in an ever-changing state. These methods do not consider the adaptability of ERZ strategies in such dynamic contexts. Moreover, ecological critical nodes were often viewed as conflict areas in modern land exploitation and conservation, which was vital for understanding the concentrated regions of ecological flows and potential conflict zones. However, existing studies fail to adequately consider how to manage and mitigate these conflicts through ERZ strategies [15]. While constructing the pattern based on nodes aids in determining the significance of ESAs, further research may be required to explore how to integrate these concepts with ERZ strategies for more comprehensive ecological restoration and protection [16].

In summary, a notable limitation of the studies mentioned above is the omission of ERZ strategies within their research frameworks. Specifically, these studies tended to focus on individual ecological elements or isolated ecological issues, lacking a systematic and holistic consideration of ERZ strategies [17]. This absence of a cohesive strategy has resulted in an incomplete understanding of the optimized allocation of ecological spaces during urbanization [8]. To address this gap, we propose a novel integrated evaluation system—the ecological habitat safety corridors system. This system assimilates three key dimensions, habitat quality, landscape connectivity, and ecological safety patterns, to comprehensively identify critical ecological areas. The innovation of this integrated evaluation system lies in providing a more comprehensive perspective for ecosystem management and protection.

The Shandong Section of the Beijing-Hangzhou Grand Canal (BHGC-SS) lies at the canal's center, passing through five cities, Zaozhuang, Jining, Tai'an, Liaocheng, and Dezhou, with a total length of 643 km. With the tourism navigation capacity of BHGC-SS reaching higher levels, it has become a "golden waterway" driving regional economic development in recent years, and its economic and ecological values are increasingly highlighted. However, a succession of environmental problems, for example, the deterioration of habitat, landscape fragmentation, and the decline of ecosystem service functions, have emerged simultaneously. Therefore, on 3 August 2020, the Ministry of Ecology and Environment, the Ministry of Natural Resources, the National Development and Reform Commission, and the Forestry and Grassland Administration jointly issued the "Special Plan for Ecological

Environmental Protection and Restoration of the Grand Canal". As an essential component of the Grand Canal, the study of ESPs and ERZ strategy for BHGC-SS will hold significant academic value and practical significance by ensuring the integrity and connectivity of ecological spaces. As a key node in the ecological network, the study of this area helps optimize regional ecological flows and processes and enhance the connectivity and integrity of ecosystems; the study of this area promotes the integration of ERZ strategies with ESPs, providing innovative ideas for formulating comprehensive ecological management strategies, and helps achieve a double win situation for ecology, society, and economic benefits [18]. In summary, the research results can provide practical guidance for policymakers and managers, helping them protect ESPs while formulating and implementing effective ERZ strategies, contributing to regional ecological security and sustainable development [19].

Drawing from the BHGC-SS framework, this study develops a model for ESPs and explores the ecological consequences of land use and land cover changes [20]. The specific content of this study includes: (1) combine landscape Multi-scale Spatial Pattern Analysis (MSPA) to extract core areas, identify ecological source areas, and comprehensively examine habitat quality and landscape connectivity to characterize the ecological network; (2) construct a resistance surface by establishing a comprehensive index system that includes natural environment, socio-economic, and accessibility factors, and identifying ecological corridors based on circuit theory; (3) optimize and restore the ESPs using ecological pinch points (EPPs) and ecological barrier points (EBPs), divide ERZ, and provide corresponding strategies.

2. Study Area and Data Sources

2.1. Study Area

BHGC-SS is situated in the Shandong province of China. It is the section of the canal with the highest elevation, the highest density of locks, and the most concentrated water conservancy engineering achievements, holding a prominent strategic position (Figure 1). BHGC-SS belongs to the semi-wet and mild monsoon climate belt, which has clear seasons, and simultaneous rain and hot weather. Its annual rainfall is around 680 mm, and the mean annual temperature is 12.8 °C. As an important channel connecting Shandong with developed provinces and cities such as Jiangsu, Zhejiang, and Shanghai, BHGC-SS has been fondly called "Shandong's Rhine". Valley topography is inclined in general, from western to eastern areas. The main types of LULC are farmland and construction land, showing a clear gradient distribution.

2.2. Data Sources

This research was based on the data (Table 1). The primary datasets are as follows: (1) LULC type data: China's 2020 land cover dynamic dataset (https://doi.org/10.5281/zenodo.5816591 (accessed on 10 February 2024)); (2) DEM data is sourced from the Geospatial Data Cloud (http://www.gscloud.cn (accessed on 9 February 2024)).

DEM data: sourced from the Geospatial Data Cloud (http://www.gscloud.cn). The DEM data used in this study have a resolution of 30 m. This resolution was selected as it strikes a balance between providing sufficient topographic detail for the analysis of ecological processes such as surface runoff, slope determination, and identification of potential ecological barriers or corridors, while also being manageable in terms of data processing and storage requirements.

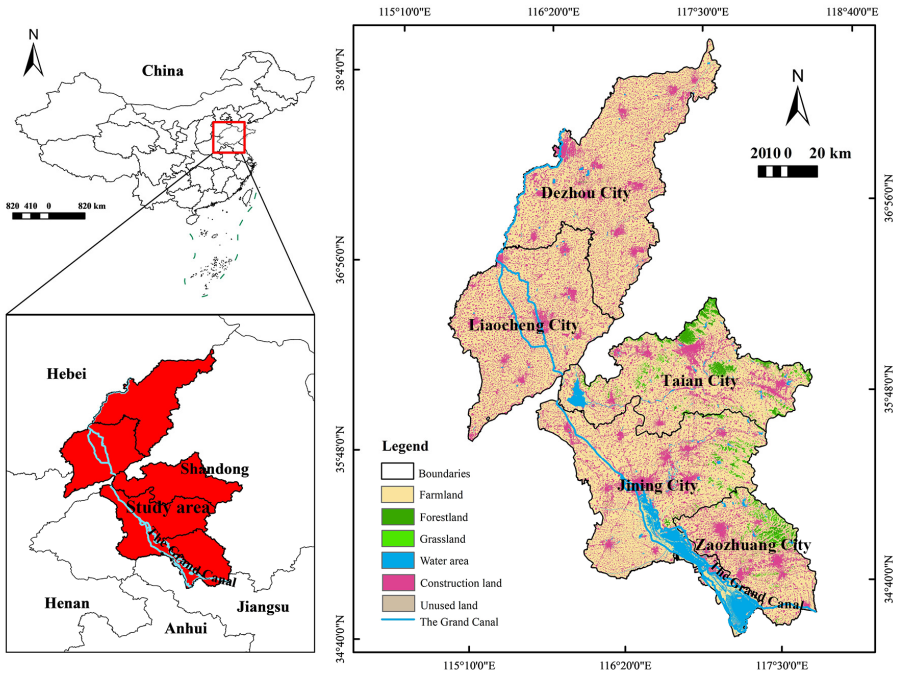


Figure 1. Administrative division and LULC map of BHGC-SS.

Table 1. Main data sources in this study.

Data Type	Data Name	Data Source
LULC data	LULC in 2020	Dynamic dataset of land cover in China for 30 years from 1990 to 2020 (https://doi.org/10.5281/zenodo.5816591 (accessed on 10 February 2024))
Natural environment	Elevation Aspect Aspect Soil type	Geospatial data cloud (https://www.gscloud.cn (accessed on 9 February 2024)) Elevation-based extraction China Soil Dataset (1:1 million)
Accessibility factor	Distance from the main river, distance from the main railway	(https://cgiarcsi.community (accessed on 9 February 2024)) Resource and Environmental Science Data Center of Chinese Academy of Sciences (https://www.resdc.cn (accessed on 9 February 2024))
Socio-economic data	Population density, gross domestic product (GDP)	Statistical yearbook, statistical bulletin

Population density data: we obtained the year-end permanent population and corresponding land area of each county-level administrative unit in the study area from the China Statistical Yearbook 2020. The population density was calculated as follows: population density (persons per square kilometer) = year-end permanent population of a county-level administrative unit/land area of the county-level administrative unit (square kilometers). During data processing, we ensured the accuracy and consistency of population and land area data. For possible administrative division adjustments or data missing, we revised them by referring to the supplementary materials of local government statistics departments or using reasonable estimation methods.

