

Article

Enhancing the MSPA Method to Incorporate Ecological Sensitivity: Construction of Ecological Security Patterns in Harbin City

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Abstract: China's urban development has reached a stage where green sustainable development must be considered. Constructing an ecological security pattern (ESP) can effectively contribute to maintaining sustainable development and ecological safety in a city. Harbin, a significant city in northeastern China, serves as the study area with a focus on its urban central district. To construct and optimize Harbin's ESP, this study utilized ecological sensitivity assessment, MSPA (morphological spatial pattern analysis), the gravity model, landscape connectivity assessment, and the MCR (minimum cumulative resistance) model to identify source areas, corridors, and nodes. Research reveals that there are 23 ecological source areas within the study area, primarily situated along the Songhua River and in the mountain woodlands of the A-cheng District. This study identified 48 corridors, predominantly situated in the Daowai District, A-cheng District, and the eastern part of Xiangfang District. Among these, 8 are deemed significant ecological corridors, along with 10 important connecting corridors. We propose the structure of ecological security pattern optimization, referred to as the "two axes, two belts, and four areas", and present corresponding ecological management recommendations. The analytical framework provides a valuable method for constructing ecological security patterns and selecting source areas at the regional scale in Harbin City, particularly in complex plain urban areas.

Keywords: urban ecological security; GIS; minimum cumulative resistance model; morphological spatial pattern analysis; Harbin central district



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1. Introduction

Over several decades of urbanization, China's urban ecosystems have increasingly faced serious environmental challenges [1–3]. Issues such as disorganized land use, vanishing ecological land, fragmented green spaces, degraded ecosystem services, ecosystem destruction, and biodiversity loss are prevalent [4]. The 2009 "Measures of the State Council on Revitalizing the Old Industrial Base in Northeast China" policy sped up urban transformation in Northeast China, leading to various ecological issues [5]. In this context, the ESP (ecological security pattern) concept has been increasingly advocated by scholars [6–10]. Originating in the 1990s, the ESP has evolved into a key aspect of landscape ecology and urban planning [11]. It is crucial for the long-term sustenance and development of life on Earth, including humans [12]. The scientific and rational establishment of ecological security patterns is vital for preserving urban ecological security [13].

The concept of the ecological security pattern was first explicitly proposed by Lester R. Brown in 1981 [14], which attracted wide international attention, and from the beginning of the 21st century to the present, the study of ecological security patterns has been further extended to the field of urban and regional planning, especially with the acceleration of the process of urbanization, and urban ecological security has become the focus of

study [15,16]. For instance, Wang WL et al. employ a focused analysis on ecological security patterns (ESPs) to elucidate the balance between urban expansion and ecological conservation, drawing upon a case study in the Changsha–Zhuzhou–Xiangtan urban agglomeration [17]. In terms of international cooperation, the study of ecological security patterns even transcends national boundaries, involving transboundary ecological security, international ecological policies [18,19], etc.

Ecological patterns exhibit spatial and temporal diversity. The construction of ecological security patterns should therefore vary across different scales and regions [20]. In urban centers, the internal built-up area is the critical component of the urban ecological security pattern. The peripheral spaces near these built-up areas serve as significant buffer zones, mitigating the built-up area's impact on the external natural environment. To achieve sustainable urban development, it is essential to create a comprehensive ecological security pattern that includes both the central urban area and its surrounding regions [8].

At present, the prevailing approach to constructing an ESP entails extracting source areas, establishing resistance surfaces, and delineating corridors [21,22]. Ecological source areas are relatively stable habitat patches in the ecosystem with certain ecological radiation functions, which are the basis for constructing an ecological security pattern. The ecological resistance surface characterizes the impact of landscape heterogeneity on ecological process flow and is the basis for analyzing the diffusion path of species in overcoming resistance. Corridors are the connecting channels of various landscape components in the ecological security pattern, as well as the main channels for the diffusion and flow of organisms and energy. In the study of regional ecosystems, the ecological source area holds immense value for conservation and ecosystem services. Identifying and extracting it represents the initial step in ESP construction [7]. Currently, two main methods are commonly used to identify source areas. The first method involves selecting ecologically beneficial areas as the primary range for screening, based on land use or functional classification within the study area, such as woodlands, grasslands, parks, or nature reserves. The identification of ecological source sites is further refined through techniques like landscape connectivity analysis [23], the InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) model [24,25], and MSPA (morphological spatial pattern analysis) [26–28]. These approaches prioritize the spatial morphological attributes of ecosystems, facilitating favorable topological relationships between source areas for functional realization within the ESP. The second approach directly conducts a multi-indicator ecological assessment of the study area, with indicators encompassing ecosystem service importance [29,30], ecological sensitivity [31,32], environmental suitability [33,34], and more. Source areas selected using these methods typically possess higher ecological and conservation values. However, these methods' evaluation systems can introduce subjectivity. MSPA (morphological spatial pattern analysis) is a tool for identifying source sites based on spatial morphological attributes such as patches and spatial relationships, mitigating the drawbacks of subjective ecological source area selection [35]. Internationally, scholars have utilized the MSPA method in urban spatial studies, such as Kang Sangjum [36] et al., who used the MSPA method to explore the green infrastructure patterns in the Seoul metropolitan area in South Korea from 2000 to 2009, and J. Velázquez [37] et al., who used the MSPA method in the Madrid metropolitan area to make plans and choices for green roofs in large urban areas. However, MSPA categorizes land cover types through raster arithmetic [38], relying on morphology to identify source areas, potentially overlooking the actual ecological needs of the study area. When ecosystems are subjected to human or natural impacts, their ecological sensitivity determines the likelihood and ease of environmental problems. Higher sensitivity results in more pronounced reactions [39]. Ecological sensitivity assessment essentially identifies potential ecological issues within the current natural environment, mapping them to specific spatial areas. This characteristic makes it a valuable tool for identifying ecological source areas [40]. Combining ecological sensitivity evaluation can enhance the conventional MSPA method, which primarily categorizes based on land cover type. This approach simultaneously improves the applicability and scientific validity of the selected ecological source sites.

