Pol. J. Environ. Stud. Vol. 34, No. 4 (2025), 4445-4463
DOI: *10.15244/pjoes/190004* ONLINE PUBLICATION DATE: 2024-09-04

Original Research

Identifing Key Areas of Ecological Restoration for Karst Cities Based on Morphological Spatial Pattern Analysis: A Case Study of Bijie City

Lingling Zheng[1, 2], Yingping Dong[1, 2]*, Shibo Li[4], Zexi Fan[3], Shuangfeng Liu[1, 2]

[1]School of Karst Science, Guizhou Normal University, Guiyang, 550025, China
[2]State Engineering Technology Institute for Karst Desertification Control, Guiyang, 550001, China
[3]School of Geography and Environmental Science, Guizhou Normal University, Guiyang, 550025, China
[4]Guizhou Forestry Survey and Design Co., Ltd., Guiyang, 550001, China

Received: 17 April 2024
Accepted: 12 June 2024

Abstract

Guizhou province, situated in the heart of the Karst region in southwestern China, faces significant ecological fragility due to the intense human-environment conflict, resulting in severe ecological damage and posing challenges for restoration efforts. This study focuses on addressing the current issue of ecological restoration, particularly related to the shrinking of ecological source areas, in Bijie City, a typical mountainous city in the southwestern Karst region. To achieve this, morphological spatial pattern analysis (MSPA) and landscape connectivity indices are employed to identify ecological source lands. Additionally, the Minimum Cumulative Resistance model and circuit-theory based connectivity analysis are utilized to extract ecological source areas and corridors, among other features, which are then graded accordingly. Subsequently, using the "Linkage Mapper" tool, critical ecological nodes are identified to pinpoint areas in Bijie City that require ecological restoration. Based on the research findings, ecological zones are determined, and corresponding restoration strategies are proposed for Bijie City. The results indicate that: (1) Bijie City encompasses 62 potential ecological source lands, covering a total area of 3944.37 km^2, with 26 critical ecological source lands spanning 2643.35 km^2, and 36 general ecological source lands covering 1302.89 km^2. (2) A total of 147 ecological corridors, measuring 1333.99 km in length, are extracted, including 45 critical corridors spanning 353.44 km, 65 important corridors covering 869.15 km, and 37 ordinary corridors spanning 111.39 km, which can potentially form an ecological network pattern. (3) Fifty-four key ecological restoration areas are identified, comprising 23 key ecological pinch points and 31 key ecological barrier points. Consequently, it is recommended to divide Bijie City into key conservation zones, buffer zones, controlling zones, optimization zones, and corridor restoration zones for effective ecological restoration. Moreover, based on MSPA and other digital analyses, critical points are proposed to optimize the ecological security pattern in Karst areas.

Keywords: ecological security pattern, morphological spatial pattern analysis (MSPA), ecological-source-lands, ecological corridors, Karst

*e-mail: dongyingping2012@foxmail.com

Introduction

The Karst landform covers approximately 73.8% of the land area in Guizhou province [1], and it characterized by binary three-dimensional structures above and below the ground, fragile surface habitats [2], severe soil erosion, poor geological stability, and frequent occurrences of geological hazards like collapses and landslides [3]. Consequently, Guizhou province represents the most typical Karst fragile ecological zone and a potential high-rocky desertification area in southern China and even in the world [4].

Given the inherent ecological fragility and significant human-land conflicts in the Karst region, it has previously been a high-risk area for relapses into poverty in China [5, 6]. With the promotion of industrial poverty alleviation, it has, on the one hand, achieved notable success in eliminating poverty and lifting people out of poverty [7]. On the other hand, certain inappropriate poverty alleviation measures have caused damage to local ecosystem functions and ecological environment quality. Additionally, the urbanization process has accelerated the fragmentation of the natural landscape structure [8, 9]. Despite the rapid increase in forest cover over the past decade, the shrinking of ecological source areas and the disruption of ecological corridors, caused by natural or anthropogenic factors, have led to the destruction of plant and animal habitats and a decline in biodiversity [10, 11]. These issues continue to pose significant threats to the ecological security of the region and require urgent and timely restoration efforts to maintain the sustainable development of the regional socio-ecological system.

The formulation of large-scale ecological restoration plans in China currently involves considering local natural geographic patterns and climatic characteristics as a primary step while respecting the inherent laws and succession mechanisms of ecosystems [12]. To address regions with ecological damage, degraded system functions, and imbalanced spatial patterns and to rectify unreasonable development in agricultural, urban, or ecological areas, comprehensive analysis from the perspective of ecosystem services is imperative for national spatial ecological restoration [13]. Based on the identification of key issues, the central and local governments take the lead in exploring these issues and commission professional institutions or universities to conduct integrated planning. This is followed by the formulation of ecosystem restoration plans and the subsequent implementation of systematic ecological restoration by relevant construction units organized by local governments [14].

The ecological security pattern, also known as the ecological security framework [15], refers to the interconnected layout of ecosystems in a landscape. It consists of key localities that play a crucial role in the landscape, as well as their spatial linkages with other surrounding landscapes or corridors. The ecological security pattern comprises key points, lines, or areas and their connections with other landscapes or corridors nearby [16]. It serves as a prerequisite and foundation for promoting ecological restoration of the national land space. The ecological security pattern is important for maintaining or controlling specific ecological processes, such as plant and animal migration, in a given area. This, in turn, improves the stability of regional ecosystems and enhances ecosystem security [17, 18].

Currently, the basic paradigm for constructing ecological security patterns is mainly based on the concept of "source areas – resistance surfaces – corridors" [19]. Ecological source lands are pivotal patches that promote and sustain the stable operation of ecosystems within the ecological security pattern. They represent crucial areas that provide high levels of ecosystem service value [20]. The selection of ecological source lands can follow several pathways. For example, contiguous ecological areas with superior environmental quality, such as natural reserves, can be defaulted as ecological source lands [21, 22]. Ecological source lands can also be comprehensively selected by evaluating the ecosystem service value, ecological environmental quality, and ecological sensitivity of the study area [23–25]. Additionally, morphological spatial pattern analysis (MSPA) can be used, where raster data is employed to visually select contiguous green spatial patterns and structures to identify ecological source areas [26, 27].

In order to fully consider the impact of obstacles on the connectivity of ecological patterns, major obstacles such as land use type, vegetation cover, and slope are often selected as resistance factors to construct resistance surfaces [28]. The Minimum Cumulative Resistance (MCR) model is commonly used for this purpose [29]. It has also been used to correct the resistance surface using nighttime light data and the Human Settlement Composite Index [30]. However, these models fail to provide a reasonable explanation for the underlying mechanisms of ecological resistance as they cannot reveal internal differences in similar regions. Moreover, ecological corridors, which serve as pathways for ecological flows, play a vital role in the movement of materials and information between ecological source lands [31]. The ecological connectivity and resistance encountered by ecological corridors form a pair of action and reaction forces. Therefore, some scholars have drawn inspiration from the theory of resistance and consider favorable factors that promote ecosystem integrity and connectivity as ecological flows, similar to "electric current", and unfavorable ecological quality factors as "electrical resistance". As a result, the "electrical resistance method" has become popular for establishing ecological resistance surfaces and is widely used to identify potential ecological corridors [32].

The MCR model reflects the minimum cost distance for information exchange between source areas but falls short of effectively capturing the flow of ecological processes [33]. The electrical resistance method, on the other hand, simulates the flow processes of ecological flow based on the characteristics of electronic wandering, thereby addressing the shortcomings of previous methods in neglecting the different migration path selections of different species [34]. It serves as a supplement to the MCR model [35]. In the corridor selection process, the mainstream approach involves extracting corridors based on the MCR model, combined with the gravity model for corridor classification [36, 37]. However, this approach is complex and computationally intensive, making it unsuitable for research areas with dispersed and numerous source areas. The ratio of cost-weighted distance (CWD) to least cost path (LCP) in the electrical resistance method reflects the relative resistance along the path [38]. This ratio can indicate the importance of ecological corridors and compensate for the shortcomings of the MCR combined with the gravity model classification method. It also allows for a more convenient selection of key ecological corridors. Additionally, the resistance method can utilize the Linkage Mapper tool to identify ecological pinch points and ecological barrier points [39].

Bijie City, located in the upper reaches of the Yangtze River and Pearl River, serves as an important ecological barrier with widespread Karst landscapes and fragile habitats and faces prominent issues of rocky desertification. The unique binary three-dimensional structure of Karst, linking above-ground and underground, emphasizes the significance of surface safety for the upper reaches of large rivers. Additionally, Bijie City has the highest concentration of poverty in Guizhou Province and has paid a considerable ecological and environmental price in the process of poverty alleviation. Therefore, spatial ecological restoration in this city is crucial. This study takes Bijie City as a typical Karst City in Guizhou province and identifies ecological source lands through Morphological Spatial Pattern Analysis (MSPA) and landscape connectivity, combined with natural reserves. It selects six resistance factors, such as land use type and overlays, to construct comprehensive resistance surfaces. Ecological corridors and key areas for ecological restoration are then identified based on the electrical resistance method. This study aims to construct the ecological security pattern of Bijie City and provide scientific references for the planning of territorial ecological restoration.

Study Area and Data Sources

Study Area

Bijie City is located in the northwest of Guizhou province (105°36′–106°43′E, 26°21′–27°46′N). It covers an area of 26,900 km^2 and is divided into 8 county-level administrative units (Fig. 1). The city has a subtropical monsoon humid climate, with an average annual temperature of 13.4°C and an annual average precipitation ranging from 849 to 1399 mm. The region has a total surface water resource of 13.487 billion m^3, with the rivers in the area belonging to the Yangtze