GDP data: also based on the China Statistical Yearbook 2020, we acquired the GDP values of each county-level administrative unit in the study area. To eliminate the influence of price factors, we deflated the data using the regional GDP index with 2015 as the base period. The specific calculation formula is real GDP = nominal GDP/(regional GDP

index/100), thus obtaining the real GDP data calculated at the constant prices of 2015. In terms of spatial allocation, we distributed the GDP data to the corresponding geographical spatial units according to the proportion of the land area of each county-level administrative unit in the total area of the study area, facilitating the subsequent analysis of the relationship between the spatial distribution of economic activities and the ecological pattern.

3. Methods

This research methodology is presented in Figure 2.

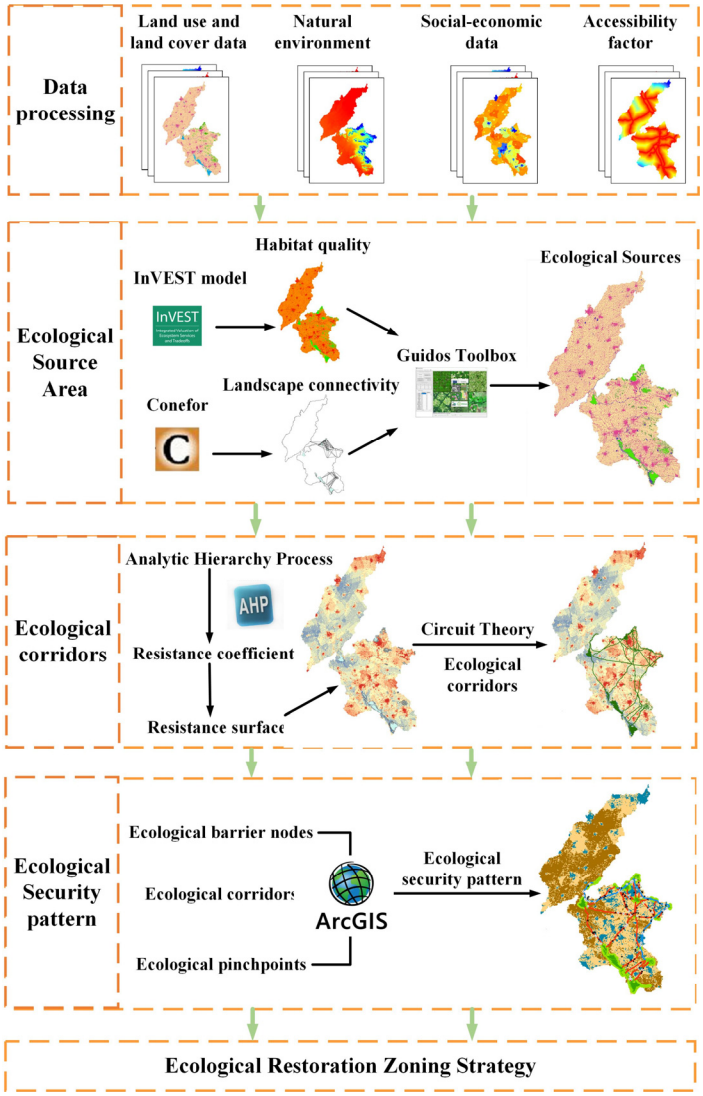


Figure 2. Methodological framework diagram.

3.1. Identification of ESA

ESAs are crucial patches of ecosystems, serving as stable habitats for organisms and the foundation for the flow and expansion of ecological elements, maintaining the integrity and connectivity of ecosystem services. Therefore, the scientific and accurate identification of ERZ is a first and basic precondition for building an ESP [21].

To this end, this research built an analytical approach for morphology and space for identifying ESAs. ArcGIS 10.8 software extracted the top 20 areas by core area size as ESAs.

3.2. Habitat Quality

Reviewing the literature in advance, organizing various threat source factors (Table 2) and ecological vulnerability (Table 3), and establishing habitat grid distance parameters concerning the proximity of habitat patches are essential. Through this method, the habitat quality component of the InVEST3.9.0 model is capable of determining both the habitat degradation index and the habitat quality index, which are then imported into ArcGIS 10.8. The configuration of parameters is guided by the model's assistance documentation and findings from prior InVEST3.9.0 igations [22]. The fundamental principle is delineated as follows:

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

where Q_{xj} denotes the habitat quality index for grid x within land use category j; H_j signifies the habitat appropriateness for land use category j; D_{xj}^z is indicative of the aggregate threat level for grid x within the j habitat; z serves as the default parameter of the model; and k is the constant proportionality factor.

Table 2. Habitat threat sources and related parameters.

Theart Factor	Max Impact Distance/km	Weight	Decay Type
Farmland	2.6	0.26	Exponential
Construction land	5.8	0.73	Linear
Unused land	2	0.25	Exponential

Table 3. Habitat suitability of LULC types and sensitivity to different threat sources.

LULC Type	Habitat Quality Score	Cultivated Land	Construction Land	Unused Land
Farmland	0.3	0.6	0.3	0.1
Construction land	1	0.6	0.4	0.2

In Table 2, the maximum impact distance of farmland is determined to be 2.6 km through on-site research, etc., as its agricultural activities significantly threaten the habitat within this range. For construction land, the 5.8 km distance is determined through long-term tracking, etc., due to the extensive influence of its development activities. The 2 km distance for unused land is set because of existing interferences and the apparent impact on the habitat within this range. The weight of farmland is 0.26, determined by its area proportion, impact degree, and comparison with other factors. The weight of construction land is 0.73, as its development causes habitat destruction and is a major threat factor. The weight of unused land is 0.25, as its threat degree is between the other two. The threat degree of farmland and unused land decays exponentially because the threat decreases rapidly with increasing distance, while that of construction land decays linearly because some of its influencing factors decay steadily. In Table 3, the habitat quality score of farmland is 0.3 due to human transformation resulting in single-vegetation, etc. The score of construction land is 1, which is a special setting or based on specific background assumptions. The score of construction land is set to 1. This is a special setting based on specific background assumptions, among which is the fact that construction land has essentially lost its ecological functions and significantly interferes with the surrounding ecosystems. Additionally, in the research, it is necessary to highlight its ecological problems and meet the requirements of data comparison. The sensitivity of farmland to cultivated

land is 0.6 because of their similarities. It is 0.3 to construction land, as it is less directly affected but has indirect impacts, and 0.1 to unused land due to weak ecological connections. The sensitivity of construction land to cultivated land is 0.6 because its expansion often encroaches on cultivated land, 0.4 to itself, as internal changes have impacts, and 0.2 to unused land, as it may be a potential expansion direction, etc. These numbers are based on on-site research, and the on-site research in this study combines field surveys, geospatial analysis, and long-term ecological monitoring to determine the ecological impacts of farmland (impact distance of 2.6 km), construction land (5.8 km), and unused land (2 km). For farmland, researchers assess habitat degradation through transect sampling and utilize remote sensing technology to quantify land use changes. The study of construction land employs multi-year satellite imagery analysis to monitor urban expansion and its ecological footprint while tracking wildlife movements to identify avoidance zones. Unused land is InVEST3.9.0 igated by analyzing historical land use records and assessing ecological recovery status. These methods effectively integrate empirical data to parameterize the InVEST3.9.0 model, demonstrating the researchers' solid grasp of ecological fieldwork protocols, and are comprehensively affected by various factors, providing a basis for habitat protection. The parameters for the threat sources in habitat quality assessment refer to previous research [23].