Finally, the construction of an ESP involves extracting corridors between crucial ecological source areas using the *MCR* (minimum cumulative resistance) model [41].

Nestled in the heart of Northeast Asia, Harbin holds a central position in Northeast China and plays a pivotal role in regional development and cross-border trade. Harbin's rich soil conditions and flat topography have positioned it as a major crop producer, boasting extensive farmland. In recent years, research has delved into the ESP of Harbin's city center [42], the regional ecological network, and the ESP of the Harbin–Changchun urban agglomeration [43]. However, there remains a dearth of studies concerning the complete urban central district. Our study focuses exclusively on the urban central district of Harbin. We conducted ecological sensitivity analyses for this area, considering its ecological background characteristics. By combining sensitivity evaluation with the MSPA method, we pinpoint ecological source sites. When constructing the resistance surface, it is imperative to consider both natural and anthropogenic factors comprehensively, employing the minimum-resistance model to extract corridors and progressively establish the ESP. Our aim is to provide scientific insights for optimizing urban ecological planning, thereby safeguarding the ecological security of urban areas and advancing sustainable urban development.

2. Materials and Methods

2.1. Overview of the Study Area

Positioned in the south-central part of Heilongjiang Province ($12^{\circ}42' \sim 130^{\circ}10'$ E, $44^{\circ}04' \sim 46^{\circ}40'$ N) and straddling both banks of the Songhua River, Harbin proudly claims the title of the largest city among provincial municipalities in China in terms of land area, covering an expansive territory of approximately 53,840 km², as visually depicted in Figure 1. Harbin has a total registered population of 9,395,000, while the nine main urban districts have a total population of 5,519,000. Harbin's terrain presents a sharp contrast between mountainous and hilly landscapes in the east and flat plains in the west, serving as an emblematic representation of the swift urbanization and ever-changing natural environment in Northeast China. The city experiences distinct seasons, with winter being the longest, lasting over four months (from late November to early March). Spring (March and April) and autumn (September and October) are relatively brief, while the most flourishing periods for vegetation occur during summer (June to August) and early autumn. Moreover, Harbin is blessed with abundant land resources and diverse soil types, including a significant proportion of arable land, firmly establishing itself as a pivotal hub for industry and agriculture in Northeast China. As outlined in the Harbin City Urban Master Plan (2011–2020) (2017 revision), the urban central district spans an approximate area of 4187 km², with our selected study area encompassing approximately 4320 km². This selected area comprises the administrative districts of Daoli, Daowai, Nangang, Xiangfang, Pingfang, and Songbei, in addition to sections of Hulan and A-cheng Districts [44].

2.2. Data Sources

Table 1 serves as a reference for our data sources. The digital elevation model (DEM) data were derived from the ALOS (Advanced Land Observing Satellite) China regional dataset, boasting a resolution of 12.5 m. Our Normalized Difference Vegetation Index (NDVI) data were derived from Landsat-8 remotely sensed data acquired in September 2021, featuring a cloudiness factor of 0.03 and processed using ENVI 5.3 software. The period from August to October each year is the most complete period for vegetation growth in the research area. The selected data for September is the one with the least cloud cover in recent years and the most suitable for interpretation. Fraction vegetation coverage (FVC) values were computed through NDVI calculations. Roadway data were sourced from regional datasets for Heilongjiang Province, available on OpenStreetMap (www.openstreetmap.org, (accessed on 13 February 2024)). We extracted water and settlement area data from land-use datasets, adhering to the classification standards set by the Chinese Academy of Sciences [45]. To enhance our analysis, we processed the DEM data using the spatial

analyst tool within ArcGIS 10.8, resulting in the generation of slope, slope direction, and topographic relief data. To ensure uniformity, we converted all vector data into raster format and resampled it to achieve a consistent resolution of $30\text{ m} \times 30\text{ m}$, aligning it with other raster datasets.

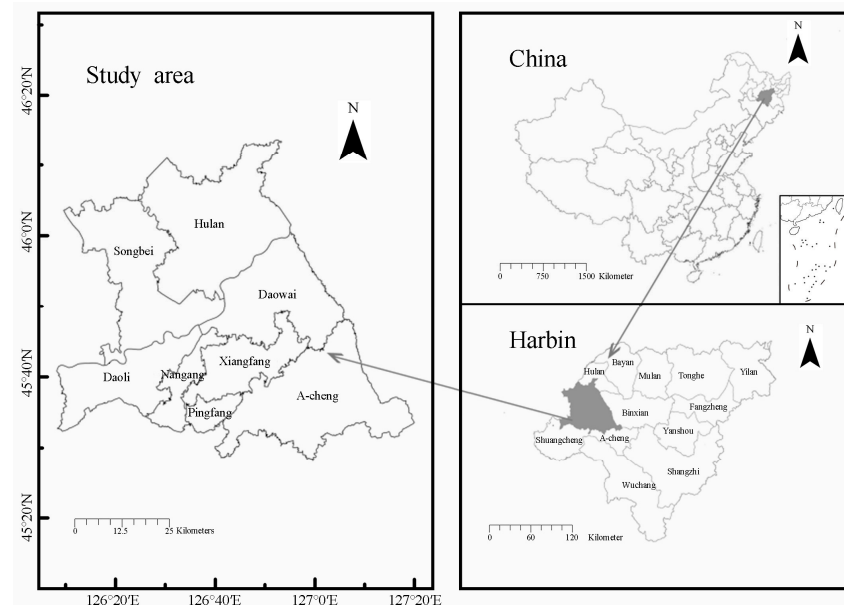


Figure 1. Geographical location of the study area.

Table 1. Data sources.