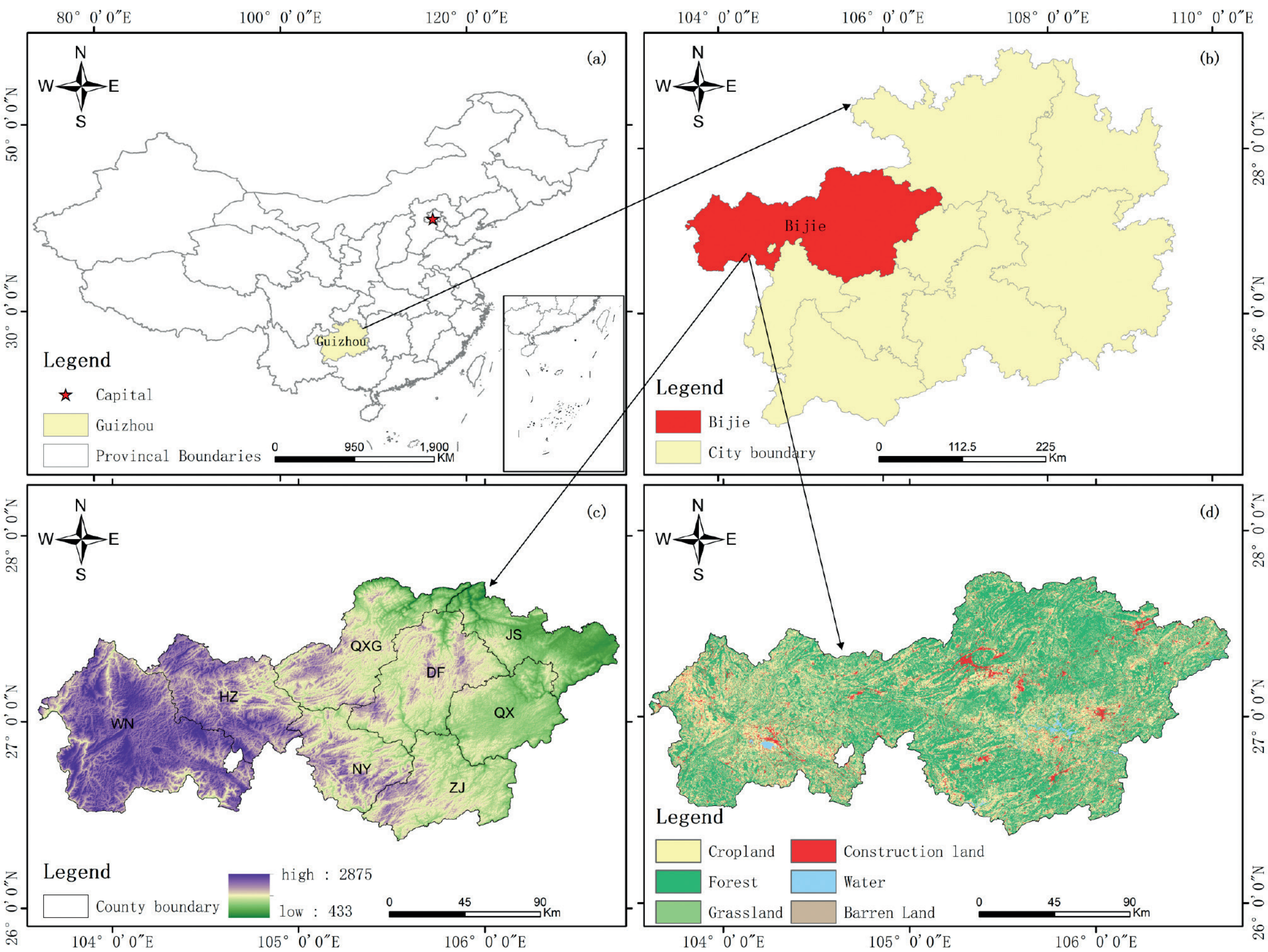

Fig. 1. Location map of the study area.

and Pearl River basins. The Yangtze River basin alone covers an area of 25,600 km^2, accounting for 95.3% of the city's land area [40]. The terrain of Bijie City slopes from west to east, characterized by complex topography and abundant Karst landforms. It is known for its vulnerable agricultural ecosystem, often referred to as the "eight mountains of water or sub-fields". As of 2022, the total population of Bijie City is 6.816 million, with a population density of over 250 people per square kilometer, which is twice the national average. It is the most populous and densely populated area in Guizhou Province. Bijie City holds the distinction of being the first central comprehensive experimental zone in China focused on poverty alleviation through development and ecological construction. This makes it a typical city in China's western development strategy.

Data Sources

The land use data and vector boundaries are obtained from the Bureau of Natural Resources and Planning of Bijie City. The NDVI (Normalized Difference Vegetation Index) data are sourced from the National Ecological Data Science Center, accessible at http://www.nesdc.org.cn/. The Digital Elevation Model (DEM) is acquired from the Geographic Spatial Data Cloud, available at http://www.gscloud.cn/search. The data on National Nature Reserves are obtained from the China National Nature Reserve Specimen Resource Sharing Platform, accessible at http://www.papc.cn/. The river and road data are sourced from the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, accessible at http://www.resdc.cn. All the above-mentioned data are projected in the WGS_1984_UTM_Zone_48N coordinate system. However, since the land use data are point data with insufficient continuity, the raster data resolution is corrected to 30m using bilinear interpolation resampling.

Research Framework

In this study, Bijie City is the focus area. The research methodology includes several steps. Firstly, core areas exceeding 10 km^2 are extracted for landscape connectivity analysis using the Morphological Spatial Pattern Analysis (MSPA) method. Ecological source areas are then identified based on the patch importance index. Secondly, six resistance factors, namely land use, vegetation coverage, terrain ruggedness, slope, distance to rivers, and distance to roads, are selected. The Analytic Hierarchy Process (AHP) and the ArcGIS platform are used to establish a comprehensive resistance surface. Thirdly, ecological corridors are extracted using the circuit method. This is based on the results of the analysis of the ecological source areas and resistance surfaces. The ecological corridors are then graded according to the ratio of cost-weighted distance to least cost path (CWD/LCP). Fourthly, a circuit-theory based analysis method is employed to identify ecological pinch points and barrier points. These critical areas are considered significant for ecological restoration. Finally, based on the findings from the previous steps and considering the natural ecological characteristics of the study area, ecological restoration zoning is conducted (Fig. 2). This zoning helps in determining the areas that require ecological restoration efforts.

Materials and Methods

Identification of Ecological-Source-Lands

Ecological-source-land is the core element of the ecological security pattern, as it provides important patches for the exchange and dispersal of ecological flow [41]. The selection of ecological-source-land should consider important principles, including high ecosystem service value, favorable habitat quality, and landscape connectivity [42]. National-level nature reserves, which serve functions such as species protection and ecological process maintenance, play a vital role in providing habitats for species and promoting their interaction. These reserves possess high ecological functionality and can be directly chosen as ecological-source-lands [43]. MSPA (Multiscale Patch Analysis) is a method based on digital morphology principles that measures, identifies, and segments the spatial pattern of raster images. It can identify areas that contribute significantly to landscape connectivity at the pixel level, making the selection of ecological-source-lands more scientifically grounded [44, 45]. Therefore, this study considers both ecological functionality and spatial structure [46]. By selecting national-level nature reserves and employing MSPA and landscape connectivity methods, ecological-source-lands can be identified more accurately.

Identification of Landscape Elements through the MSPA Method

Based on the current land use data of Bijie City in 2022, the data is rasterized using ArcGIS 10.6 software to extract forest land, grassland, and water bodies with high ecosystem service values as foreground elements for MSPA analysis. Cultivated land, urban areas, and bare land are considered the background [47]. The Guidos Toolbox software is then used to apply an octagon-analysis approach, resulting in the identification of seven landscape types: core zone, island-like patch, hole, edge, branch-line, circle, and bridge [48] (Table 1). Among these, the core zone, characterized by the highest ecological suitability and richest biodiversity, is considered the primary alternative area for ecological source sites.

Studies have shown that only patches of a certain size can positively contribute to the maintenance of ecological security [49]. In this study, important core areas are selected based on their size and distribution for landscape connectivity analysis, aiming to assess their significance and potential as ecological source areas.

Screening Ecological-Source-Lands Based on Landscape Connectivity

Landscape connectivity refers to the extent to which the structure of terrestrial landscapes facilitates or impedes

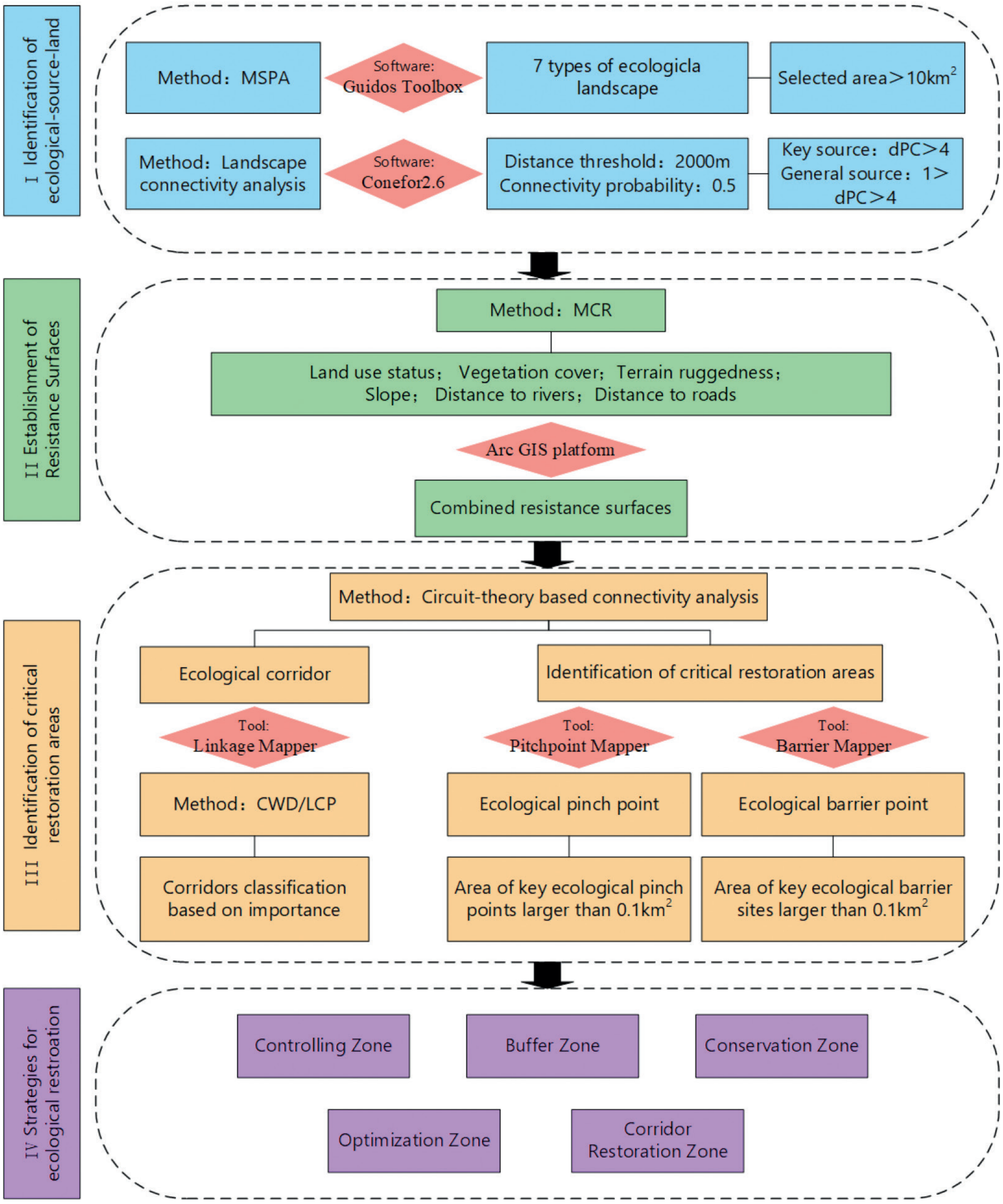

Fig. 2. Research framework.

Table 1. Meaning of MSPA landscape types.

Landscape types	Ecological implications
Core Zone	Larger habitat patches in the foreground image provide larger habitats for species and are ecological-source-lands in ecological networks.
Island	Isolated, fragmented and poorly connected small patches that are not connected to each other, with less potential for internal material and energy exchange and transfer.
Hole	Transition areas between core and non-green landscape patches, i.e. internal patch edges (edge effects).
Edge	Transition area between the core area and the main non-green landscape areas.
Circle	Corridors connecting the same core area, shortcuts for species migration within the same core area.
Bridge	Narrow areas connecting to the core, corridors connecting patches in the ecological network.
Branch-line	Areas connected to edge, bridge, circle or pores at one end only.

Table 2. Grading and weight assignment of ecological resistance factors.