3.3. Ecological Landscape Connectivity

The calculation of landscape connectivity aids in identifying ecological patches with significant connectivity contributions within fragmented habitats, which can be prioritized for protection to maintain the migration of biological populations and the exchange of genes [24]. Multi-scale Spatial Pattern Analysis (MSPA) mainly relies on pixel-level recognition and processing to detect critical ecological patches and corridors that play crucial roles in landscape connectivity [6]. In ArcGIS 10.8, data preprocessing was conducted by categorizing LULC data, with forests, grasslands, and water areas assigned as the foreground and valued at 2, while the rest were considered the background and valued at 1. Subsequently, we employed data analysis in Guidos3.2.0, combined with the MSPA option to extract core areas, and utilized the Conefor 2.6 plugin in ArcGIS to analyze landscape connectivity. The equivalent connectivity range dynamically changed on a continuous spectrum from 0 to 1. Its growth rate was proportional to the connectivity improvement and did not depend on the specific distribution of adjacent habitat patches or cells in the analysis dataset. The precise calculation formula is as follows:

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

where m is the total number of ecological nodes; a_i and a_j are the attributes of nodes i and j, respectively; P_{ij}^{*} is the maximum product probability of all paths between patches i and j; and A_L is the attribute of the largest landscape. Within this framework, m denotes the aggregate count of ecological nodes; a_i and a_j correspond to the characteristics of nodes i and j, respectively; the product of P_{ij} and P_{ij} denoted as P_{ij}^{*}, signifies the utmost likelihood of connectivity across all potential routes interlinking patches i and j; and A_L embodies the characteristic of the most extensive landscape.

3.4. Construction of Ecological Landscape Resistance Surface

An ecological resistance surface can be established to show how easy or difficult it is to migrate a species in a realistic setting [25]. The evaluation results were used as a cost resistance surface, which, combined with cost distance, results in a minimal accumulation of resistance. To make the results more scientific, this study integrated a variety of natural and anthropogenic factors, selecting population density, distance to rivers, distance to

railways, LULC, DEM, slope, and GDP as resistance factors [26] (Figure 3). In constructing the ecological landscape resistance surface, population density, distance to rivers, distance to railways, LULC, DEM, slope, and GDP were selected as resistance factors. Population density and construction land indicate human activity intensity, with high-density human activities and construction land expansion causing habitat fragmentation and impeding species migration. DEM and slope represent terrain features, where complex terrains like high mountains and steep slopes act as natural barriers. The distance to rivers is crucial, as rivers are important ecological resources, and areas far from them pose challenges to species migration. GDP reflects economic development, and higher GDP-related activities can damage habitats and disrupt migration. The distance to railways matters because railway-related activities create disturbances, causing species to avoid nearby areas and fragment their habitats. Overall, these factors comprehensively represent the challenges species face during migration, which is essential for understanding ecological security patterns and formulating protection strategies. The Yaahp1.2.0 (https://www.metadecsn.com/ (accessed on 7 February 2024)) was used, and the weights for every resistance coefficient were determined by the Analytic Hierarchy Process (AHP) (Table 4). The calculation formula is as follows:

$$R = \sum_{i=1}^{k} (F_i \times W_i) \quad (3)$$

where R signifies the impedance level; F_i represents the coefficient of resistance associated with resistive element i; W_i denotes the relative importance of resistive element i; and k indicates the overall tally of resistive elements.

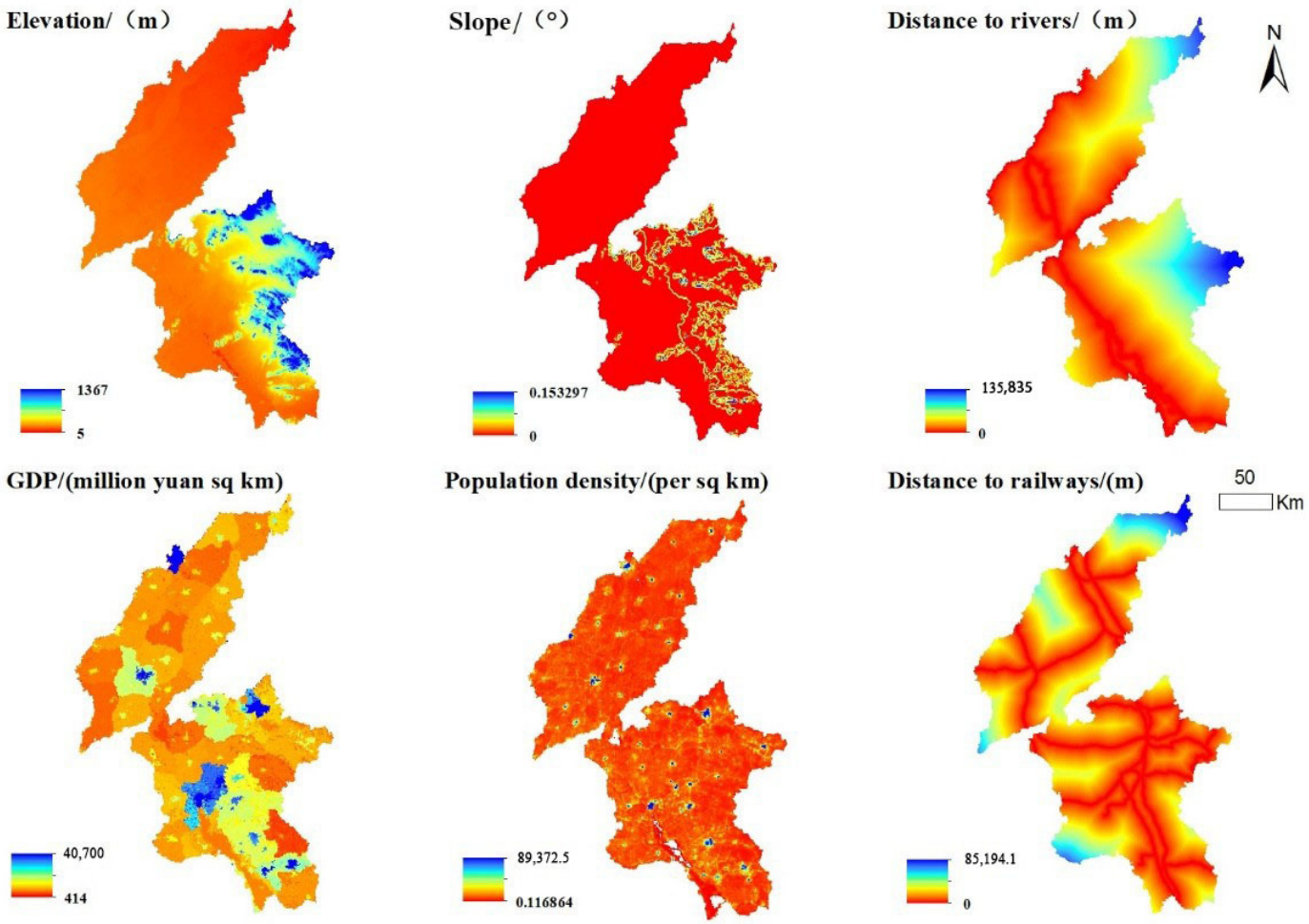


Figure 3. Driving factors in the study area.

Table 4. Ecological resistance values and weights.