Data Types	Period	Resolution	Sources
Land-use data	2020	30 m	Land-use dataset of China GeoState Data Cloud (www.dsac.cn , (accessed on 13 February 2024))
Digital elevation model	2020	12.5 m	ALOS (Advanced Land Observing Satellite) China regional dataset (https://www.earthdata.nasa.gov/ , (accessed on 13 February 2024))
Landsat-OLI remote sensing data	2021	30 m	Geospatial Data Cloud, China (https://www.gscloud.cn/#page1/3 , (accessed on 13 February 2024))
Soil texture data		1 km	Harmonized World Soil Database v1.2 (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12 , (accessed on 13 February 2024))
Annual precipitation data in China	2011–2020	1 km	The National Earth System Science Data Center, China (www.geodata.cn , (accessed on 13 February 2024))
Roads	2023	Shapefile	OSM (www.openstreetmap.org , (accessed on 13 February 2024))
Railways	2020	Shapefile	Resource and Environment Science and Data Center, Chinese Academy of Sciences (www.resdc.cn , (accessed on 13 February 2024))
NDVI	2021	30 m	Decode by using remote sensing data
Fraction vegetation coverage (FVC)	2021	30 m	Calculated by using NDVI
Settlement area/water area	2020	30 m	Calculated by using land-use data
Soil erodibility		1 km	Calculated by using soil texture data
Slope/slope direction/topographic relief	2020	12.5 m	Calculated by using DEM

2.3. Methodology

The initial step in this study revolves around identifying ecological source sites, and we propose a method that combines ecological sensitivity assessment and morphological spatial pattern analysis (MSPA). To assess ecological sensitivity, we considered 11 indicators, encompassing elevation, slope, slope direction, topographic relief, fraction vegetation coverage (FVC), soil type, soil erodibility, rainfall, land-use type, distance from settlements, and watershed buffer. These indicators were overlaid and analyzed to yield results for composite sensitivity evaluation, categorized into five distinct grades. Our focus encompassed areas classified as extremely and highly sensitive, in addition to woodlands, grasslands, water areas, and mudflat areas, all foregrounded in the MSPA. Through our calculations, we identified seven landscape types: core, bridge, edge, loop, perforation, branch, and islet. Ecological source areas were selected from regions characterized as core in landscape type and exhibiting a high delta of the probable connectivity index (dPC). The subsequent phase entails calculating the resistance surface. By amalgamating six individual resistance factor surfaces, we generated a composite resistance surface, delineating varying levels of ecological security areas. With the composite resistance surface and ecological source areas, we derived a minimum cumulative resistance surface. This surface facilitated the identification of critical corridors and potential corridors based on ecological source points. Sequentially, we identified ecological strategy points and ecological breakpoints. To conclude, this study provides recommendations and conclusions for establishing an ecological security pattern in Harbin's urban central district. The research steps are visually represented in Figure 2.

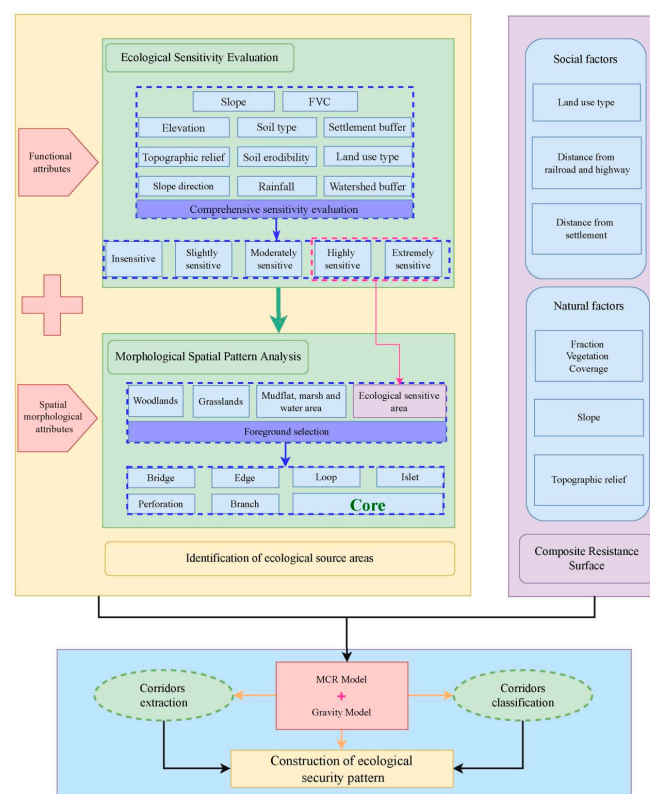


Figure 2. Research steps.

2.3.1. Evaluation of Ecological Sensitivity

(1) Selection and ranking of evaluation factors

Ecological sensitivity is the degree of responsiveness of ecosystems to anthropogenic disturbances and changes in the natural environment, indicating the ease and likelihood of occurrence of regional ecological problems [39]. This study combines the current status of the ecological environment in the Harbin area and selects evaluation factors based on

the topography and geomorphology of Harbin, soil safety, vegetation and water system, and anthropogenic activities. Elevation, slope, slope direction, degree of topographic relief, soil type, soil erodibility, rainfall, watershed buffer, fraction vegetation coverage (FVC), settlement buffer, and land-use classification were identified as single factors for ecological sensitivity evaluation. According to the Interim Regulations on Ecological Functional Zoning Techniques (Ministry of Ecology and Environment, Beijing, China), ecological sensitivity is categorized into five levels, which are extremely, highly, moderately, and slightly sensitive, and insensitive [31]. The grades were assigned values of 9, 7, 5, 3, and 1 to obtain the grading table for single-factor evaluation of ecological sensitivity, as shown in Table 2.

Table 2. Grading criteria for single-factor evaluation of ecological sensitivity.