Resistance factors	Resistance value					Weight	References
	1	3	5	7	9		
Land use type	forest,water body	grassland	cultivated land	bare land	construction land	0.276	[58]
Vegetation cover	> 0.72	0.58–0.72	0.42–0.58	0.20–0.42	< 0.20	0.138	[59]
Terrain ruggedness	< 18	18–30	30–46	46–71	> 71	0.109	[60]
Slope	< 4.27	4.27–12.64	12.64–23.55	23.55–38.48	> 38.48	0.087	[61]
Distance from rivers	< 500	500–1000	1000–1500	1500–2000	> 2000	0.195	[62]
Distance from roads	> 1000	800–1000	500–800	500–200	< 200	0.195	[58]

biotic flows, and its strength can be used to judge the degree of connectivity between patches as well as to reflect the spatial structure of ecosystem landscape elements [50–52]. This study uses the probable connectivity index (PC) and the patch importance index (dPC) to analyze the level of connectivity of core areas and their importance to landscape connectivity. Utilizing Conefor Sensinode 2.6 software, 2000m is selected as the distance threshold based on the core patch size and distribution in the study area, and the connectivity probability is set to 0.5. The formulas for calculating PC and dPC are as follows:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i \cdot a_j \cdot p_{ij}^{*}}{A_L^2} j \tag{1}$$

$$dPC = \frac{PC - PC_{\text{remove}}}{PC} \times 100\% \tag{2}$$

In this formula, n stands for the total number of patches in the study zone, a_i and a_j corresponds to the areas of patches i and j respectively, while p_{ij}^{*} represents the highest path connectivity between patches i and j. PC_{remove} is the value of the likelihood connectivity index for a given patch removal. The larger the dPC value, the greater the connectivity importance of the patch.

Construction of the Ecological Resistance Surface

The ecological resistance surface, a virtual resistance surface mirrors the challenges and impediments encountered by species during migration in reality [53]. The construction process unfolds as follows: Initially, comprehensively considering the impacts of the natural environment, topography, and anthropogenic activities in the study area, six indicators, namely, land use type, vegetation cover, terrain ruggedness, slope, distance from rivers, and distance from roads, are selected as the resistance factors for the ecological-source-lands. Subsequently, the range of values for these factors is set to be between 1 and 9 [54–57], where higher values indicate greater resistance and vice versa. Finally, the Analytic Hierarchy Process (AHP) and leveraging the natural breaks method available in the ArcGIS platform are used to grade and assign weights to each factor (Table 2), and the weighted summation is calculated to obtain the integrated resistance surface.

Extraction of Ecological Corridors

The ecological corridor plays a crucial role in facilitating the smooth movement of matter, information, and energy between ecological source areas [63]. It also serves as a low-resistance pathway for ecological flows between neighboring ecological source areas [64]. By combining the connectivity model with the random-walk theory in the electrical resistive method, this study provides a more accurate evaluation of least-cost paths. Areas with higher current density indicate better connectivity and lower ecological resistance in the region [65]. Therefore, the electrical resistive method is employed to extract the ecological corridors in the study area. The Linkage Mapper plugin in ArcGIS 10.6 is used to extract the least costly path that connects the two ecological source areas, which serves as the ecological corridor.

Identification of Key Areas for Ecological Restoration

Ecological pinch points (PinchPoints) are critical locations for biological migration that, when degraded or obstructed, have a significant impact on ecological stability. From the perspective of electrical current theory, pinch points are landscape patches characterized by high current density and low resistance. They can be considered “bottleneck zones” that influence landscape connectivity, and their degradation or loss can potentially disrupt habitat connectivity [66]. Ecological barriers, on the other hand, are resistance points that impede normal ecological flow. Restoring high barrier points can enhance the connectivity of the natural landscape and ensure the smoothness and integrity of biological migration processes [67]. Therefore, this study focuses on identifying and analyzing ecological pinch points and barriers to identify key areas for

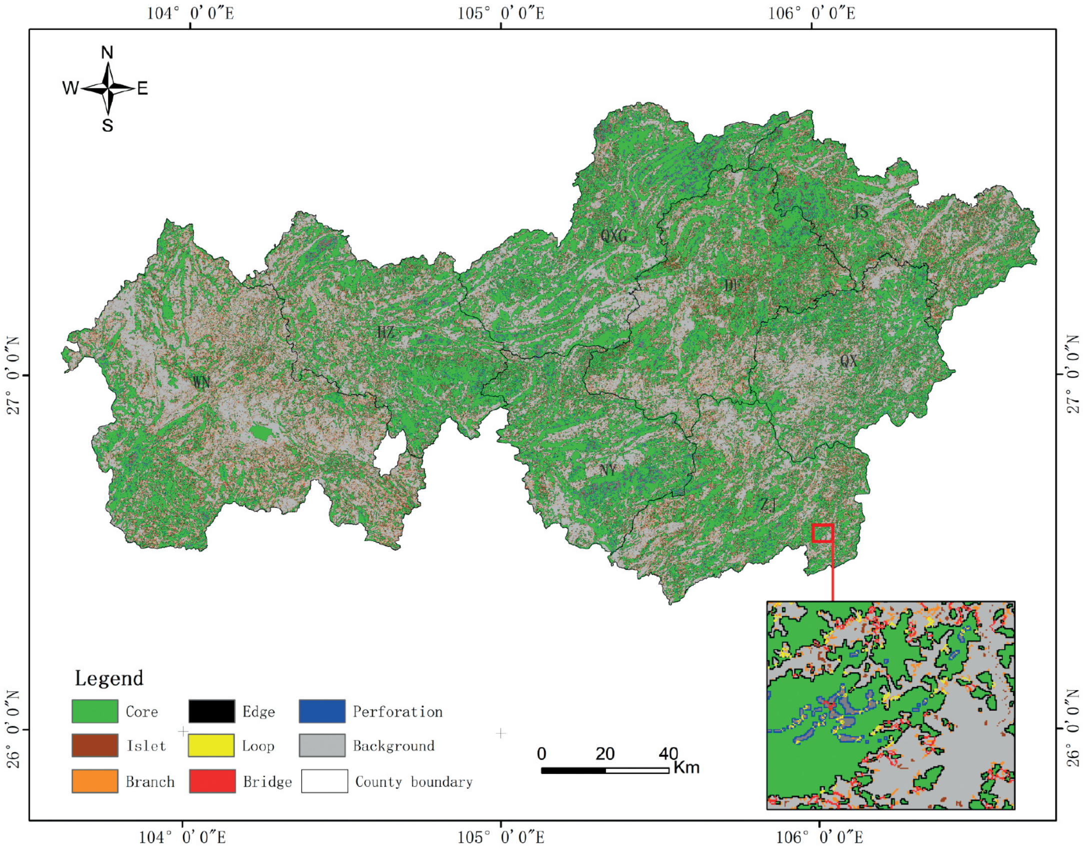

Fig. 3. Distribution of MSPA landscape types in Bijie.

ecological restoration in the study area [68]. The Pitchpoint Mapper mode of the Circuitscape plugin is employed for identifying ecological pinch points, while the Barrier Mapper module is used for identifying ecological barrier points.

Results and Analysis

Identification of Ecological-Source-Lands

MSPA Model Identification

According to the results of the Multi-Scale Patch Analysis (MSPA) shown in Fig. 3 and the statistical data analysis of landscape types presented in Table 3, it is evident that the core area of Bijie City covers 60.98% of the foreground landscape area, making it the predominant landscape type in the MSPA model. The core area is primarily located in the northern and central regions of Bijie City, characterized by a significant degree of fragmentation. The edge and hole areas, serving as transition zones both within and outside the core area, contribute to its protection and account for 20.81% and 2.43% of the foreground landscape area, respectively. When combined, their area is second only to that of the core area, indicating that the core area of Bijie City exhibits better stability and a stronger edge effect. The bridge and branch-line areas function as connectors between landscape patches, representing 4.98% and 6.52% of the foreground landscape, respectively. The bridge area plays a crucial role as a pathway for species migration, information exchange, and energy flow between core areas [69]. However, the proportion of bridge zones is relatively low, which is not conducive to species migration and exchange. Therefore, future efforts should focus on the protection and enhancement of connectivity in bridge zones in order to construct ecological security. The circle areas constitute the smallest proportion among various landscape types, accounting for only 2.04%. Island landscapes serve as stepping stones for species migration but occupy a relatively small proportion, comprising only 2.23% of the total area.

Selection of Ecological-Source-Lands

After conducting the MSPA analysis, patches with a core area larger than 10 km^2 are selected and imported into Conefor2.6 for landscape connectivity calculation. By combining the results of the patch importance analysis presented in Table 4 with the current national-level nature reserves and the actual situation of the study area, a total of 62 patches are identified as ecological source lands (Fig. 4), with a combined area of 3944.37 km^2. Among these patches, those with an area larger than 20 km^2 and a dPC

Table 3. Statistics on the area and percentage of MSPA landscape types in 2022.

Landscape types	Area (km^2)	Percentage of foreground landscape(%)	Percentage of overall landscape(%)
Core Zone	9138.16	60.98	34.04
Island	334.39	2.23	1.25
Hole	364.29	2.43	1.36
Edge	3119.03	20.81	11.62
Circle	305.90	2.04	1.14
Bridge	745.91	4.98	2.78
Branch-line	977.21	6.52	3.64
Total	14984.88	100.00	55.82

Table 4. Landscape connectivity of ecological-source-lands.

Patch number	dPC	Area (km^2)	Patch number	dPC	Area (km^2)	Patch number	dPC	Area (km^2)
1	35.10	431.26	20	4.53	41.14	39	1.97	21.72
2	29.17	96.27	21	4.33	25.57	40	1.94	58.40
3	28.79	168.90	22	4.05	75.73	41	1.93	10.55
4	24.69	240.78	23	4.03	20.29	42	1.76	31.34
5	23.94	291.29	24	4.02	19.07	43	1.49	27.68
6	21.00	366.92	25	3.86	15.64	44	1.43	32.75
7	20.23	55.53	26	3.84	105.09	45	1.43	29.31
8	19.12	181.87	27	3.82	36.70	46	1.36	14.82
9	11.38	18.52	28	3.46	17.01	47	1.33	39.58
10	11.08	31.97	29	3.26	11.12	48	1.32	26.80
11	10.67	10.17	30	3.22	50.97	49	1.24	38.87
12	10.21	31.85	31	3.13	57.52	50	1.24	25.89
13	9.04	59.42	32	2.82	13.90	51	1.11	24.94
14	8.03	20.59	33	2.68	105.02	52	1.08	14.06
15	7.12	103.37	34	2.59	15.43	53	1.08	13.14
16	7.09	34.55	35	2.49	19.11	54	1.07	19.39
17	6.47	19.25	36	2.36	50.54	55	1.02	21.76
18	5.77	31.82	37	2.30	46.38	56	1.02	29.95
19	5.60	37.34	38	1.98	43.87	57	1.01	123.02

(patch importance index) greater than 4 are selected as key ecological source lands, in addition to the national-level nature reserve patches. This results in a total of 26 source areas with a combined area of 2643.35 km^2, accounting for 67% of the total source area. These key source areas are mainly distributed in the QXG district, DF, and NY counties in the northern, central, and southern regions of Bijie City. Patches 61 and 62 correspond to the Rare and Endemic Fish Nature Reserve and the Caohai Nature Reserve in the Bijie segment of the upper reaches of the Yangtze River, respectively, with a combined area of 229.72 km^2, representing 5.82% of the total source area.