Resistance Classification	Resistance Factors	Weights	Units	Resistance Coefficient				
				Level 1	Level 3	Level 5	Level 7	Level 9
Natural environment	DEM	0.0563	m	5–74	74–161	161–282	282–527	527–1367
	Slope	0.0397	(°)	0–0.5	0.5–1.7	1.7–3.6	3.6–6.9	6.9–16.9
Ecological resources	LULC	0.2960	—	Water area	Forestland	Grassland	Farmland	Construction land
	Distance to the river	0.0870	km	0–13.8	13.8–31.0	31.0–51.3	51.3–78.4	78.4–121.6
Social economy	Distance to the road	0.1305	m	0–5.8	5.8–12.7	12.7–20.7	20.7–32.0	32.0–55.0
	Population density	0.3289	people/km^2	0–1031	1031–3734	3734–10,216	10,216–30,864	30,864–89,372
	GDP	0.2072	K yuan	0–10.6	10.6–53.3	53.3–175.0	175.0–557.0	557.0–312.4

Using the reclassification tool in ArcGIS 10.8 software, the data were evenly divided into 5 grades, with resistance values assigned as 1, 3, 5, 7, and 9, and then a weighted sum was calculated to determine the complete ecological resistance surface for BHGC-SS.

In ecological research, using ArcGIS 10.8 software to classify data levels and assign resistance values has significant advantages. Dividing the data evenly into five levels can accurately reflect the complexity of the ecosystem. It can clearly distinguish areas with different ecological characteristics, such as core areas, transition areas, and marginal areas, avoiding information omission. At the same time, this classification is consistent with the actual ecological gradient, better reflecting the continuous change from ecological source areas to disturbed areas, making the analysis results more in line with the actual spatial distribution. In addition, the multi-level setting facilitates comparative analysis between different regions. It can intuitively present the distribution and proportion of each level, helping to evaluate the structure, and these values reflect the gradient change of ecological resistance, which helps to deeply understand the relationships between regions within the ecosystem and the dynamics of ecological processes. These accurate assignments also provide a solid foundation for weighted calculations. Combined with the weights of other factors, a more accurate ecological resistance surface can be obtained, thus more effectively serving ecological research and management.

Ecological corridors refer to green pathways that connect adjacent animal habitats or isolated, dispersed other ecological environments, facilitating the life, migration, diffusion, and exchange of organisms [27]. Establishing and maintaining ecological corridors can significantly reduce habitat fragmentation, thereby effectively protecting and enhancing biodiversity, and they are essential components in constructing ESPs. In circuit theory, landscape is equivalent to the representation of conductive surfaces, with low-resistance landscapes promoting species movement and high-resistance landscapes doing the opposite. An ESA is regarded as a circuit node, and the cumulative resistance of each link between two nodes is calculated based on the minimum cost path from the resistance surface. This study laid its foundation on circuit theory and utilized the Linkage Mapper1.0.1software to identify ecological corridors. It did so by mapping the lowest-cost connections between core areas using core habitat vector patches and resistance grids [2].

3.5. Optimization of ESPs

The ESA is a region that should be protected first, and it significantly affects the connection between the research areas. On the other hand, ecological barrier points (EBPs) hinder the migration of organisms and remove these areas, which can improve ecological connectivity and facilitate effective ecological restoration work. In this paper, the Pinchpoint Mapper1.0.0 of Circuitscape6.0 is applied to detect ecological pinch points (EPPs), and the Barrier Mapper1.0.0 is used to identify EBPs. This tool is based on circuit theory and MSPA. The theory is to model the connectivity of various landscapes with the properties of random charge walks. In this process, the landscape functions as an electrically conducting surface, with those which have the greatest permeability or are best suited for ecology will be given less resistance, whereas those which obstruct the ecology will be given greater resistance [28]. The Pinch Point Mapper is designed to detect high-current-density bottlenecks in an ecosystem [29]. The obstacle mapping component is specifically designed to identify areas where removing all obstacle points within a specific radius search area can significantly improve the score ratios. We divided the natural break method into four levels. Among them, the top point was identified as a key location for EPPs and EBPs.

Based on ESAs, a buffer zone with a radius of 3 km was set up for analysis to obtain ecological buffer zones. In the field of ecological research, the precise determination of corridor width is of great significance for maintaining the functions of the ecosystem. After comprehensive consideration, 3 km is selected as the optimal corridor width. From the perspective of species migration and dispersion, many animals and plants need continuous ecological space with a certain width during seasonal migration, searching for new habitats or expanding their territories. During long-distance migrations of large mammals and cross-regional flights of birds, corridors several kilometers wide are required to meet their needs, such as activities, rest, and foraging. A width of 3 km can just meet these basic requirements, effectively ensuring gene exchange and population stability among species. A width of 2 km is too narrow to meet the activity range of large animals, increasing the risk of contact with interference sources. A width of 5 km is too wide for small species, prone to causing waste of resources, and it will face more restrictions from human activities and land use challenges in practical planning. In terms of maintaining ecological flows, a corridor of this width is conducive to the stable transfer of material flow, energy flow, and information flow within the ecosystem. It can promote the two-way and efficient exchange of soil nutrients and water between rivers and land, ensure the reasonable distribution of vegetation for efficient absorption and conversion of solar energy, and provide sufficient space to transmit chemical and visual signals among organisms. However, a 2 km corridor will impede the material cycle and reduce the material exchange efficiency of the ecosystem. Although a 5 km corridor is beneficial for material transmission, it is likely to lead to unbalanced energy distribution and poor resource utilization in some areas. In the face of natural disasters such as fires and floods, as well as human-induced disturbances such as road construction and land development, a 3 km corridor has a stronger buffering capacity and can effectively protect the core ecological area. A 2 km corridor is insufficient to resist high-intensity disturbances and difficult to ensure the integrity of the ecosystem. A 5 km corridor responds slowly to local disturbances, easily expanding the scope of influence. Past research comparing the ecological benefits of corridors with different widths has found that when the width is less than 3 km, key functional indicators of the ecosystem, such as biodiversity and stability, significantly decline. When the width reaches 3 km or more, the ecosystem tends to be stable and good. When the width increases to 5 km, the improvement in ecological benefits is limited, but it brings greater pressure on land use resources and ecosystem management costs. Overall, a 3 km corridor achieves the best balance among ecological benefits, resource utilization, and practical feasibility. The

latest research indicates that urban ecological corridors are crucial for sustainable urban development, yet determining their optimal width remains a challenge. To address this, we established the functional connectivity threshold by integrating species distribution models with piecewise linear regression to delineate urban ecological corridors [30]. In future work, the authors of this paper will also explore the integration of these models to refine the determination of the connectivity threshold.

The remaining areas of the study area were classified according to the ecological tolerance of the natural break approach: transition zones, optimization zones, and management zones maximizing the differences between categories to optimize the ESPs of BHGC-SS.

4. Results

4.1. Identification of ESAs

The habitat quality range of BHGC-SS was [0.097, 0.940], and it could be seen from the habitat quality map (Figure 4) that the overall level was relatively low. Spatially, habitat quality was significantly correlated with LULC types. The ESAs were situated in the lower reaches of BHGC-SS. They had a scattered distribution in the eastern part of the region. The predominant land use types in these areas were water areas, forests, and grasslands. Low-grade areas were primarily found in urban centers. They were also sporadically present in towns and villages. In these low-grade areas, the land use was dominated by construction land with dense populations. Human activities were more intense in these regions, leading to a higher degree of threat to biodiversity. The remaining areas were characterized by cultivated land.