Guideline	Ecological Indicator	Ecological Sensitivity Grade					Weight
		1	3	5	7	9	
Topography and Geomorphology	Elevation (m)	<140	140–190	190–240	240–290	>290	0.0283
	Slope (°)	3	8	15	25	>25	0.0848
	Slope Direction	Flat, south	Southeast, southwest	East, west	Northeast, northwest	North	0.0599
	Topographic Relief (m)	10	23	45	74	>74	0.1199
Soil Security	Soil Type	Loamy sand	-	Loam	Silt loam	Clay loam	0.0479
	Soil Erodibility	Extremely low	Low	Medium	High	Extremely high	0.1580
	Rainfall (mm)	<562	562–577	577–592	592–614	>614	0.0870
Vegetation and Water Systems	Watershed Buffer (m)	>400	200–400	100–200	50–100	<50	0.1036
	Fraction Vegetation Coverage (%)	<0.25	0.25–0.4	0.4–0.55	0.55–0.65	>0.65	0.1036
Human Activities	Land-Use Type	Construction land	Other unutilized land	Arable land	Grassland, swamp	Water area, woodland	0.1726
	Settlement Buffer (m)	<200	200–400	400–600	600–800	>800	0.0345

(2) Factor weight assignment

In this study, the expert consultation and scoring method was used to compare and assign values to the relative importance of each evaluation factor for elevation, slope, slope direction, topographic relief, soil type, soil erodibility, rainfall, watershed buffer, fraction vegetation coverage (FVC), settlement buffer, and land-use type. Based on the Analytic Hierarchy Process (AHP) [46], the weights of the factors were identified by constructing a judgement matrix using Yaahp 10.3 software. Then, the consistency of the factors was tested to ensure that the test coefficients met the requirements. Eventually, the weights of the ecological sensitivity factors in the urban central district of Harbin can be obtained, as shown in Table 2.

2.3.2. Ecological Source Area Identification

The MSPA model processes raster images through mathematical morphology principles, reclassifying original shapes to describe their morphological characteristics, thereby generating landscape ecological patches at the pixel level. In the initial step, we designated woodland, grassland, water area, mudflat, and marsh as the foreground in the MSPA model, while the remaining area was categorized as background [47]. Subsequently, taking into account the specific features of Harbin's urban central district, we incorporated areas assessed as extremely and highly sensitive in terms of ecological sensitivity into the

foreground. Using ArcGIS 10.8 software, we conducted data reclassification, assigning a value of 2 to the foreground, 1 to the background, and 0 for missing data. We opted for an edge width of 1, with an associated edge effect of 30 m, consistent with data accuracy [48]. We further scrutinized the TIF plots obtained through MSPA to identify seven distinct landscape types, including core, bridge, islet, and perforation. To gauge connectivity, we calculated the *IIC* (overall connectivity index) and the *PC* (probable connectivity index) for core area patches using Conefor 2.6 software. These indices quantified the level of connectivity within ecological patches. Within this study, ecological source areas were selected from patches displaying a higher delta of *PC* (*dPC*). The results were derived using the following formulas.

$$IIC = \left(\sum_{i=1}^n \sum_{j=1}^n \frac{a_i \times a_j}{1 + nl_{ij}} \right) / A_L^2$$

$$PC = \left(\sum_{i=1}^n \sum_{j=1}^n P_{ij}^* a_i a_j \right) / A_L^2$$

$$dPC = (PC - PC_{remove}) / PC \times 100\%$$

In the formula, $i \neq j$, n denotes the total number of extracted ecological source patches, a_i is the area of patch i , a_j is the area of patch j , nl_{ij} denotes the number of connections between patches i and j , A_L^2 denotes the total area of the core area, P_{ij}^* is the probability of the maximum product of all the paths between patch i and patch j , and PC_{remove} is the index value for all other patches except for a specific one. First, combined with the situation of the study area, core patches with area sizes in the top 30 were selected. Next, the connectivity probability was set to 0.5, and landscape connectivity analysis was performed with the help of Conefor 2.6. Finally, 23 regions with a *dPC* greater than 0.1 were selected as source areas.

2.3.3. Constructing a Resistance Surface

The flow of ecological material between ecological source areas necessitates overcoming site resistance. Ecological resistance surfaces are data surfaces that incorporate resistance values at various locations within a site [49]. These surfaces reflect trends and possibilities in landscape ecological functions and eco-spatial processes. Drawing from relevant studies [50–53], distinctions in habitat suitability arising from land type, topography, and vegetation fraction coverage were delineated, taking into consideration the current conditions in Harbin's urban central district. Factors influencing resistance were identified based on their characteristics, including land-use type, topographic relief, slope, vegetation fraction coverage, and distance to settlements. Values were assigned to each resistance factor in accordance with the attenuation principle, among other criteria. To determine the weights, the Analytic Hierarchy Process (AHP) was employed, and Yaahp 10.3 software was utilized to construct the discriminant matrix and conduct consistency tests, resulting in the weights detailed in Table 3. Leveraging these weights, ArcGIS 10.8 software was employed to compute the resistance surface, which amalgamates individual single-factor resistance surfaces.

Table 3. Resistance values and weights of different resistance factors.

Resistance Factor	Weight	Grade	Resistance Value
Land-Use Type	0.391	Woodland	10
		Grassland	30
		Mudflat and marsh	50
		Arable land	100
		Water area	200
		Unutilized land	700
		Construction land	1000

Table 3. Cont.

Resistance Factor	Weight	Grade	Resistance Value
Vegetation Fraction Coverage (%)	0.138	>0.65	10
		0.65	30
		0.55	50
		0.4	500
		0.25	800
Topographic Relief (m)	0.131	10	10
		23	30
		45	50
		74	200
		188	600
Slope (°)	0.065	3	10
		8	20
		15	80
		25	200
		>25	600
Distance from Railroad and Highway (m)	0.163	>800	10
		800	20
		600	100
		400	400
		200	800
Distance from Settlement (m)	0.112	>800	10
		800	30
		600	150
		400	500
		200	800

2.3.4. Ecological Corridors and Node Extraction

Ecological corridors serve as conduits for the flow of energy and materials within a region, constituting pivotal ecological components that sustain connectivity in ecological processes and functions across the area. In this study, we employed the minimum cumulative resistance (MCR) model to derive ecological corridors. This model calculates the target resistance value between two source areas based on the ecological resistance surface and subsequently determines the least-cost path between them. The results were computed using the following formula.

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

In the formula, MCR is the minimum cumulative resistance value, f is a positive function of the migration process of the minimum cumulative resistance value, D_{ij} denotes the spatial distance of energy or material from j to i , and R_i denotes the resistance value of the landscape surface i .