Additionally, patches with an area larger than 10 km^2 and 4 > dPC >1 are identified as important ecological source areas, resulting in 33 source areas with a combined area of 1191.49 km^2, accounting for 30.2% of the total source area. These areas are primarily located around the key source sites, with a few patches also found in the western region of Bijie City. Notably, patches 58, 59, and 60 in the western region of Bijie City hold significant positions, each with an individual area exceeding 10 km^2. Considering the spatial distribution structure of the landscape pattern in the western region, patches 58, 59, and 60 are chosen as important ecological source

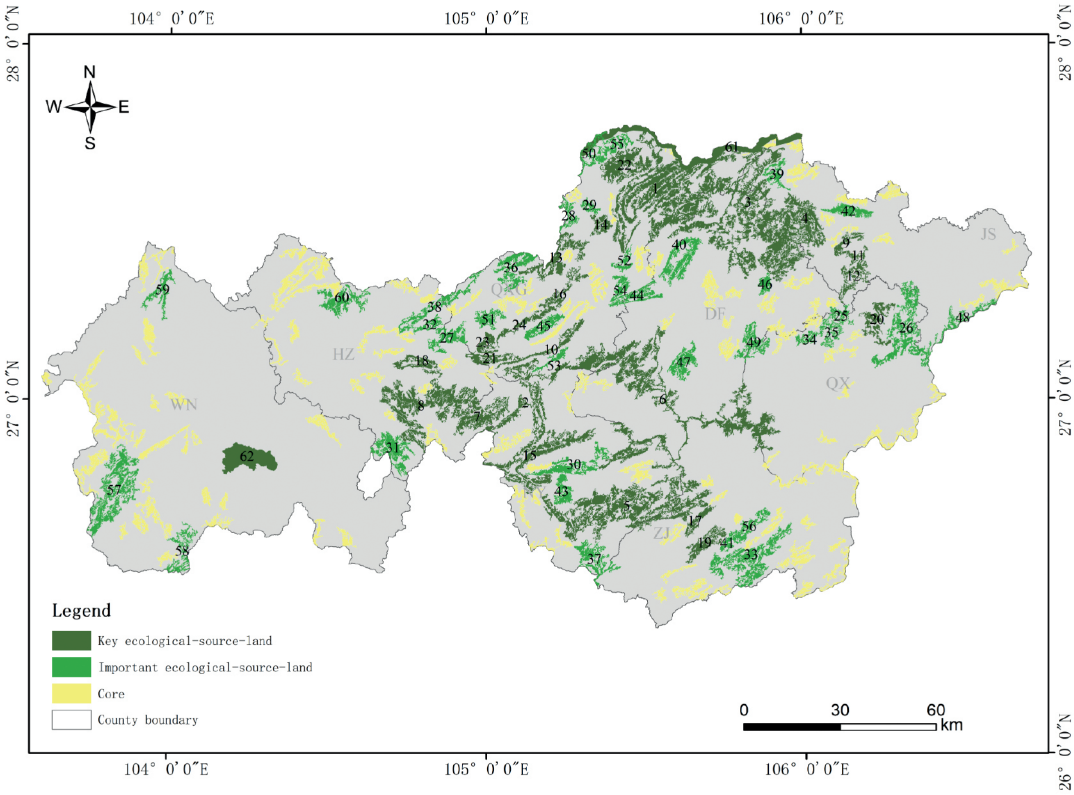

Fig. 4. Distribution map of ecological-source-lands in Bijie.

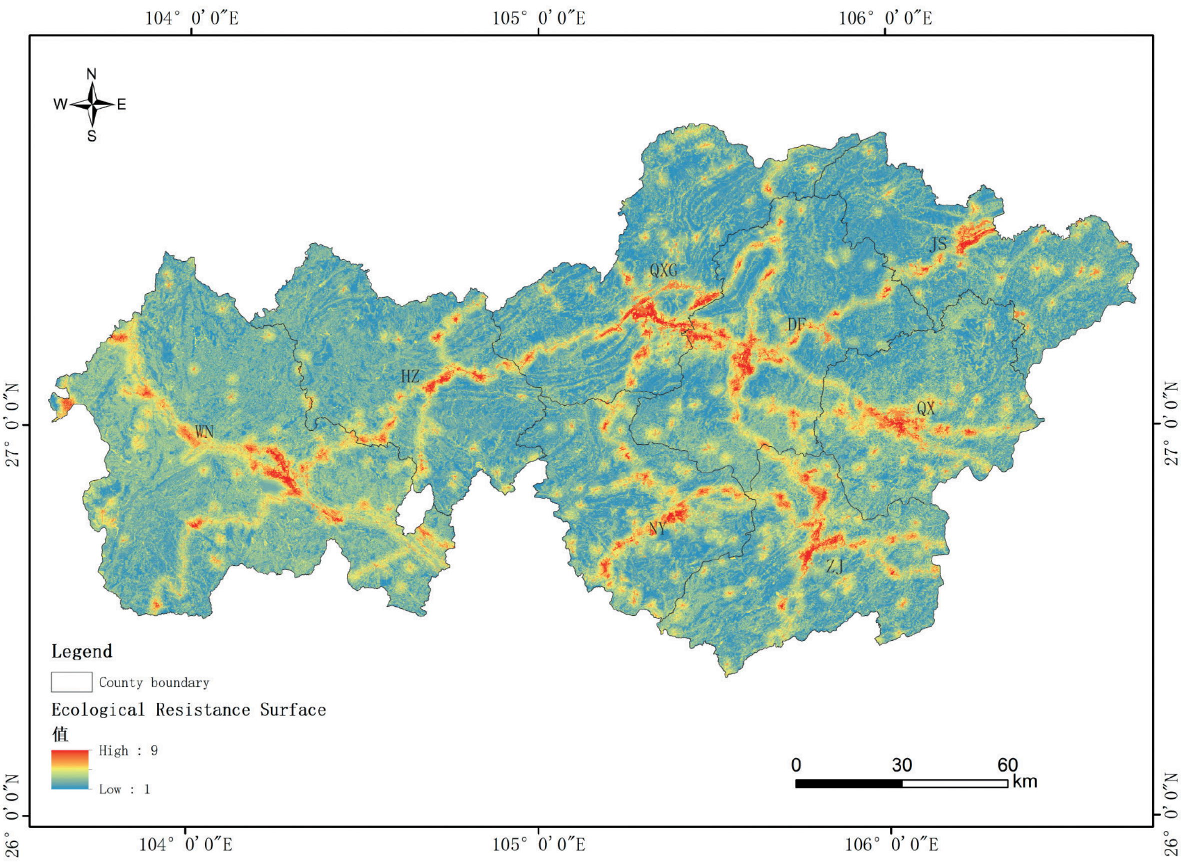

Fig. 5. Comprehensive resistance surface.

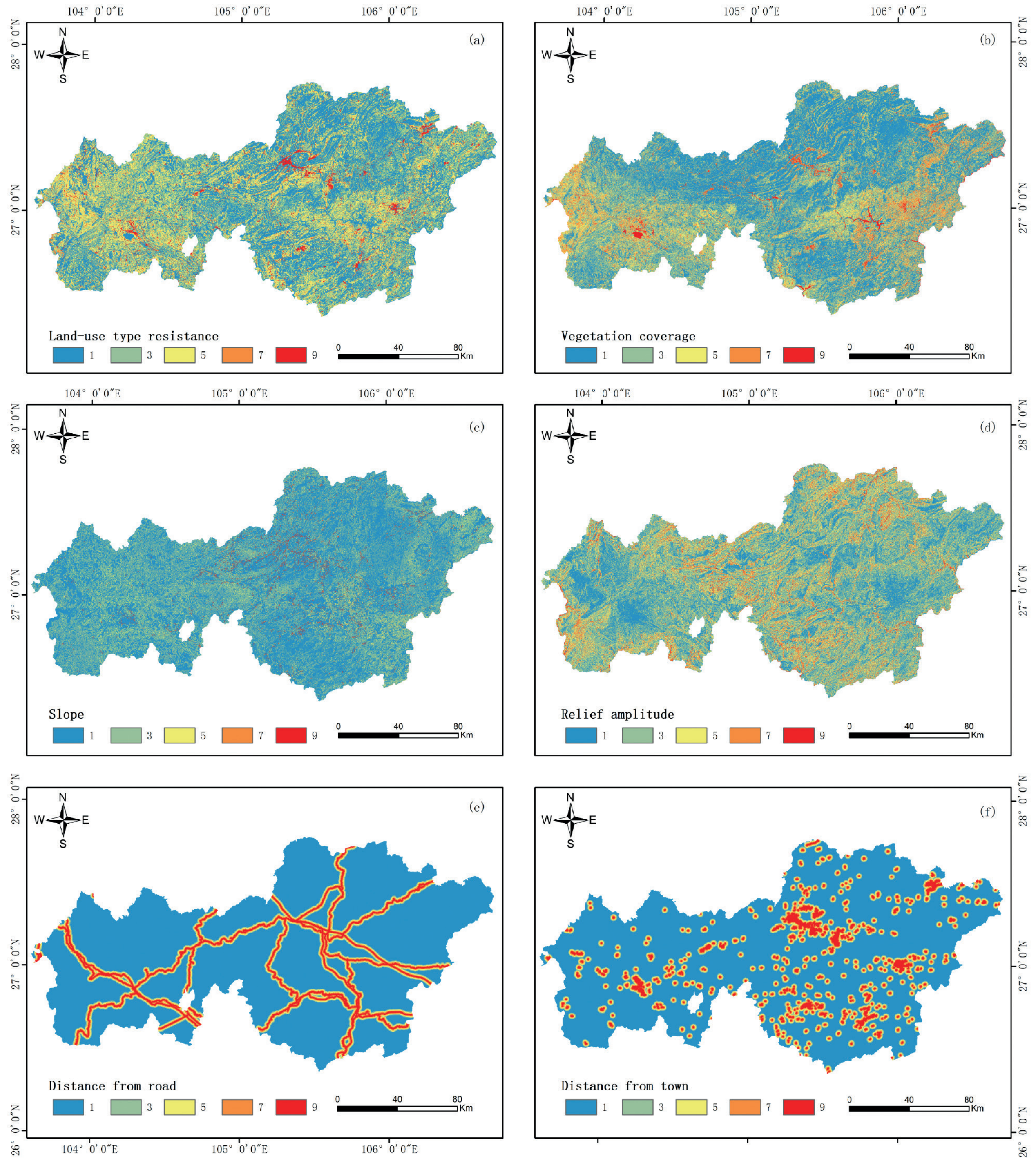

Fig. 6. Resistance surface of each indicators.

lands, with a combined area of 111.40 km^2, representing 2.83% of the total source area.