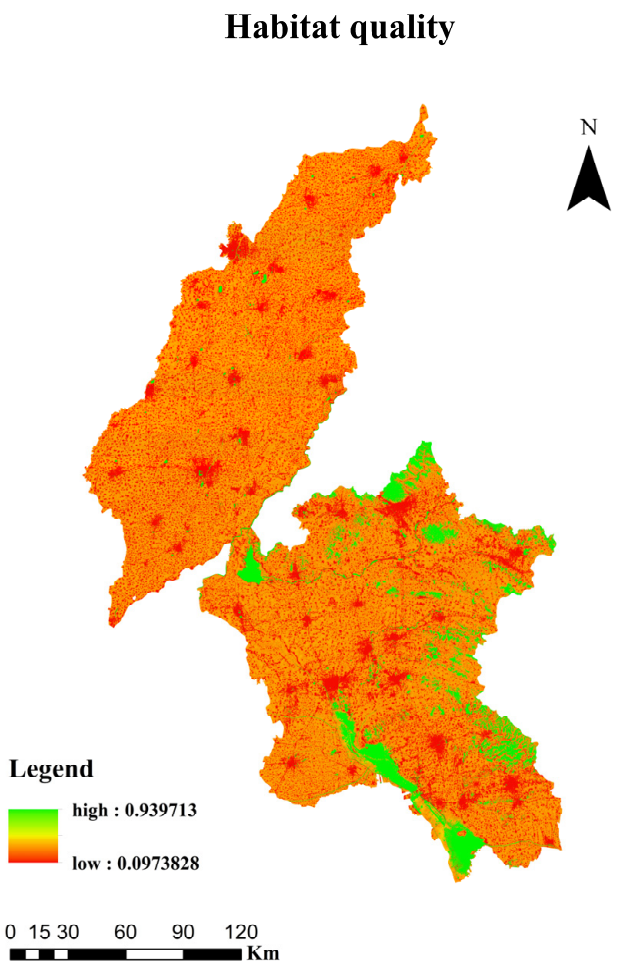


Figure 4. Habitat quality map for 2020.

The ESAs in the lower reaches of BHGC-SS were scattered in the east, mainly consisting of water areas, forests, and grasslands (Figure 5). Low-grade areas, concentrated in cities and sporadic in towns and villages, were dominated by construction land with high human activity and significant threats to biodiversity (Figure 6). From the perspective of spatial distribution, ESAs were mainly concentrated in the lake areas and eastern regions of BHGC-SS. At the landscape composition level, the main land use forms in the ecological source area were mainly water, forests, and grasslands, where water has a larger proportion, and forests have a smaller proportion than grasslands; regarding the distribution in administrative regions, Jining City had the highest number of ESAs, and most ESAs larger than 10 km^2 were distributed in this area.

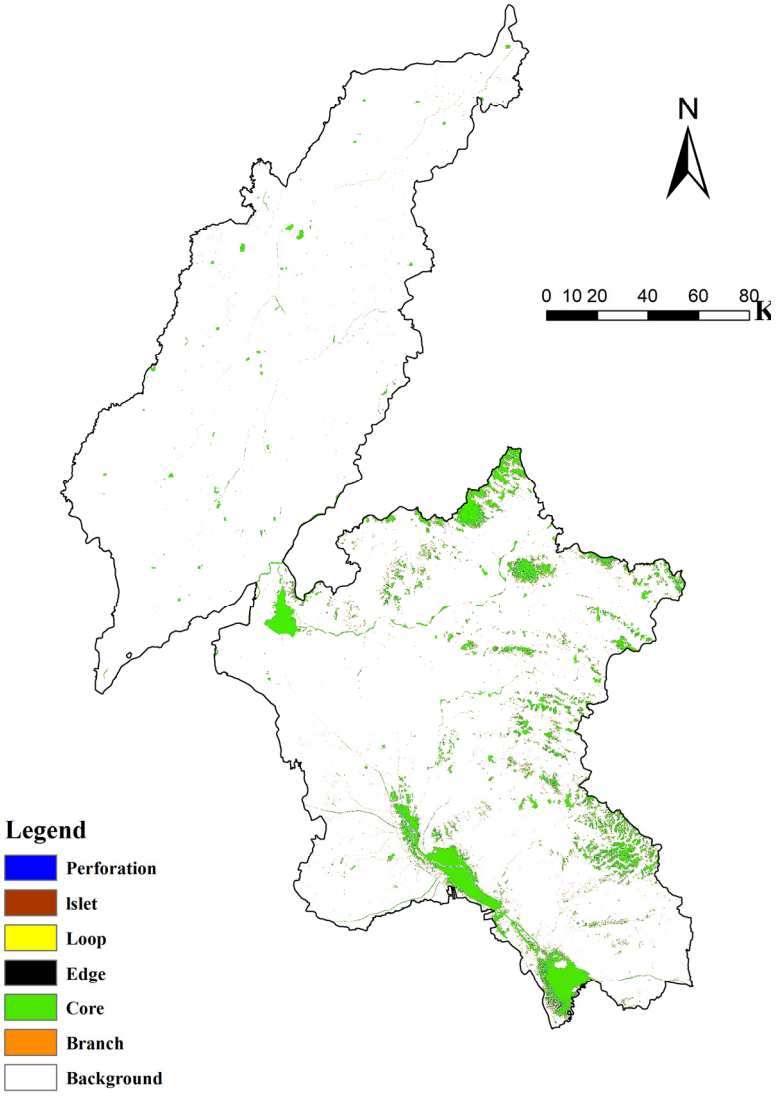


Figure 5. Landscape pattern analysis based on MSPA.

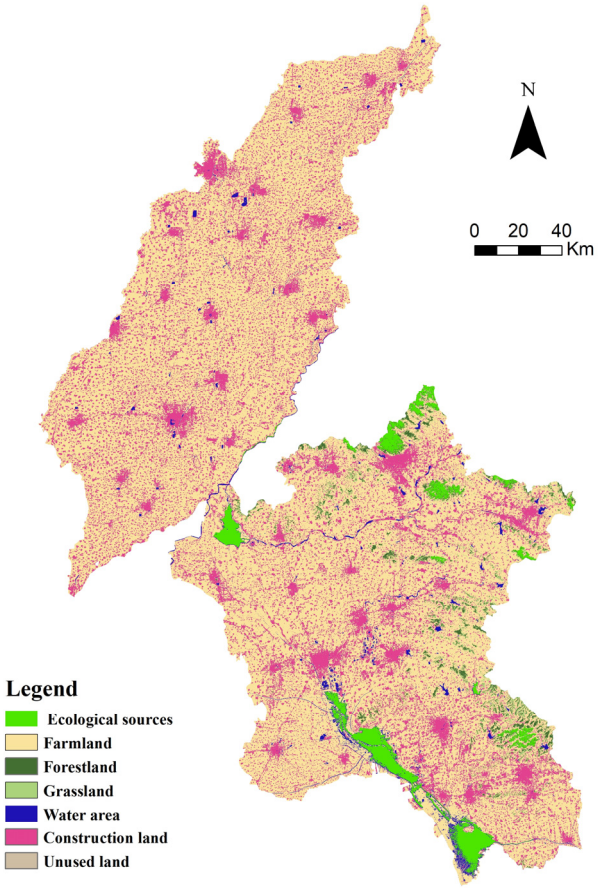


Figure 6. ESA map for 2020.

4.2. Selection of Ecological Corridors

The resistance surface constructed by integrating natural environmental, socio-economic, and accessibility factors can intuitively reflect the degree of obstruction species encounter during migration between ESAs [31]. The weight of natural environmental factors was high, reaching 0.50, among which the weight of LULC types was 0.1504. The highest resistance of BHGC-SS was 6.62, the minimum was 1, and the average value was relatively high. High values were mostly distributed in the construction land where the population was concentrated, indicating that frequent human activities posed a significant barrier to the flow of ecological processes. Low values were concentrated in the down-stream areas of BHGC-SS, as well as in the lake and east zones, which were consistent with the ESAs and demonstrated that the ESA classification was accurate and reasonable (Figure 7).