Based on the composite resistance surface, the MCR value among the source areas was obtained, and the MCR model was used to generate potential ecological corridors in the study area. Corridors that are closely distributed with overlapping or similar corridors need to be screened out, and only those corridors that are more important to regional ecological security will be retained. The method of judgement is to calculate the interaction force between the source areas. The results were calculated by using the following formula.

$$F = G_{ij} = \frac{N_i \times N_j}{D_{ij}^2} = \frac{L_{\max}^2 \times \ln(S_i \times S_j)}{L_{ij}^2 \times P_i \times P_j}$$

In the formula, G_{ij} denotes the ecological gravity between patches i and j , N_i and N_j denote the weight values of patches i and j , D_{ij} is the normalized value of the potential corridor resistance between i and j , P_i and P_j denote the resistance values of patches i and j , L_{ij} denotes the cumulative resistance value between patches i and j , and $L_{\max}$ denotes the maximum resistance value of the potential corridor. The results of the gravity value F are used to distinguish important corridors from general corridors, and the differentiation value is chosen to be 10.

Ecological nodes are an important part of ecological flow pathways and often occur at locations of sudden changes in ecological function [54–56]. In this study, the ecological nodes are divided into two levels. The intersection of a corridor with a resistance ridge line is a level-1 node, and the intersection between a corridor and another corridor is a level-2 node.

2.3.5. Ecological Security Pattern Construction

The ESP of the urban central district of Harbin is constructed by the superposition of sources areas, corridors, important nodes, and ecological security areas. The natural-breaks method was used to reclassify the resistance surfaces in the study area to obtain five levels of ecological safety areas, namely high-, higher-, medium-, lower-, and low-level ecological security areas.

Through expert consultation and fieldwork, we comprehensively assessed the current state, challenges, and future trends in the spatial dynamics of urban development, agriculture, ecology, and scenic recreation within Harbin's urban central district. Taking into account the distribution of railroads, highways, and national highways in the study area, we intersected and overlaid ecological corridors using ArcGIS 10.8, subsequently identifying ecological corridor breakpoints. By integrating these findings, we can formulate a scientifically sound, effective, and practical strategy for ecological protection, restoration, and spatial optimization.

3. Results and Analysis

3.1. Ecological Sensitivity and Ecological Source Area Identification for MSPA

3.1.1. Ecological Sensitivity Classification

From the single-factor sensitivities in Figure 3, it can be seen that sensitivities regarding topography and geomorphology are generally low; sensitivities regarding soil safety are moderate; and sensitivities related to vegetation, watersheds, and human activities are significantly higher within the study area. This situation is typical of cities in the plains: influenced by the topography and geomorphology, there is a significant difference between the few hilly and the large plain areas. The hilly areas in the southeast are higher in elevation and have steeper slopes, making them difficult to exploit and therefore less affected by human activities. Moreover, this area is prone to landslides and has high sensitivity, but the area is not large. The region is characterized by the presence of large areas of agricultural land and forests as a whole, with high vegetation fraction coverage and associated sensitivities. The soil consists mainly of loam and is not very sensitive overall. Precipitation is significantly higher in the southeastern region than in the northwestern region. The study area is characterized by the presence of large wetlands and mudflats with a relatively homogenous ecological structure. Moreover, the area lacks a sufficient number of high-level communities such as forests to serve as barriers, and watershed ecological sensitivity is high.

Table 4 and the integrated sensitivity evaluation presented in Figure 4 reveal that ecological sensitivity in the study area is primarily characterized by moderate and slight sensitivity, constituting 36.13% and 30.87% of the total study area, respectively. This suggests that the overall ecological condition is relatively average, primarily attributed to the significant presence of construction land and arable land. In the study area, overall sensitivity exhibits a lower distribution in the northwestern region and a higher distribution in the southeastern region. Extremely high and high sensitivity areas account for 3.71%

and 12.22%, respectively, with the majority located in the hilly areas of the southeast and a few scattered in the central and northwestern regions. These areas are predominantly characterized by land-use types such as forests, grasslands, and wetlands. In contrast, insensitive areas consist mainly of urban built-up land, which serves as the primary site for human activities, encompassing 17.07% of the total area. This urbanized region poses a greater threat to other areas with higher ecological sensitivity. Consequently, the moderately sensitive area, covering 36.13% of the study area, assumes a critical role as an essential buffer zone, necessitating focused protection efforts.