Establishment Results of Resistance Surface

The different resistance factors are combined and overlaid using weighted summation analysis, resulting in the creation of the Comprehensive Resistance Surface for Bijie City (Fig. 5) and the individual indicator resistance surfaces (Fig. 6). Fig. 5 illustrates that the comprehensive ecological resistance surface in Bijie City is generally high, with localized areas reaching very strong levels of resistance. At the same time, there is pronounced spatial heterogeneity, with the highest resistance values above moderate levels observed in the southwestern region, while the northern region exhibits lower resistance. It is worth noting that the crimson-colored regions representing the highest resistance values in both figures are intricately intertwined with both natural and anthropogenic factors. Fig. 6 demonstrates that terrain ruggedness has a significantly

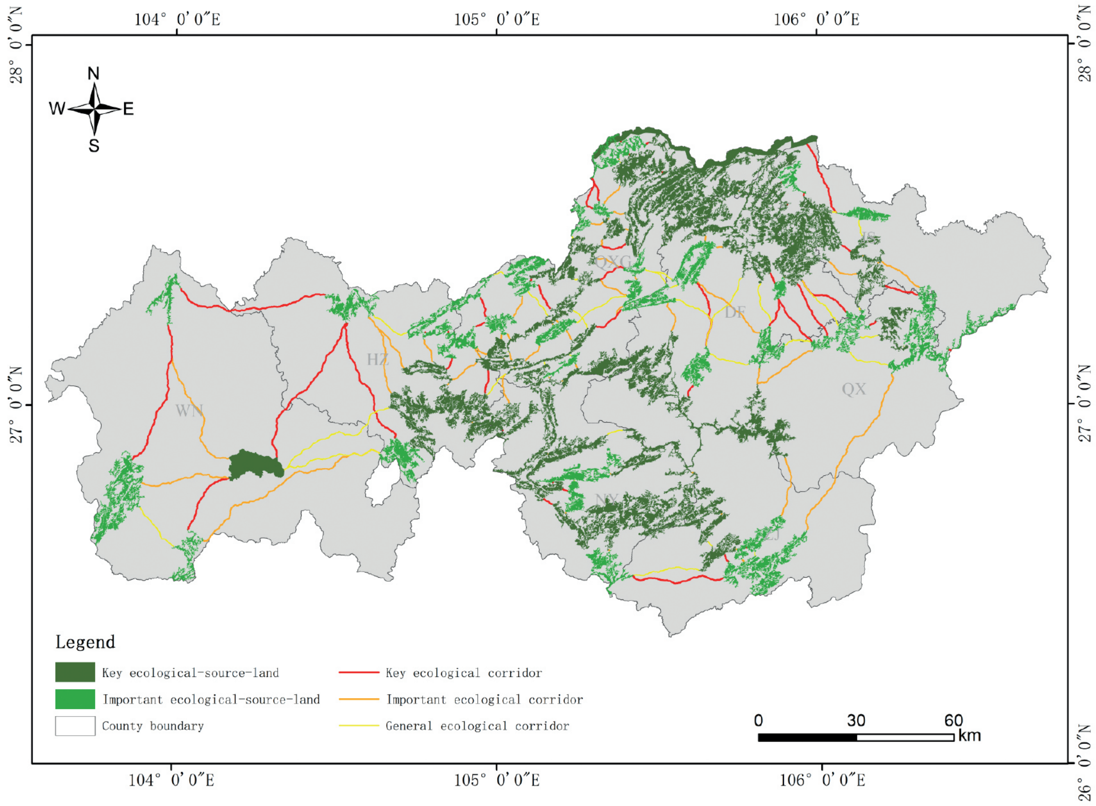

Fig. 7. Distribution of ecological corridors.

greater influence on the resistance surface compared to slope. Terrain ruggedness shows a more than moderate resistance influence throughout the city, while slope does not have a discernible impact on resistance. Vegetation cover exhibits concentrated pockets of moderate-to-high resistance zones in the southwestern and southeastern parts of Bijie City. However, in extensive areas spanning the central, northern, and southern-central regions, resistance remains predominantly minimal. The influence of land use is distributed ubiquitously and is particularly pronounced in the western zone, where the distribution of resistance is denser at the upper end of the medium range. However, the areas with the highest red resistance values are more distributed in the northern region. The most significant influence on the comprehensive resistance surface is the distribution of roads and towns, with areas of high resistance values highly correlated with the extent of roads and urbanization in each county. At the county level, the highest concentration of high resistance values is found in the QXG district adjacent to DF county, followed by the three counties or municipalities of NY, ZJ, and QX, which are located in the southern part of Bijie City. In these areas, high resistance values are primarily associated with roads and construction land. The western WN county, known for having the most cultivated land in Bijie City, exhibits a higher distribution of surrounding high resistance values compared to other counties and cities, except for the construction of land and roads. Low resistance values in Bijie City are mainly found in the northern areas of DF and JS counties, which are dominated by forests and have fewer construction sites for land and roads, resulting in lower resistance values compared to other areas.

Extraction Results of Ecological Corridors

Based on the analysis results of ecological-source-lands and the resistance surface, ecological corridors are identified by calculating the least-cost pathway using the Linkage Mapper tool (Fig. 7). A total of 147 corridors are extracted, with corridor lengths ranging from 0.05 to 72.63 km, resulting in a total length of 1333.99 km. Spatially, the western region of Bijie City, which has a scarce and diffuse distribution of ecological-source-lands, predominantly consists of long-distance corridors. These corridors facilitate the exchange of species and information between the western and eastern source sites. On the other hand, the QXG district and DF county, where source sites are abundant and concentrated, exhibit a higher concentration of medium and short-distance corridors, ensuring strong connectivity. By calculating the ratio of Cost-Weighted Distance (CWD) to the Least Cost Path (LCP), the corridors are classified into three grades using the natural breakpoints method. A smaller ratio indicates less resistance encountered by species along the path, and vice versa. Consequently, the corridors are categorized into critical ecological corridors, important ecological corridors, and general ecological corridors based on the CWD-to-LCP ratio. Among these corridors, there are 45 critical ecological

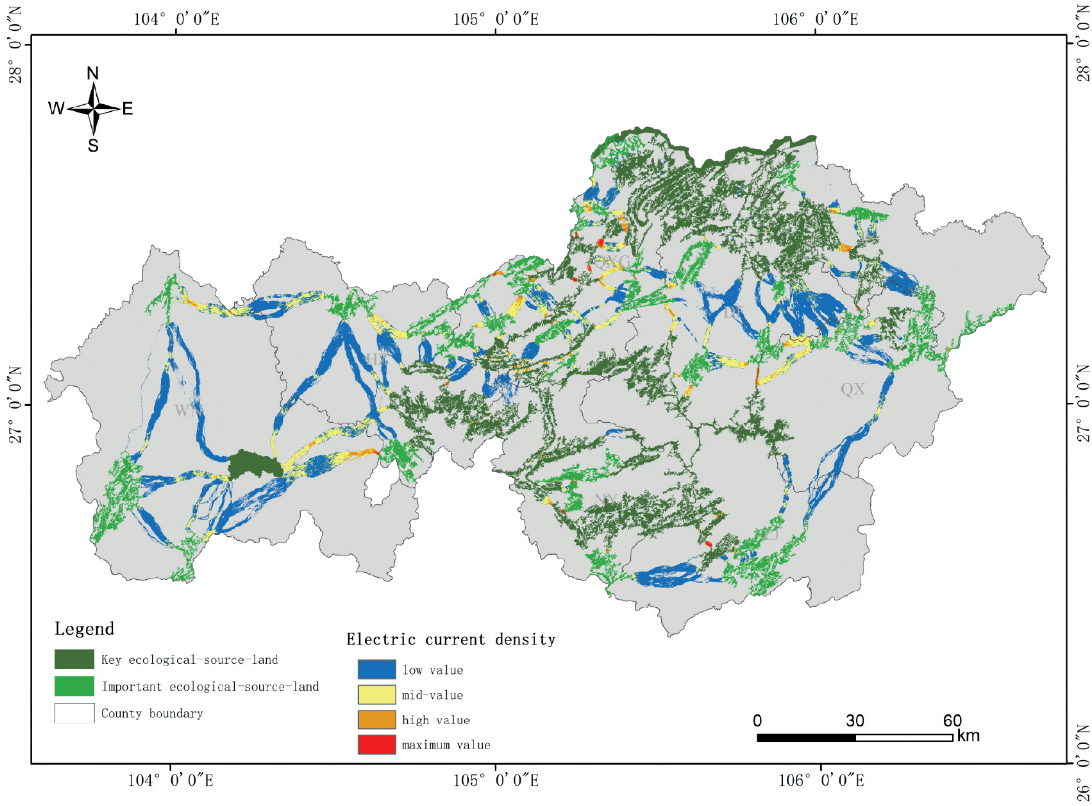

Fig. 8. Distribution of ecological pinch points.

corridors with a total length of 353.44 km. The longest corridor spans 52.53 km, connecting source sites 59 and 60. Additionally, there are 65 important ecological corridors with a total length of 869.15 km. The longest corridor extends for 72.63 km, making it the longest ecological corridor in Bijie City, connecting source sites 31 and 58. Lastly, there are 37 general ecological corridors with a total length of 111.39 km. The longest corridor measures 22.65 km, connecting source sites 44 and 47.

Identification of Key Areas

The analysis of ecological corridors includes the identification of ecological pinch points using the Pinchpoint Mapper tool in "All to One" mode. The current density is classified into four levels using the natural break point method, and the highest current density level is selected as the alternative pinch point. Redundant patches with an area smaller than 0.1 km^2 are removed. In total, 23 key ecological pinch points are extracted, covering an area of 10.85 km^2. The results indicate that areas with higher current density are mostly located on both sides of the corridors. The land use types at the pinch points primarily consist of forests, cultivated lands, water bodies, and grasslands (Fig. 8, 10). The spatial distribution analysis of ecological pinch points reveals that not every corridor has pinch points along its route, and the distribution of pinch points is more concentrated in the northern and central regions of Bijie City. In the QXG district, which has abundant and compact source sites and shorter corridors, there is a higher current density and concentration of ecological pinch points, facilitating frequent species exchange and migration. At the boundary junction of DF and JS counties, a string of ecological pinch points forms along a natural river corridor. These pinch points serve as stepping stones and should be prioritized for protection. In the western region, which has the only key pinch point, there is intensive species exchange and vital interaction with eastern source areas.

Using the Barrier Mapper module, the ecological obstacle areas in Bijie City are identified with a search radius of 200m. They are divided into five levels using the natural break point method, and the areas with the highest cumulative current density are extracted as alternative ecological barrier sites. Fragmented and redundant patches are eliminated, and areas larger than 0.1 km^2 are selected as critical ecological barrier points in Bijie City. In total, 31 barrier points were extracted, covering a total area of 25.70 km^2. The spatial distribution of ecological barrier points is predominantly concentrated in the central and northern regions of Bijie City, with fewer occurrences in the western and southern areas, and no distribution in the eastern part (Fig. 9, 10). Among these, the distribution of barrier points is most concentrated in the QXG district, DF county, and HZ county. Multiple barrier points can be found along a single corridor, possibly due to

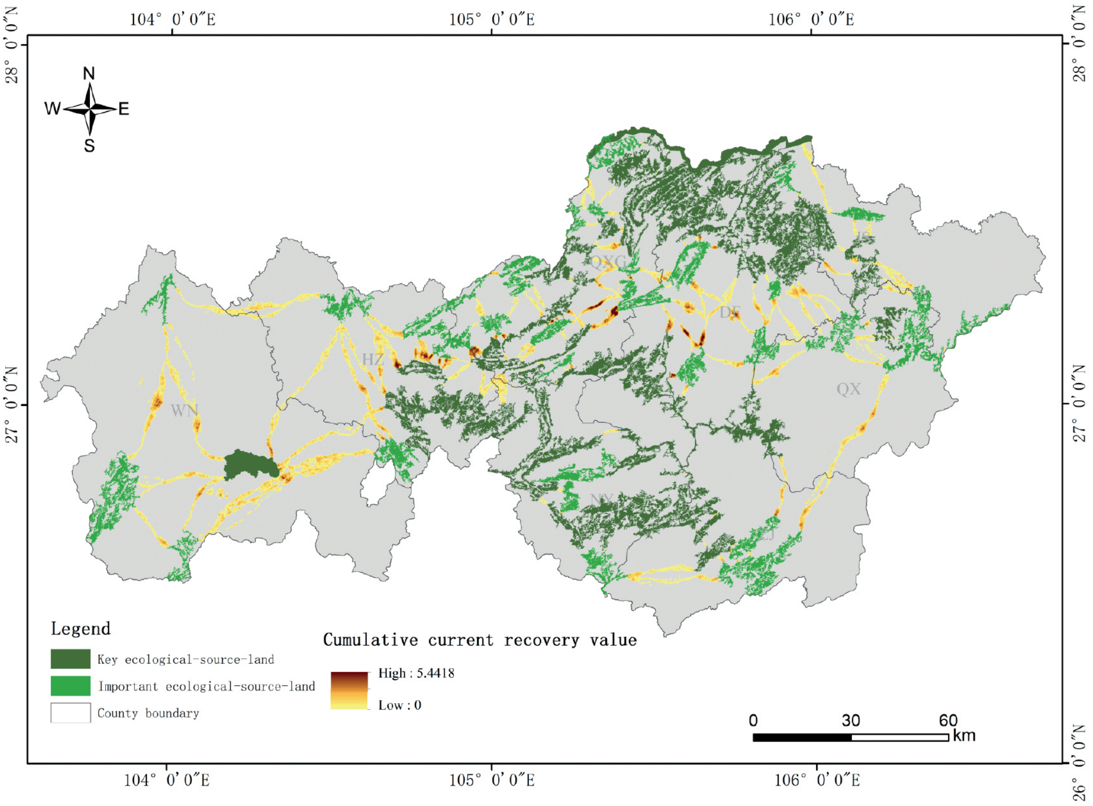

Fig. 9. Distribution of ecological barrier points.