The basic ESPs include the ESAs and the ecological corridors. Ecological corridors enhance the connection of the region's landscape and its ecosystem by linking them together, and are the fundamental framework for maintaining regional ecological safety. In this paper, the Linkage Mapper1.0.11.0.1 was applied to detect the ecological corridors by simulating minimum-cost routes. The cost-weighted distance threshold of the shortening path is set to 30,000 by default. A total of 40 ecological corridors were generated for the 20 ESAs in BHGC-SS. The spatial distribution of ecological sources and corridors generated by this study is generally consistent with historical ecological monitoring data and field survey results. By overlaying the "Ecological Functional Zoning Map" and the "Biodiversity Survey Report" published by the Shandong Provincial Department of Ecology and Environment from 2015 to 2020, it was found that approximately 82% of the ecological sources (such as the Nansi Lake wetland and the Tai Mountain range) overlap with historical core protected

areas. The distribution of east–west corridors matches the bird migration route monitoring data with a degree of 76%, indicating that the model effectively reflects actual ecological processes. Local differences are mainly evident in areas of urban expansion (e.g., eastern Jining), where recent land development has led to the disappearance of some historical wetlands [32], and the model results focus more on optimizing current connectivity. It is recommended that future efforts combine remote sensing dynamic monitoring with species tracking data to further improve spatial matching accuracy.

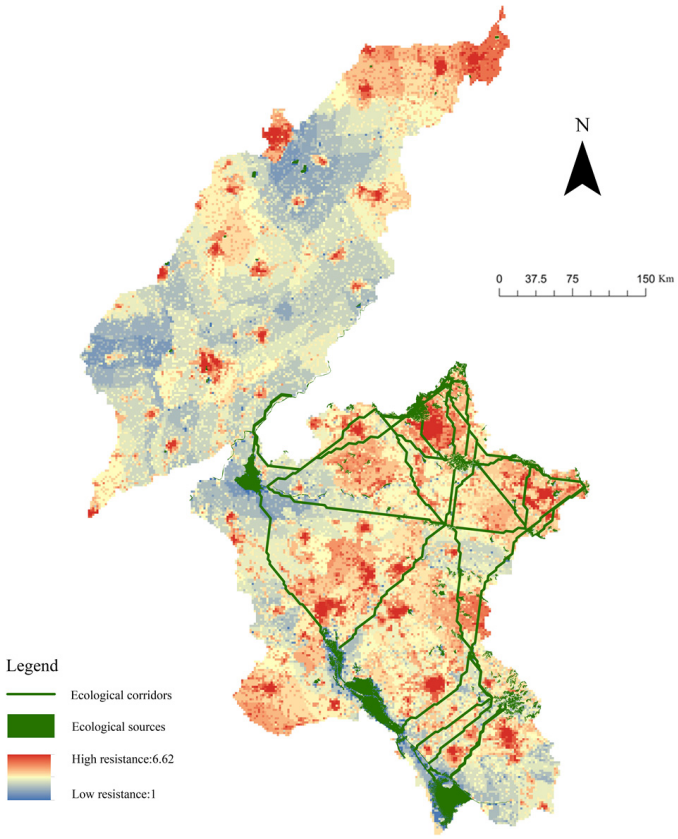


Figure 7. Ecological resistance surfaces and ecological corridors.

4.3. Construction and Optimization of ESPs

Ecological optimization seeks the equilibrium of exploitation of natural resources and conservation of the environment. In this paper, the ESP of BHGC-SS was established and optimized on the basis of the "ecological source area-ecological corridor-key node" model (Figure 8). The regulatory zoning results were divided into core areas, buffer areas, transition areas, optimization areas, and governance areas. The core area mainly refers to regions with high ecosystem integrity, rich biodiversity, and intact ecological functions in BHGC-SS. As the Shandong section is a transitional zone between the north and south climates, it is rich in animal and plant resources and wetland resources, and has a relatively complete water network system. The primary objective is to protect and recover the core ecosystem, maintaining its natural state and ecosystem service functions. It generally includes nature reserves, national parks, etc. The buffer area is set around the core area, adjacent to the core area, providing a protective barrier for the core area, reducing human activity interference, and maintaining the stability of the core area's ecosystem; ecologically sensitive areas, scenic spots generally belong to this category; transitional region lies between said buffer zone and said optimized zone. The primary objective is to harmonize the ecosystem functions between the central and optimized regions, promoting species migration and genetic exchange. It generally includes secondary

forests, wetlands, etc. The optimization area is located outside the transition area and exists to optimize the ecosystem structure and function and improve the ecosystem service capacity, generally including artificial forests, farmland, etc. The governance area has serious ecological and environmental problems and needs focused governance. Restoration of degraded ecosystems and improvement of environmental quality is essential. These include contaminated areas, disused mines, and so on. In this research region, there were 20 ESAs linked by 40 corridors, 48 EPPs, and 75 EBPs.

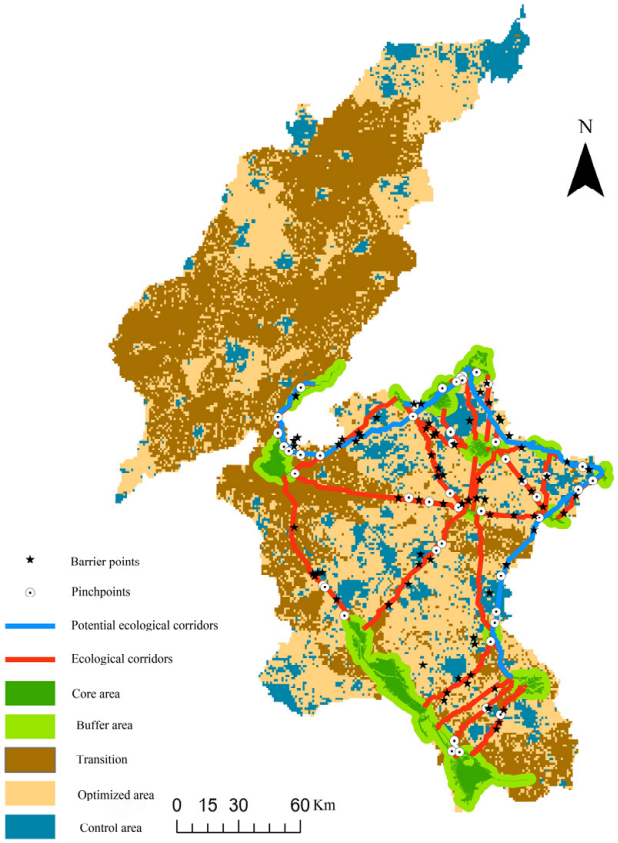


Figure 8. Optimization map of ESPs in 2020.

The ESAs of BHGC-SS are rich in vegetation, flora, and fauna, and excellent ecosystem services. They can be divided into three zones based on location: the lake area, the eastern area, and the northern area. Ecological corridors dominate the priority protection areas and form the basic framework of ESPs, determined by the position of the ESAs. Ecological corridors of the lake district extend from SW to NE, and the east regions had radial distribution. Obviously, there was a remarkable space difference among the corridors in this research region. First, they were dense in the south lake area, and compared with the eastern area, the ecological corridors were shorter and more concentrated, which were closely associated with the dense and scattered distribution of ESAs. Secondly, the area distribution was concentrated, with the top two ESAs accounting for a larger proportion.

The corridors can be divided into northern, middle, and southern corridors. The northern section functions as an ecological security safeguard corridor. Proximity to water sources enables enhanced construction of riverside vegetation to conserve water sources, protect water quality, connect ecological patches, and ensure biodiversity, thus maintaining the ecological security pattern at the source. The middle section serves as an ecological restoration and function enhancement corridor, where river restoration, construction of ecological buffer zones, and development of ecological industries are carried out to achieve a virtuous interaction between ecology and economy, optimizing

the ecological security pattern. The southern section acts as an ecological connectivity and landscape optimization corridor. It strengthens connectivity with surrounding ecosystems, constructs an ecological network, optimizes the landscape ecology, enhances aesthetic value and recreational functions, and promotes the coordinated development of ecology, economy, and society, providing support for the ecological security pattern. Each section of the corridor works in synergy to contribute to the ecological security and sustainable development of the area.