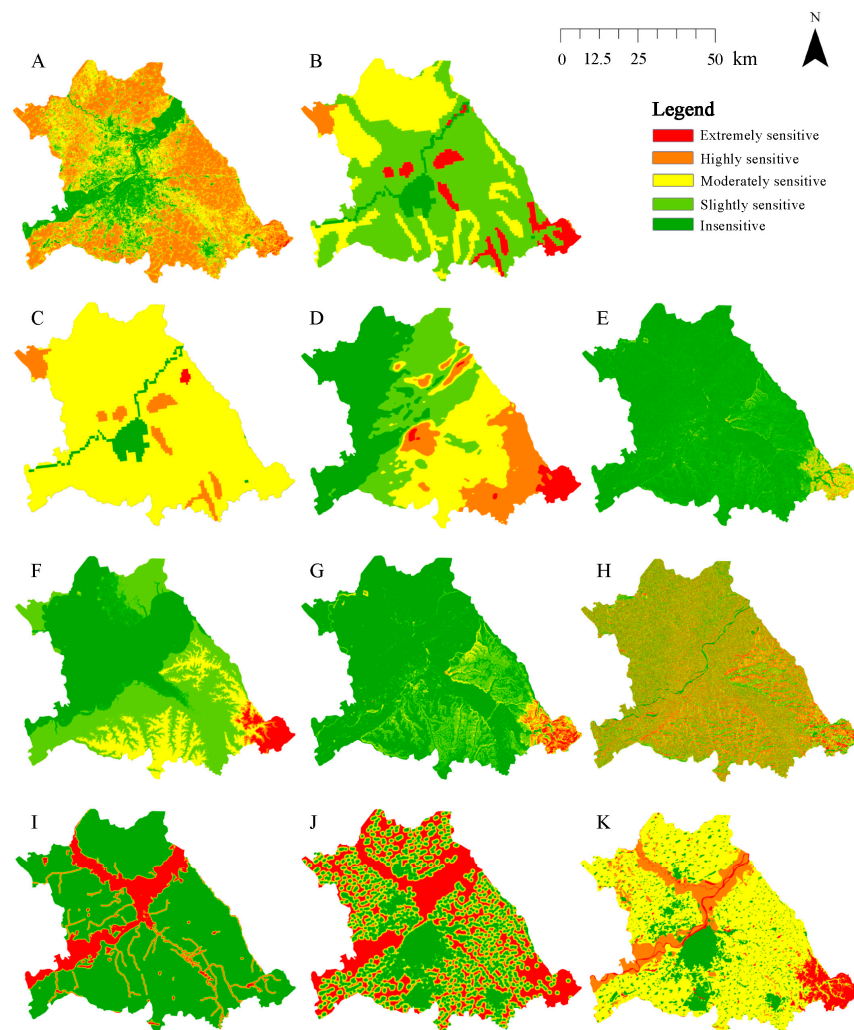


Figure 3. Ecological sensitivity evaluation. (A) Fraction vegetation coverage. (B) Soil erodibility. (C) Soil type. (D) Rainfall. (E) Slope. (F) Elevation. (G) Topographic relief. (H) Slope direction. (I) Watershed buffer. (J) Settlement buffer. (K) Land-use type.

Table 4. Area and proportion of different ecological sensitivities.

Sensitivity Classification	Area (km ²)	Percentage (%)
Insensitive	737.371	17.07
Slightly Sensitive	1333.487	30.87
Moderately Sensitive	1560.703	36.13
Highly Sensitive	527.866	12.22
Extremely Sensitive	160.26	3.71
Total	4319.687	100

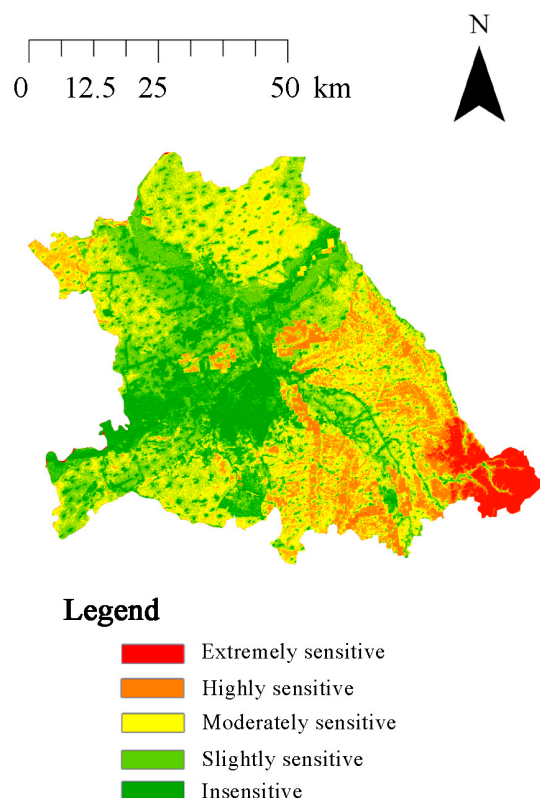


Figure 4. Integrated ecological sensitivity evaluation.

3.1.2. Determination of Source Areas

Figure 5 and Table 5 were obtained by MSPA. Figure 5 illustrates a comparison of results at 30 m, 60 m, and 90 m resolutions, demonstrating the superior effectiveness of the 30 m resolution in identifying core areas. The sum of the seven landscape types totals 1252.35 km², representing 28.99% of the overall. Of all the landscape types, the core area, with an area of 916.94 km², holds the largest proportion of landscape area at 73.22%. The core patches are larger and more stable in the mudflats and marshes area along the Songhua and Hulan Rivers, which includes national and provincial ecological reserves such as Sun Island National Wetland Park, Alejin National Wetland Park, and Hekou Wetland Park. In addition, the patch stability is also stable in the mountain forest area, which is located in the southeast of Hongxing Township in A-cheng District, adjacent to the Changshou Mountain National Forest Park and Jinlong Mountain National Forest Park. The core patches are smaller and more fragmented, which are distributed in Duiqingshan Township located in Songbei District, along the Ashihe River located in A-cheng District and the west part of Chenggaozi Township, etc. Bridge patches are 68.80 km², accounting for 5.49% of the ecological landscape area. They are heavily located in the southeastern portion of the study area, suggesting that the source areas in this region have significant fragmentation but good connectivity. Edge and perforation patches are capable of producing edge effects. For this study, the edge and perforation patches accounted for 1.59% and 0.19% of the study area, respectively. Edge patches accounted for 9.36% of the area of the seven landscapes combined, and perforation patches possessed a 0.65% share. The large area of edge patches indicates that patches in the study area are heavily fragmented. The small area of perforation patches suggests that the core patches with larger area are stable. Islet patches are isolated ecological landscape patches characterized by their small size and fragmented distribution. They serve as stepping stones in the ecological network and account for 4.88% of the area of the seven landscapes combined. Branch patches also have some connectivity effects, accounting for 5.04% of the total ecological landscape area. Loop patches are small, representing only 1.35% of the total ecological landscape area.

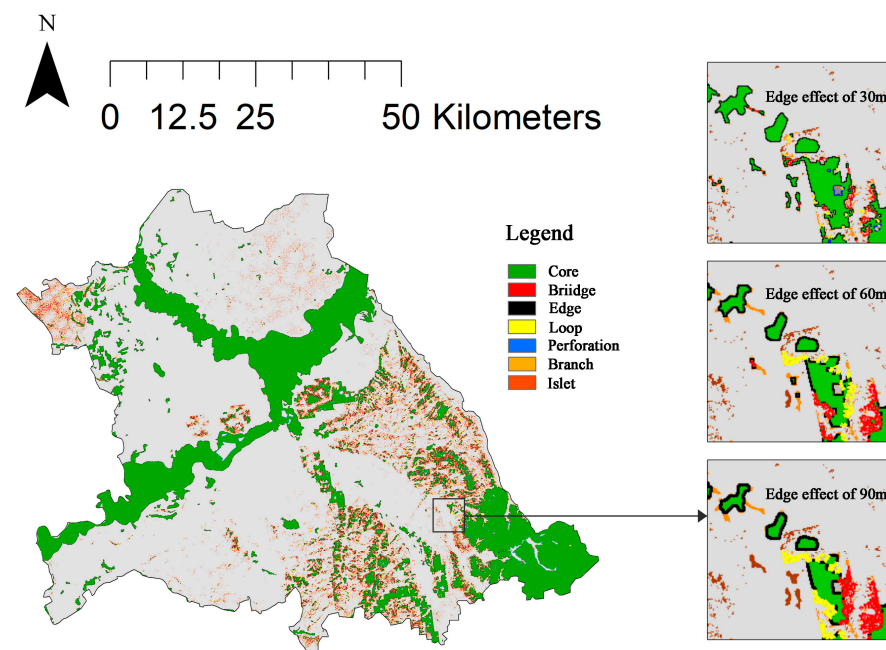


Figure 5. Extraction of ecological source areas using MSPA: distribution of landscape types.