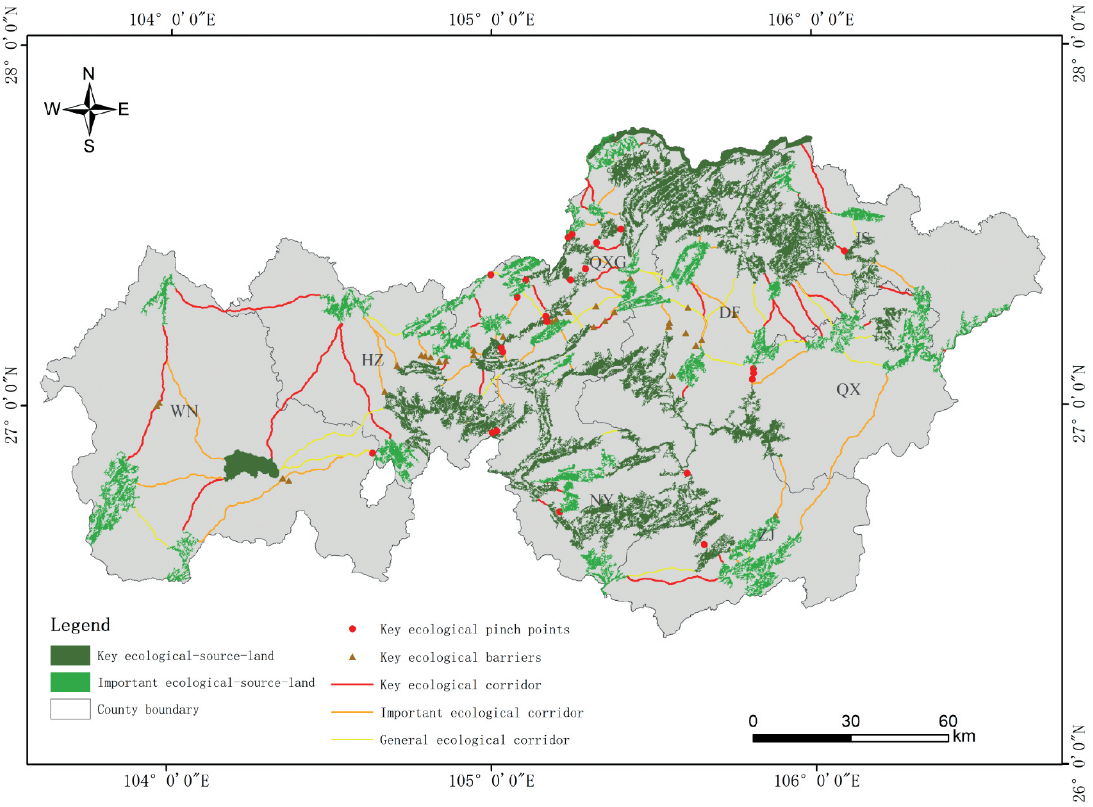

Fig. 10. Key ecological pinch points and barrier points.

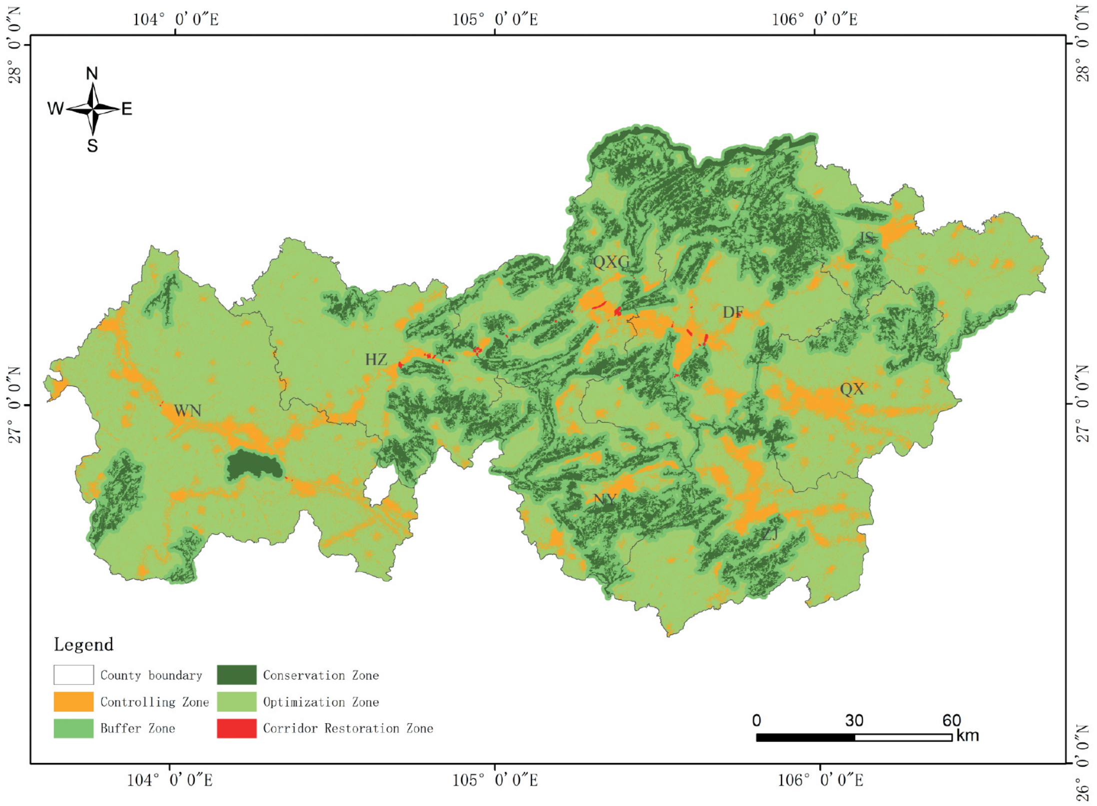

Fig. 11. Ecological restoration zoning.

transportation infrastructure such as railways and national highways hindering species exchange along the corridors. Barrier points are predominantly concentrated in areas designated for construction and agricultural land use, which are influenced by human activities and lead to increased cumulative current values.

Ecological Restoration Strategies for Key Areas

Ecological Restoration Zoning

Based on the ecological security needs and the characteristics of natural ecosystems in Bijie City, and considering the requirements of territorial spatial sustainability for ecosystem integrity, systematicity, and continuity, the land cover types in Bijie City are divided into five areas: ecological controlling zone, buffer zone, conservation zone, optimization zone, and corridor restoration zone. This division is done to establish the potential ecological restoration pattern of the territorial spatial space in Bijie City (Fig. 11). Ecological-source-lands, which have high ecological service values and good environmental quality, and ecological pinch points, which are important nodes with high current density and frequent species exchange, are considered priority areas for ecological protection. The edge areas of ecological-source-lands and pinch points play a crucial role in maintaining the healthy functioning of ecosystems and promoting continuous species exchange. Therefore, a 1 km buffer zone is established between ecological-source-lands and pinch points as an ecological radiation zone to enhance connectivity and integrity between source sites and pinch points. Ecological barrier points hinder species exchange and migration and disrupt landscape connectivity. Thus, high-value areas of ecological barriers are designated as key areas for ecological restoration. The comprehensive resistance surface map indicates that high resistance value areas are mostly associated with construction areas and roads. However, socio-economic development should not come at the expense of the ecological environment. Therefore, based on the distribution characteristics of the resistance surface, the comprehensive resistance surface is divided into five levels using the natural break method. The top two levels are selected as ecological control zones, while the remaining levels are designated as ecological enhancement zones.

Ecological Restoration Strategies

Strategies for five types of ecological areas are proposed as follows:

In the ecological conservation area, which consists primarily of forests, grasslands, and water bodies, strategies should focus on minimizing the expansion of construction land and reducing human interference. It is crucial to strictly prohibit any changes to the current land use status and strengthen monitoring and control measures. Respecting and adhering to the natural processes of plant and animal succession is essential, and activities that disrupt natural growth and life processes should be strictly forbidden. Illegal logging, deforestation, and pollution discharge must be strictly prohibited. Afforestation can be implemented in narrow ecological pinch points to widen the width of these areas, and any activities that may harm biodiversity within pinch point areas must be strictly prohibited. Establishing a comprehensive environmental monitoring system and conducting regular assessments in sensitive areas is necessary to address issues promptly. Additionally, considering the uneven distribution of ecological-source-lands in Bijie City, it is advisable to increase ecological source areas in the eastern and western regions. Restoration efforts in these areas should focus on expanding core areas and enhancing patch connectivity by restoring larger areas of forests and grasslands.

In the ecological buffer zone, which acts as subordinate areas for ecological-source-lands, strategies should encompass both ecological conservation and restoration. The key objective is to repair fragmented patches outside the source sites and establish connections between these patches through ecological corridors or man-made connective points based on local conditions. Environmental protection should be prioritized in human activities within this region, and efforts to protect and restore the environment should be strengthened. Strict control measures should be implemented to regulate the current land use status, and measures to control the expansion of construction facilities are necessary.

In the corridor restoration zone, which is primarily located in high-resistance value areas, restoration efforts should focus on enhancing connectivity between source areas and facilitating species exchange. This area consists mainly of construction land, cultivated land, and grassland. In construction land areas, it may not be feasible to remove dwellings or traffic roads, but the construction of ecological corridors such as culverts, tunnels, or flyovers in the vicinity can facilitate species migration and exchange. For cultivated land areas, planting forestry industries such as fruit trees around the cultivated land can maximize ecological and economic benefits. Additionally, fallow land can be returned to forests to restore and protect vegetation cover, thus reducing ecological resistance. In grassland areas, reasonable grazing management and rotational grazing systems should be implemented to control the intensity of grazing. Strengthening the control and management of invasive plants and harmful organisms is crucial to prevent damage to the grassland ecosystem and reduce ecological resistance.