Key ecological corridors and nodes play an important role in linking ecological resources, and this research prioritized them as areas for ecological protection. Most of them were located in the east and south of BHGC-SS. Because the quantity and size of the water resources in the lake region and the east part of BHGC-SS were quite big, this study considered the nine ecological corridors connecting the two areas as potential ecological corridors, with the remaining 40 as ecological corridors. Because of its critical character, these priority recovery zones have important meaning for the ESPs in BHGC-SS and importance, and they require focused protection and restoration.

4.4. EZR Strategy

In this paper, we used the MCR model to compute the eco-resistant value of this region and classified it into 5 grades by nature breaking point. Finally, core areas, buffer areas, transition areas, optimization areas, and governance areas were delineated, and the corresponding measures and suggestions for each zone were proposed [33]. The core region was the background of ESAs, and it is essential to build ESPs. Therefore, it is important to focus on water source conservation and biodiversity protection in forests while also establishing the concept of balancing conservation and development, reasonably developing animal husbandry, formulating laws and regulations to supervise and standardize productive activities according to actual conditions, establishing an ecological monitoring network, regularly monitoring biodiversity and the health status of ecosystems, identifying problems promptly, and taking corresponding measures. At the same time, it strengthens public education and participation, raises people's awareness and motivation for ecological protection, and creates an atmosphere of ecological protection participation by the whole society.

In the study area, the distribution of ecological source areas is uneven. The Taishan Mountain range in Tai'an City, due to its rich mountain forest ecosystem and unique geographical conditions, forms large continuous patches, providing habitats for rare animals and plants. Around Nansi Lake in Jining City, the ecological source areas are distributed along the lake relying on the wetland, playing a crucial role in regulating the regional ecological environment. The ecological source areas in Dezhou, Liaocheng, and Zaozhuang cities are scattered in riverbanks, some mountainous regions, and undeveloped areas. Although small in area, they are significant for maintaining local ecological balance and promoting ecological connectivity.

5. Discussion

Based on this, for the Taishan Mountain range, it is necessary to strengthen the management of the core protected areas, restrict activities such as tourism development, build and maintain ecological corridors to promote species communication, and increase scientific research, monitoring, and ecological restoration efforts. For the Nansi Lake wetland, comprehensive protection of the ecosystem is required, including the treatment of surrounding pollution sources, the implementation of ecological function enhancement and restoration projects, and the encouragement of community residents to participate in the sustainable utilization of the wetland. Cities like Dezhou should integrate and connect scattered ecological source areas, construct ecological corridor networks, and

implement characteristic protection measures according to the characteristics of their respective ecological source areas. For example, Dezhou should strengthen the protection of riverbanks, Liaocheng should create wetland ecological parks, and Zaozhuang should carry out mine restoration and eco-cultural tourism. At the same time, extensive public education activities should be carried out to guide the public in participating in the protection and supervision of ecological source areas.

Through these measures, ecological source areas can be protected more effectively, ecological balance can be maintained, the sustainable development of the ecosystem can be promoted, and their comprehensive benefits in ecology, biodiversity, and the economy can be realized.

As one of the most important components of ERZ, it is necessary to make full use of the natural resources to guarantee ecological sustainability, implement clean energy, increase the construction of protective forests around ecological corridors and their surrounding lake areas, and safeguard the channels for biological migration and flow. At the same time, sustainable agriculture and ecological tourism should be promoted to protect the ecological environment while promoting local economic development. Establish a real-time water quality monitoring system by 2025, managed by the Shandong Provincial Department of Ecology and Environment, with automated sensors deployed at 50 key nodes along BHGC-SS. Data will be publicly accessible through a provincial platform, and quarterly compliance reports will mandate corrective actions for polluting industries. Additionally, a community-based 'River Guardian' program will be launched, training local volunteers to conduct monthly water sampling and report anomalies via a mobile app. Focus on the rectification of industrial pollution along the mainstream of BHGC-SS and important water areas, implement key rectification measures, and use the implementation of new environmental protection laws as a starting point to layout grid-based supervision, promote industry rectification, and clean up and upgrade cities and industrial parks along the river, close and relocate heavily polluting enterprises such as chemical, printing, and electroplating, and implement time-limited rectification for enterprises involving heavy metals, optimize the industrial pattern along the canal, and protect the water environment of the canal. The sewerage of cities and industrial areas along the Grand Canal should be taken as a key task in the construction of urban pipe networks, while rainwater and sewage diversion and network transformation should also be carried out to reduce the inflow of industrial sewage, domestic sewage, and surface runoff sewage.

The transition area can promote the construction of comprehensive protective forest systems in farmland and ecological restoration projects in farmland. Develop a 3-year phased agricultural training program (2025–2027) targeting 10,000 farmers across BHGC-SS cities. Workshops will demonstrate integrated pest management (IPM) techniques and subsidize organic fertilizer adoption. Collaborate with the Ministry of Agriculture to implement a 'Green Certification' system, offering tax incentives to farms reducing synthetic inputs by 30% annually, implementing river buffer zone non-point source reduction projects, and building various ecological green spaces to reduce the amount of non-point source pollution entering the canal from both the runoff volume and the degree of rainwater pollution. In typical agricultural areas, the government should build artificial wetlands and other natural treatment facilities to reduce the amount of pollutants entering the river. Achieve a virtuous cycle of agricultural production and the ecological environment while strengthening farmer training and technical support to improve farmers' awareness and ability to protect the ecological environment.

The optimization area and the governance area can carry out vegetation restoration and develop eco-rehabilitation programs, such as rehabilitation of wetlands, land reclamation, plant introduction, etc. In aquaculture areas, ecological breeding should be

implemented, feed input should be controlled, and the input of pollutants with feed should be reduced. Strengthen the restoration and reconstruction of landforms and ecosystems. At the same time, strengthen ecological environment monitoring and evaluation and adjust rectification measures in a timely manner to ensure the long-term stability of ecological restoration effects.

Existing studies, such as the analysis of habitat quality change trends, focus on ecosystem services and combine landscape connectivity or use ecological risk assessment to define key ecological areas. In this study, we have developed a comprehensive evaluation system that integrated habitat quality, landscape connectivity, and ESP, three key factors, to determine key ecological areas. This system comprehensively considers these three dimensions, aiming to avoid ecological deterioration, ensure the continuous and stable supply of ecosystem services, and protect the integrity of ecosystems.

The establishment of a resistance surface is the precondition to recognizing the ecological corridors. Most of the research has been carried out on the basis of LULC patterns for establishing eco-resistant surfaces. Some scholars used more indicators to improve evaluation accuracy and strengthen the interpretation of ecological resistance values [34], such as ecological vulnerability [35], impervious surface [36], and nighttime light index [37]. The relative magnitude of the resistance measures how difficult it is to migrate. There has been no unified standard for how to assign values in current research, but a multi-dimensional, multi-factor mainstream model has been formed; that is, each resistance factor is graded and assigned, and then the resistance value is obtained by weighted summation according to the weight [25]. This research chose seven kinds of resistant factors, such as LULC, DEM, gradient, GDP, population density, and the distance to the river and the rail, from the three-dimensional environmental, socio-economic, and accessibility factors for building a resistant surface.

This study employed circuit theory to identify ecological corridors to overcome the limitations of the MCR model in describing the random dispersal of species and identifying corridors within specific ranges. This strategy not only improved the accuracy of the model, but also significantly expanded its potential applications in actual ecological planning. Moreover, by introducing circuit theory, we can further refine the identification process of ecological corridors to ensure that the selected corridors are theoretically optimal, feasible, and effective in practical applications. These improvements significantly enhance the practicality and predictive ability of our model, enabling it to play a greater role in ecological protection and land planning.