Table 5. Area and percentage of landscape types.

Landscape Types	Area/km ²	Percentage of the Study Area	Percentage of Total Ecological Landscape Area
Core	916.94	21.23%	73.22%
Bridge	68.80	1.59%	5.49%
Edge	117.24	2.71%	9.36%
Loop	16.96	0.39%	1.35%
Perforation	8.16	0.19%	0.65%
Branch	63.17	1.46%	5.04%
Islet	61.09	1.41%	4.88%
Total	1252.35	28.99%	

The core area patches were ranked according to their size from largest to smallest, and the top 30 patches were selected. The dIIC and dPC were then calculated for each area using Conefor 2.6 software. Finally, 23 important core patches were identified based on dPC and DIIC calculations. The geometric center of the source area is the point of eco-source. And Table 6 presents the ecological indices for each source area.

Table 6. Ecological indices of source areas.

Node	dIIC	dPC	Area	Node	dIIC	dPC	Area
1	0.01	0.02	253.72	13	0.08	0.15	155.97
2	0.34	0.45	194.30	14	0.06	0.05	176.88
3	0.03	0.04	609.86	15	0.06	0.05	141.39
4	0.40	0.45	230.43	16	1.68	2.27	220.71
5	1.18	1.70	1008.36	17	18.52	18.95	21,534.43
6	0.01	0.01	206.22	18	0.10	0.09	226.03
7	0.41	0.50	237.30	19	0.19	0.24	227.77
8	0.09	0.16	155.15	20	1.63	2.19	909.51
9	0.38	0.52	351.74	21	81.00	80.47	47,079.82
10	0.32	0.44	188.34	22	0.94	1.15	1459.40
11	0.04	0.04	1087.49	23	0.30	0.38	578.13
12	0.31	0.40	184.49				

3.2. Ecological Resistance Surface Construction

Based on the weight values obtained through AHP calculations, we overlaid all the single-factor resistance surfaces, as shown in Figure 6, to generate the composite resistance surface presented in Figure 7A. The resistance values within this composite surface range from 10.65 to 786.6. As indicated in Table 2, the most crucial factor is land-use type, followed by distance from highways and railroads, and vegetation fraction coverage. The majority of land-use types consist of cultivated land and water areas, with moderate resistance values. Areas characterized by high resistance values are primarily situated in the built-up areas in the central core of the study area, as well as in surrounding settlements, highways, and railroads. These regions have suffered significant ecological damage due to human activities, resulting in elevated ecological resistance and substantial impacts on the migration of regional biological species and bioenergy flow. Given that the study area is predominantly located in flat terrain, both the slope resistance surface and the undulation resistance surface exhibit overall low values.