In the ecological optimization area, which covers the largest areas in Bijie City and includes various land use types, strategies should be tailored to specific landscapes. For small-sized forests and low-connectivity landscapes, efforts should focus on conserving existing forests, planting appropriate trees in marginal areas, and improving connectivity. Pollution in cultivated lands should be reduced, and the promotion of eco-friendly agricultural technologies such as organic farming, precision agriculture, and water-saving agriculture can contribute to the ecological environment and improve the quality and safety of agricultural products. The ecological landscape of farmland should be rationally planned, with the establishment of forbidden lines and landscape green belts to recover ecological functions and provide better ecosystem services and biological habitats. Implementing rotational or rest grazing systems can help in the recovery and productivity growth of grassland ecosystems, reducing overuse pressure. Controlled application of fertilizers contributes to soil quality recovery and meets the needs of grassland production while reducing water and soil pollution. Rational management and utilization of water resources are essential for ensuring the abundance of water ecosystems and a stable supply of aquatic products. When necessary, water purification and pollution control measures should be adopted to control agricultural and industrial wastewater discharge. Protection strategies for wetlands can increase connectivity among water bodies and wetlands, provide better habitats, and promote biodiversity conservation, thereby stabilizing aquatic ecosystems.

In the ecologically controlling zone, which is characterized by intensive human activities and high resistance values, areas such as urban regions, rural residential areas, and transportation corridors are typically included. It is recognized that economic development is crucial for people's livelihoods, especially in remote rural areas. However, this development should not come at the expense of unacceptable ecological degradation. Therefore, it is important to clearly define the scope and boundaries of the ecologically controlled areas. To regulate development activities and minimize ecological degradation, various measures can be implemented. Billboards, educational advertisement boards, and scientific or notice boards should be set up around the perimeter of the control zone to raise awareness and inform the public about the importance of ecological protection. Law enforcement and supervision over the controlling areas should be strengthened to effectively regulate development activities, including preventing illegal mining and unauthorized construction. Additionally, efforts should be made to repair and restore damaged habitats within the control zone. This can be achieved by providing economic and technical support, encouraging local residents and enterprises to participate in protection and restoration efforts, and offering reasonable compensation and sustainable development opportunities. By involving local stakeholders and providing incentives for conservation and restoration, it becomes more feasible to achieve ecological protection goals while also addressing economic development needs.

Discussion

The study utilizes the MSPA model (morphological structure pattern analysis) to analyze the natural ecological conditions of the study area. The research framework of “identifying source sites-establishing resistance surfaces-extracting ecological corridors” is applied, incorporating MSPA and landscape connectivity analysis methods.

The identification of ecological-source-lands is conducted by selecting existing nature reserves and considering source distribution, connectivity, and integrity. The extraction of ecological corridors involves the use of a minimum cumulative model and circuit-theory based calculation model to determine the optimal path of ecological corridors. This allows for an overall connectivity analysis of the study area. The identification of ecological pinch points and barriers provides potential sites or areas for territorial spatial ecological restoration, contributing to a holistic and systematic approach.

However, the study has some limitations. Firstly, the identification of ecological-source-lands does not consider the ecosystem service value of each land use type or the ecological environment conditions of different regions. It also does not account for the characteristics of ecological vulnerability in the study area. Ground verification is necessary to validate the results, but due to limitations in time and funds, full verification has not been possible.

Secondly, the identification of ecological pinch points and barrier points may vary depending on different lengths and radii. In future studies, the research team intends to consider the ecological conditions and vulnerability characteristics of the study area. They will also explore different threshold lengths and radii to identify optimal ecological pinch points and barrier points. This will help establish more refined ecological restoration zones for Bijie City.

Conclusions

Based on our research, following the framework of “identifying source sites-establishing resistance surfaces-extracting ecological corridors”, we analyze and construct the ecological security pattern of Bijie City in southwest China. We also identify ecological pinch points and barriers, propose ecological restoration zones, and prescribe corresponding strategies and recommendations. From this analysis, the following conclusions are drawn:

(1) A total of 62 ecological source sites covering an area of 3944.37 km^2 are identified in Bijie City through MSPA (Multiple Scale Permutation Analysis). Among these, 26 key ecological source sites covering a total area of 2643.35 km^2 are determined to be more significant. Additionally, 36 general ecological source sites covering a total area of 1302.89 km^2 play a relatively less important role in the city. High-value areas with higher resistance are typically found near human residential areas and transportation infrastructure. A total of 147 ecological corridors are extracted, spanning a distance of 1333.9 km. These include 45 key ecological corridors covering 353.44 km, 65 important ecological corridors covering 869.15 km, and 37 general ecological corridors covering 111.39 km. Overall, these corridors exhibit a distribution pattern of “three horizontal and one vertical”.

(2) In Bijie City, 23 key ecological pinch points are identified, covering an area of 10.85 km^2, primarily located in the QXG district. These areas are characterized by dominant land cover types such as forests, grasslands, and cultivated lands. Additionally, 31 key ecological barrier points are identified, covering an area of 25.70 km^2, mainly situated in the center of the QXG district, DF, and HZ county. The land cover types at these barrier points mainly consist of constructed lands and cultivated lands.

(3) To optimize the ecological security pattern, this study suggests dividing Bijie City into ecological conservation priority areas, ecological buffer areas, ecological optimization areas, ecological controlling zones, and ecological restoration corridors. Detailed restoration strategies are proposed based on the overall research. These findings provide valuable insights into the ecological security and conservation planning of Bijie City in southwest China. Please note that the information presented is based on the research conducted.

Acknowledgements

This paper was jointly supported by the Planning Project supported by Humanities and Social Sciences Research Fund of Chinese Ministry of Education (22YJAZH013) and Guizhou Provincial Key Technology R&D Program (Grant No. Qiankehe Zhicheng 2023 Yiban 211).

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. ZHU M., ZHOU Z.F., WU X.P., LIU R.P., ZHENG J.J., WANG J.L., WAN J.X. Response of vegetation carbon sequestration potential to the effectiveness of vegetation restoration in Karst ecologically fragile areas in Guizhou, southwest China. Ecological Indicators, **158**, 111495, **2024**.
2. LIU X.J., FU Z.Y., ZHANG W., XIAO S.S., CHEN H.S., WANG K.L. Soluble carbon loss through multiple runoff components in the shallow subsurface of a Karst hillslope: Impact of critical zone structure and land use. Catena, **222**, 106868, **2023**.
3. LI C.F., WANG Z.Z., LI Z.W., XU X.L. Research progress of soil erosion in Karst areas of southwest China. Carsologica Sinica, **41** (6), 962, **2022**.
4. ZHANG T., ZUO S.Y., YU B., ZHENG K.X., CHEN S.W., HUANG L. Spatial patterns and controlling factors of the evolution process of Karst depressions in Guizhou province, China. Journal of Geographical Sciences, **33**, 2052, **2023**.
5. CHEN Q.W., XIONG K.N., DAN W.H., NIU L.L. Coupling characteristics of ecological and poverty in typical Karst area: case study of 9000 provincial level poor villages in Guizhou Province. Acta Ecologica Sinica, **41** (8), 2968, **2021**.

6. XIA S.Y., ZHAO Y., WEN Q., XU X., CUI P.P., TANG W.M. Spatiotemporal dynamics and influencing factors of poverty in ecologically fragile areas of a Karst region: A case study of Guizhou Province. Acta Ecologica Sinica, **39** (18), 6869, **2019**.
7. YANG B.L., ZHANG Y., XIONG K.N., HUANG H.Q., YANG Y.A. Review of eco-product value realization and eco-industry with Enlightenment toward the forest ecosystem services in Karst ecological restoration. Forests, **14**, 729, **2023**.
8. BAO Y.B., WANG Y.Z., LU F., LIU Z.Z., MA D.W., YANG Y., ZHANG Y.K. Construction of an ecological security pattern and zoning optimization for territorial space in the Liupan Mountain Area. Arid Zone Research, **40** (7), 1172, **2023**.
9. WANG C., WU X., FU B.J., HAN X.G., CHEN Y.N., WANG K.L., LI Z.S. Ecological restoration in the key ecologically vulnerable regions: Current situation and development direction. Acta Ecologica Sinica, **39** (20), 7333, **2019**.
10. XU X.L., WANG S.Y., RONG W.Z. Construction of ecological network in Suzhou based on the PLUS and MSPA models. Ecological Indicators, **154**, 110740, **2023**.
11. SOLOW R. On detecting ecological impacts of extreme climate events and why it matters. Philosophical transactions of the Royal Society of London. Series B, Biological sciences, **372** (1723), 20160136, **2017**.
12. CHEN X.C., LI X.Q., LV Y.H., LIU H.X., GUO J.Y. Review of spatial identification of ecological restoration. Acta Ecologica Sinica, **39** (23), 8717, **2019**.
13. GAO J.X., XU D.L., QIAO Q., ZOU C.X., WANG Y., TIAN M.R., WANG Y. Pattern construction of natural ecological space and planning theory exploration. Acta Ecologica Sinica, **40** (3), 749, **2020**.
14. WANG Z.K. Accurately grasp the policy to strengthen process management-policy Interpretation of the circular of the general office of the ministry of natural resources on strengthening the implementation and supervision and management of ecological restoration projects in land space. Resource Guide, **5**, 16, **2023**.
15. XIAO X. Research on construction of ecological security pattern in mining cities with ecological Supply and demand. Wuhan, Wuhan University of Science and Technology, **2019**.
16. MA S.F, LAO C.H., JIANG H.Y. Ecological restoration zoning of territorial space based on the pattern simulation of eco-security scenario: A case study of Guangdong-Hong Kong-Macao Greater Bay Area. Acta Ecologica Sinica, **41** (9), 3441, **2021**.
17. CHEN Y., HA K., HE W.L., WANG Z.T., FENG F., MEN M.X., DING Q.L. Study on the change and optimization of landscape pattern in the basin of Northwest Hebei Mountains – A case study of Huailai County, Hebei Province. Journal of Natural Resources, **31** (4), 556, **2016**.
18. FANG Y., WANG J., HUANG L.Y., ZHAI T.L. Determining and identifying key areas of ecosystem preservation and restoration for territorial spatial planning based on ecological security patterns: A case study of Yantai City. Journal of Natural Resources, **35** (1), 190, **2020**.
19. FU F.J., LIU Z.H., LIU H. Identifying key areas of ecosystem restoration for territorial space based on ecological security pattern: A case study in Hezhou City. Acta Ecologica Sinica, **41** (9), 3406, **2021**.
20. PENG J., ZHAO S.Q., DONG J.Q., LIU Y.X., MEERAMANS J, LI H.L., WU J.S. Applying ant colony algorithm to identify ecological security patterns in megacities. Environmental Modelling & Software, **117**, 214, **2019**.
21. MA X.L., GUO S.S., XU Y., WEI Z.Q., GAO Z.T., YU L., HOU J.L. Research on ecological security pattern construction in vulnerable ecological region. Acta Ecologica Sinica, **43** (22), 9500, **2023**.
22. ZHU Z.Z., ZHONG Y.X., FENG X.H. Evolution of ecosystem service value and security pattern optimization in Min-Xin axis belt. Journal of Fujian Normal University (Natural Science Edition), **37** (5), 66, **2021**.
23. YANG L.A., LI Y.L., JIA L.J., JI Y.F., HU G.G. Ecological risk assessment and ecological security pattern optimization in the middle reaches of the Yellow River based on ERI+MCR model. Journal of Geographical Sciences, **33** (4), 823, **2023**.
24. HUANG P.Z., ZHAO H.F., WU K.N., QIAN J.S., LI X. Research on land-space ecological restoration zoning based on the type of Earth's critical zone: A case study of Xixia County, Henan Province. Geological Bulletin of China, **42**, 1, **2023**.
25. ZHAO J.H., YANG Y.C., WANG T., YANG M.H., XIE Y.L., GUO Z.W., CHEN J.W. Evolution of ecological network and identification of key restoration areas in the Loess Plateau during 2000–2020. Bulletin of Surveying and Mapping, **8**, 19, **2023**.
26. HU C.G., WANG Z.Y., HUANG G.L., DING Y.C. Construction, Evaluation, and Optimization of a regional ecological security pattern based on MSPA–Circuit Theory approach. International Journal of Environmental Research and Public Health, **19**, 16184, **2022**.
27. YE H., YANG Z.P., XU X.L. Ecological corridors analysis based on mspa and mcr model – a case study of the Tomur world natural heritage region. Sustainability, **12** (3), 959, **2020**.
28. YU C.L., LIU D., FENG R., TANG Q., GUO C.L. Construction of ecological security pattern in Northeast China based on MCR model. Acta Ecologica Sinica, **41** (1), 290, **2021**.
29. WEI B.J., SU J., HU X.J., XU K.H., ZHU M.L., LIU L.Y. Comprehensive identification of eco-corridors and eco-nodes based on principle of hydrological analysis and Linkage Mapper. Acta Ecologica Sinica, 42 (7), 2995, **2022**.
30. LI Q.Y., TANG L.N., QIU Q.Y., LI S.J., XU Y. Construction of urban ecological security pattern based on MSPA and MCR Model: a case study of Xiamen. Acta Ecologica Sinica, **44** (6), 2284, **2024**.
31. ZHANG L.Q., PENG J., LIU Y.X., WU J.S. Coupling ecosystem services supply and human ecological demand to identify landscape ecological security pattern: A case study in Beijing-Tianjin-Hebei region, China. Urban Ecosystems, **20** (3), 701, **2017**.
32. ZHU Q., YUAN Q., YU D.P., ZHOU W.M., ZHOU L., HAN Y.G., QI L. Construction of ecological security network of Northeast China forest belt based on the circuit theory. Chinese Journal of Ecology, **40** (11), 3463, **2021**.
33. ZHOU L., LI M.H., ZHOU Q.G., MENG H.B., PENG C.H., LIU X.W. Construction of ecological security pattern in very large mountainous City based on circuit Theory-taking Chongqing Metropolitan area as an example. Research of Soil and Water Conservation, **28** (2), 319, **2021**.
34. FAN F., TIAN G.X., LIU H., WANG H., LI H.W. Identification of critical areas for ecological restoration of territorial space in Zhengzhou City. Bulletin of Soil and Water Conservation, **43**, 1, **2024**.
35. MA M., ZHANG Y.M., LIN J.J., LI J.J., HAN S.S. Research on ecological network construction and spatial