The construction of canal ecological corridors has become a key point in urban ecological restoration. Nationwide, many large- and medium-sized cities have elevated the protection and control of the canal and its banks to an important agenda of government work to enhance the core value of the Grand Canal. In constructing eco-corridors, each section focuses on conserving soil and water, conserving water resources, retaining soil and water, and protecting forest construction. Rivers such as the Yellow River [38], Yangtze River [39], and so on, which are connected to the canal water system, have all been taking corresponding measures to protect and improve water quality and the ecological environment. Internationally, the experience of Thames River basin management emphasized the importance of the natural succession path and resilience threshold of ecosystems, as well as the necessity of comprehensive ecological restoration [40]; Panama City has taken forward-looking environmental protection measures in canal management, demonstrating a responsible attitude towards environmental heritage and promoting the transformation of the canal shipping industry towards a low-carbon and environmentally friendly direction [41]. In this study, the construction of ecological corridors for BHGC-SS focuses on overall measures, such as increasing green corridors and viewing corridors, relying on

geographical advantages and urban characteristics, and transforming and highlighting ecological and locational characteristics of cultural landscapes. By increasing the modernization of corridor infrastructure, maintaining public services, and developing new tourism resources, a limited spatial development concept is formed, enhancing the green mobility of the population in the area, which is conducive to the planning of green spaces crisscrossed by canals and other rivers.

The ESP can efficiently restrain the disorderly expansion of urban building land, optimize the distribution of urban ecological space, and offer guidance to restore the environment [42]. In this research, we consider the main factors of ESPs and ecological barriers and construct a basic framework with the "ecological source area-ecological corridors-key node" as the core, which provides an important reference for future studies. Based on the concept of the ESP, this study divides the areas along BHGC-SS into several functional areas, including core protected areas, buffer areas, transition areas, optimization areas, and governance areas. This zoning strategy aims to achieve a double-win situation for nature conservation and economic development, promoting the harmonious coexistence of urbanization and ecological environment protection. This study identifies key ecological corridors and critical ecological nodes identified as priority areas for recovery, with accurate conservation and recovery actions to effectively manage environmental sustainability.

The division strategy for ERZ is a necessary component in the regional development plan and eco-civilization building. It is a continuously evolving dynamic process in which policy direction and growth goals play a crucial role in the layout of spatial elements [43]. In response to the current static analysis limitations in ESP research, this study proposed a series of action recommendations based on the results of the regulatory zoning, aiming for long-term development and adaptive optimization of regional ecological security goals from dynamic, comprehensive, and visual perspectives. Designate core areas as 'No-Go Zones' under the National Ecological Red Line Policy, enforced by satellite surveillance and drone patrols. Deploy an AI-powered 'EcoWatch' 4.0 platform by 2026, integrating IoT sensors for real-time biodiversity tracking (e.g., endangered species habitats). Violations will trigger automatic alerts to local enforcement agencies, with penalties aligned with China's Revised Environmental Protection Law (2023), achieving dynamic, comprehensive, and visual modern management of protected areas.

Through this ERZ strategy, we would like to offer an integrated frame of ecosystem rehabilitation and administration in BHGC-SS and other cities, achieving the coordination between nature conservation and economic development and promoting harmony between city development and protecting ecology. Furthermore, this paper also points out its shortcomings and the key points for further study. (1) How to decide the weights of various elements in an eco-resistant surface. The selection of factors in this paper focuses more on the natural aspects, and it also needs to be corrected with other human factors such as the nighttime light index. (2) The current ecological corridors are only preliminarily screened through circuit theory and have not been further divided into different types of corridors through other indicators and targeted protection strategies [44]. (3) This paper has not discussed in detail the role of different levels of ecological pinch points and ecological barrier points and further screening work, which is the direction for future in-depth research.

6. Conclusions

This study took the five cities of BHGC-SS as the study region based on the main frame of the choice of source selection-resistance surface construction-corridor identification. Optimized and restored division of eco-critical points were increased, which offered a new way to construct an ESP. Applying MCR and circuitry in an integrated way to

identify eco-corridors and scientific factors can provide references for new ways to identify ecological corridors.

In the research of ecological security patterns, the traditional paradigm focuses on "ecological source identification, resistance surface construction, and corridor extraction", but it neglects to apply the ecological restoration zoning (ERZ) strategy. The methods for identifying ecological source areas also fail to consider the adaptability of this strategy in dynamic situations. Most traditional studies either qualitatively select ecological source areas based on regional structural characteristics or solely conduct quantitative assessments based on factors such as ecological connectivity. In contrast, the ecological habitat security corridor system constructed in this study innovatively integrates three dimensions: habitat quality, landscape connectivity, and ecological security patterns. Throughout all aspects of this research, the ERZ strategy is closely integrated, comprehensively considering the ecological characteristics and restoration requirements of different regions, thus providing a more systematic perspective for ecosystem management and protection.

Regarding ecological corridor identification, the traditional Minimum Cumulative Resistance (MCR) model struggles to accurately describe the random dispersal behavior of species, and has limitations in identifying corridors within specific ranges, resulting in poor feasibility in practical applications. This study introduces circuit theory, analogizing the landscape to a conductive surface, and determines corridors by calculating the cumulative resistance between nodes. This approach overcomes the limitations of the MCR model, significantly improving the accuracy of identification and its practical application potential and providing more operational guidance for ecological conservation and land planning.

This study comprehensively applies various methods to research the ecological security pattern. Each method has its applicability and certain limitations. In identifying ecological source areas, the morphological and spatial analysis method is constructed and used to extract areas based on the core area size in ArcGIS software. Although this method is easy to operate and can quickly screen large key areas, it heavily relies on high-precision LULC data. Otherwise, it is likely to lead to deviations in identifying source areas. Moreover, it fails to consider the internal quality of the ecosystem, making it easy to overlook small areas of high value. The InVEST3.9.0 model is adopted to evaluate habitat quality. This method can comprehensively consider the impacts of multiple threat sources and applies to areas with multiple land use types. However, data acquisition requires a large amount of threat source information, and the model parameters rely on empirical settings, which need to be adjusted in different regions. Improper settings will affect the accuracy of the results. MSPA and the Conefor 2.6 plugin are used to calculate landscape connectivity, which can identify key ecological patches and corridors and is applicable to fragmented landscapes. However, the classification and assignment of LULC data during data preprocessing affect the results, and this method focuses on landscape patterns, insufficiently considering the actual migration behavior of organisms. When constructing the ecological landscape resistance surface, multiple factors are integrated, and the Analytic Hierarchy Process (AHP) is used to determine the weights, which can comprehensively reflect the resistance to species migration. However, data collection is difficult, and the accuracy and resolution of multi-source data are inconsistent. At the same time, the determination of weights by AHP is highly subjective, and different expert judgments can lead to deviations in the weights. Ecological corridors are identified using the Linkage Mapper1.0.1 software based on circuit theory, overcoming the limitations of the traditional MCR model. However, this method has high requirements for the quality of resistance surface data, and the assumption that species migration is similar to the flow of electric current differs from the actual migration behavior of organisms, with insufficient consideration of various factors.

Until now, for various reasons, scholars have rarely studied the module of ecological restoration in the ecological governance plan of BHGC-SS. Based on the analysis of the ESP of BHGC-SS in 2020, this paper will put forward some strategic suggestions on the basis of each ecosystem recovery area. Though there are some shortcomings in this paper, the findings have great significance in policy and practice, which may be helpful in constructing ESPs and land use planning in BHGC-SS. This paper also makes up for the lack of the study on the ecological corridors and the ESPs in BHGC-SS, and can provide certain references for other similar areas.

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