optimization of Huainan City based on MSPA and Circuit Theory. Journal of Mianyang Teachers'College, **42** (2), 100, **2023**.
36. HU J.Q., JIAO S., XIA H.W., QIAN Q.Y. Construction of rural multifunctional landscape corridor based on MSPA and MCR Model-taking Liukeng Cultural and ecological tourism area as an example. Sustainability, **15** (16), 12262, **2023**.
37. YANG C.H., GUO H.J., HUANG X.Y., WANG Y.X., LI X.N., CUI X.Y. Ecological network construction of a National Park based on MSPA and MCR Models: An example of the Proposed National Parks of "Ailaoshan-Wuliangshan" in China. Land, **11** (11), 1913, **2022**.
38. SONG L.L., QIN M.Z. Identification of ecological corridors and its importance by integrating circuit theory. Chinese Journal of Applied Ecology, **27** (10), 3344, **2016**.
39. ZHANG H.L., YE C.S., HU M.S. Identification and restoration strategy of key areas of ecological restoration in urban agglomeration around Poyang Lake based on ecological security pattern. Research of Soil and Water Conservation, **30** (2), 393, **2023**.
40. People's Government of Bijie. Introduction to Bijie (general). Available online: https://www.Bijie.gov.cn/hhBijie/sq/Bijiejj/
41. WU J.S., YUE X.X., QIN W. The establishment of ecological security patterns based on the redistribution of ecosystem service value: A case study in the Liangjiang New Area, Chongqing. Geographical Research, **36** (3), 429, **2017**.
42. LIU J.L., LI S.P., FAN S.L., HU Y. Identification of territorial ecological protection and restoration areas and early warning places based on ecological security pattern: a case study in Xiamen-Zhangzhou-Quanzhou Region. Acta Ecologica Sinica, **41** (20), 8124, **2021.**
43. SU C., DONG J.Q., MA Z.G., QIOA N., PENG J. Identifying priority areas for ecological protection and restoration of mountains-rivers-forests-farmlands-lakes-grasslands based on ecological security patterns: a case study in Huaying Mountain, Sichuan Province. Acta Ecologica Sinica, **39** (23), 8948, **2019**.
44. CHEN J., ZHAO C.C., ZHAO Q., Xu C.M., LIN S., QIU R.Z., HU X.S. Construction of ecological network in Fujian Province based on morphological spatial pattern analysis. Acta Ecologica Sinica, **43** (2), 603, **2023**.
45. GAO Y., MU H.K., ZHANG Y.L., TIAN Y., TNAG D.W., LI X. Research on construction path optimization of urban-scale green network system based on MSPA analysis method: Taking Zhaoyuan City as an example. Acta Ecologica Sinica, **39** (20), 7547, **2019**.
46. YE X., ZOU C.X., LIU G.H., LIN N.F., XU M.J. Main research contents and advances in the ecological security pattern. Acta Ecologica Sinica, **38** (10), 3382, **2018**.
47. LIU X.P., LI X.Y., LI Y.M., ZHAO S.T., DAI Z.Y., DUAN M.J. Construction and optimization of ecological network in rapidly urbanized area: A case study of Daxing District, Beijing. Acta Ecologica Sinica, **43** (20), 8321, **2023**.
48. ZHANG X.F., CUI X.W., LIANG S.M. Evolution and optimization of an ecological network in an arid region based on MSPA-MCR: A case study of the hexi corridor. Sustainability, **16** (4), 1704, **2024**.
49. LIU Y.M., YANG S.N., NI W., HE J.B. Comprehensive assessment method on ecological patch importance: a case study in Sichuan Province, China. Acta Ecologica Sinica, **40** (11), 3602, **2020**.
50. HAN M.W., ZHANG S.P., XU Q.X., DAI J.F., HUANG G.L. Construction of cross-basin ecological security patterns based on carbon sinks and landscape connectivity. Environmental Science, **45**, 1, **2024**.
51. LI H., ZHENHG Y.T., HUANG H., CHEN F.P. Construction of Lushan ecological network based on MSPA and MCR model. Journal of Central South University of Forestry & Technology, **44** (2), 98, **2024**.
52. LIU T., OUYANG S., GOU M.M., XIANG W.H., LEI P.F., LI Y.B. Analysis connectivity of urban heat island in a new-type urbanization based on MSPA model. Acta Ecologica Sinica, **43** (2), 615, **2023**.
53. XIOA Y., ZHOU X., JIANG X., ZHANG J., LI H.G. Research on ecological security maintenance of Guiyang City based on evaluation of ecosystem service function. Ecological Science, **39** (4), 244, **2020**.
54. DONG R.C., ZHANG X.Q., LI H.H. Constructing the ecological security pattern for sponge City: A case study in Zhengzhou, China. Water, **11** (2), 284, **2019**.
55. XIOA S.C., WU W.J., GAO J., OU M.H., YU T. An evaluation framework for designing ecological security patterns and prioritizing ecological corridors: application in Jiangsu Province, China. Landscape Ecology, **35** (11), 2517, **2020**.
56. HAN S.H., MEI Y.G., YE C.Y., ZHANG K., YIN X.X. Construction of ecological security pattern in Yanping District of Nanping City, Fujian Province based on minimum cumulative resistance model. Bulletin of Soil and Water Conservation, **39** (2), 192, **2019**.
57. ZHENG Q.M., SHEN M.Z., ZHONG L.S. Construction of ecological security pattern in Pudacuo National Park. Acta Ecologica Sinica, **41** (3), 874, **2021**.
58. LIU T. Research on landscape planning of Karst mountain villagebased on landscape safety theory: A case study of Fanhua Village, Guanling County, Guizhou Province. Guiyang, Guizhou Normal University, **2023**.
59. ZHAI X., LAN A.J., LIAO Y.M., MAO C.Y., SHI H.J., ZHONG J.S. Quantitative identification of key areas for ecological restoration in national land space based on ecological security pattern - A case study of Guizhou Province. Research of Soil and Water Conservation, **29** (6), 322, **2022**.
60. ZHANG W.J., FU Y.Y., WANG X.J. Construction of ecological security pattern in Xinzhou City based on evaluation of ecosystem service value. Research of Soil and Water Conservation, **30** (4), 355, **2023**.
61. YAO C.Y., HE Y.M., CHENG J.B., ZHANG T.Y., PAN H.Y., MA H.J. Evaluation of ecological security pattern and optimization suggestions in Minjiang River Basin based on MCR model and gravity model. Acta Ecologica Sinica, **43** (17), 7083, **2023**.
62. SU X.P., ZHOU Y., LI Q. Designing ecological security patterns based on the framework of ecological quality and ecological sensitivity: a case study of jianghan plain, china. International Journal of Environmental Research and Public Health, **18** (16), 8383, **2021**.
63. WU X.T., PAN J.H., ZHU X.W. Optimizing the ecological source area identification method and building ecological corridor using a genetic algorithm: A case study in Weihe River Basin, NW China. Ecological Informatics, **81**, 102519, **2024**.
64. WEN X.J., ZHOU Z., ZHANG M.L., ZHANG P.T., ZHANG G.J., ZHANG Q.R. Identification of key areas of territorial ecological restoration in Taihang Mountains-A case study of Tang County. Chinese Journal of Eco-Agriculture, 29 (12), 2093, **2021**.
65. XU A.K., HU M.J., SHI J., BAI Q.Z., LI X.H. Construction and optimization of ecological network in inland river basin based on circuit theory, complex network and ecological

sensitivity: A case study of Gansu section of Heihe River Basin. Ecological Modelling, **488**, 110578, **2024**.

66. GONG J., XIE Y.C., ZHAO C.X., GAO Y.J. Landscape ecological risk assessment and its spatiotemporal variation of the Bailongjiang watershed, Gansu. China Environmental Science, **34** (8), 2153, **2014**.
67. LIU J.H., YANG S., LU Y.Q. Identification and diagnosis of critical areas for ecological rehabilitation based on eco-security patterns and ecological vulnerability assessment - a case study over Wenshang County. China Environmental Science, **42** (7), 3343, **2022**.
68. ZENG W., XIA F.Y. Identification and restoration strategies of key areas of ecological restoration in territorial space based on ecological security pattern: A Case Study of Hanyuan County. Urban & Rural Planning, 1, 1, **2023**.
69. ZHENG Q.M., SHEN M.Z., CAO L., HU J.H. Research on the construction of scenic byway based on MSPA and Tourism Flow: Taking Hunan Province as an example. Journal of Natural Science of Hunan Normal University, **46** (5), 17, **2023**.