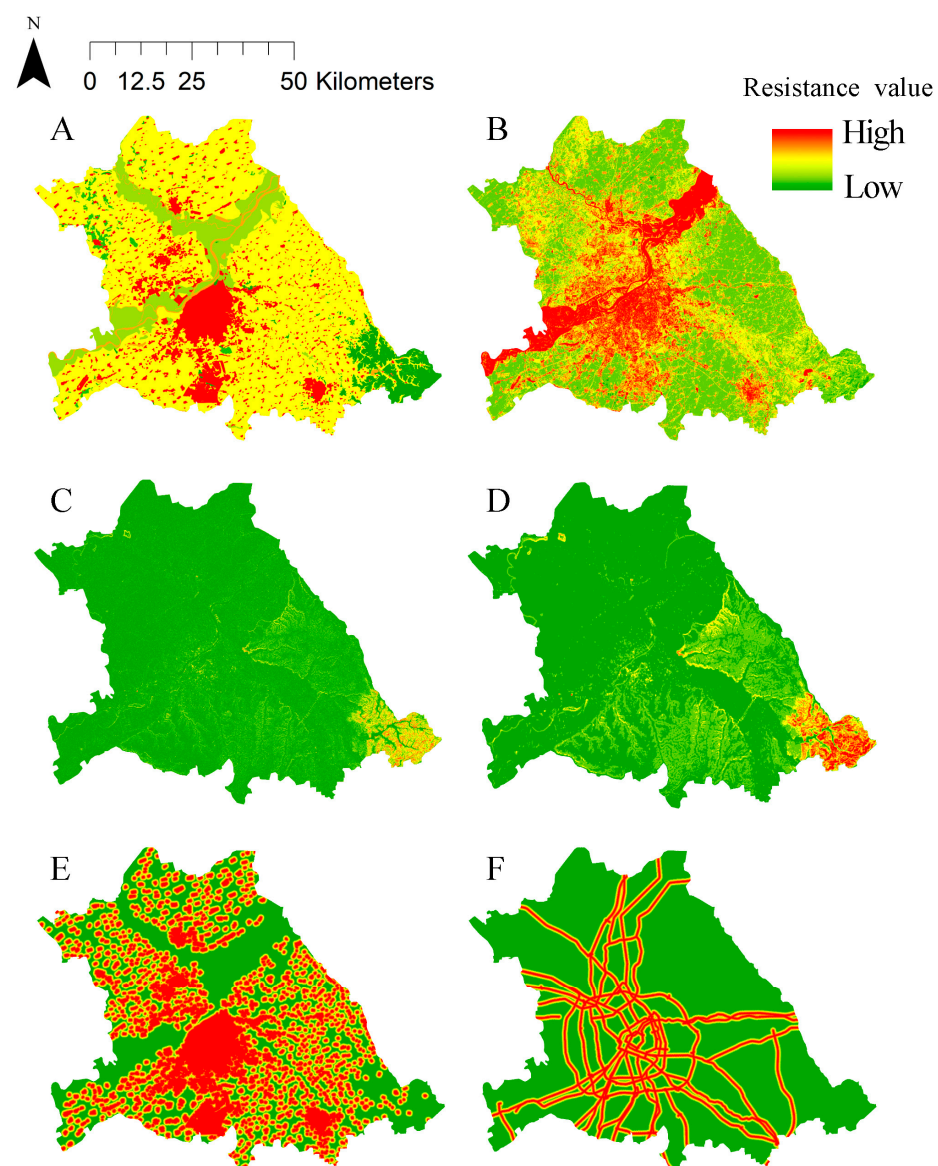


Figure 6. Distribution of ecological resistance surfaces. (A) Land-use type. (B) Fraction vegetation coverage. (C) Slope. (D) Topographic relief. (E) Distance from settlement. (F) Distance from railroad and highway.

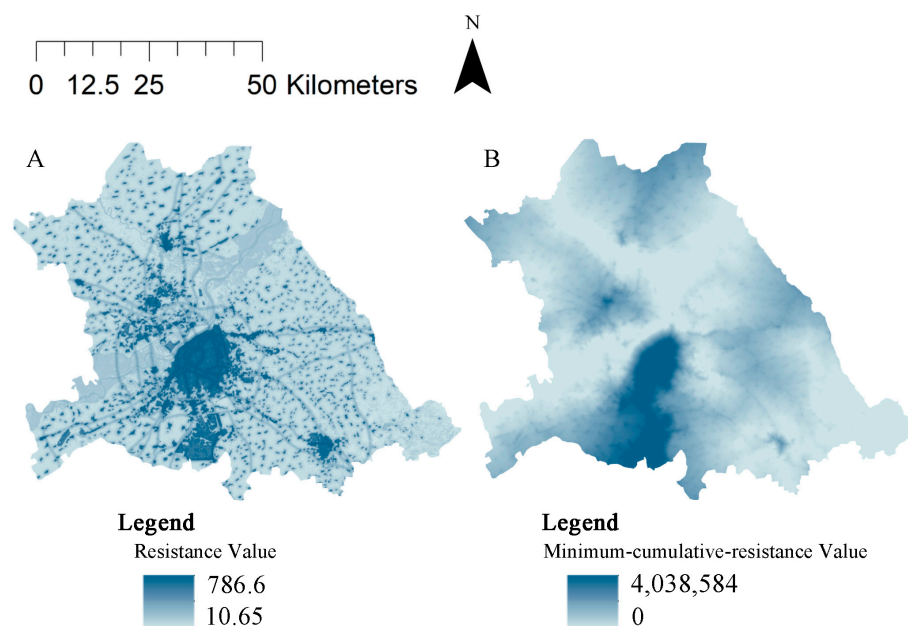


Figure 7. (A) Composite ecological resistance surface. (B) Minimum cumulative resistance surface.

The minimum cumulative resistance (*MCR*) surface was computed using the cost distance tool within ArcGIS 10.8, combining the source areas and composite resistance surfaces, as depicted in Figure 7B. Regions characterized by extremely high resistance are predominantly situated in Daowai, Nangang, and Pingfang Districts. Higher resistance zones can be observed in the built-up areas of University Town in Songbei District, along South Main Street in Hulan District, and along Zhongdu Street in A-cheng District. Notably, the south bank of the Songhua River exhibits an overall higher resistance value compared to the north bank. This disparity can be attributed to the presence of densely developed urban areas, including the city center, as well as a network of highways and railroads on the south bank. Conversely, areas featuring lower resistance values on the south bank are primarily concentrated in the mountainous forest regions in the southeast, along with the Ash River National Wetland Park and the Huicai Gulch, located to the south of the park. These areas hold significant importance in the establishment of the ecological pattern.

3.3. Extraction of Ecological Corridors and Nodes

According to resistance surfaces and the location of ecological source points, 253 least-cost paths are obtained which are potential ecological corridors. The gravity matrix can be obtained by utilizing the gravity model to calculate the gravitational values for each potential corridor, as shown in Table 7. Ultimately, as shown in Figure 8, 48 ecological corridors can be obtained after excluding corridors with potential corridor gravity values below 0.2 and with overlapping occurrences. The total length of these corridors is 807.17 km. Ten corridors with gravitational values greater than 10 were selected as important corridors, with a combined length of 82.55 km. Eight important connecting corridors with higher gravitational values and connecting to more distant sources were chosen, with a combined length of 195.26 km. The remaining 30 are general ecological corridors.

The ecological corridors primarily traverse the southeastern region, encompassing A-cheng District, Hongxing Town, Chenggaozi Town, and Xiangyang Town. These areas house a majority of the source areas, situated in close proximity to each other, exhibiting strong gravitational pulls, and featuring a well-connected network. A smaller segment of the corridors extends northward, passing through Democracy Town to reach Hulan District, Duiqingshan Town, and then looping southward back to Songbei District. These interconnected corridors serve as the sole pathways bridging the ecological land on the south bank to the north bank. Within the study area, ecological corridors are marked

by an uneven distribution and limited quantity. One contributing factor is the absence of ecological source areas for connectivity in the northeastern region. Additionally, the southern urban built-up area presents significant resistance, posing challenges to corridor establishment in that vicinity. Nevertheless, the Songhua River coastal area alone serves as a substantial source area characterized by linear features, effectively spanning and connecting the eastern and western as well as the northern and central portions of the study area. The ecological corridor establishes connections between the central and western parts of the study area, resulting in an overall positive ecological profile. Future planning endeavors may involve the inclusion of additional stepping-stone patches in the northeastern and southern regions, along with the protection of existing ecological corridors.

Table 7. Gravity matrix between ecological source areas.

No.	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0.19	9.07	0.23	0.17	3.2	0.07	0.05	0.12	0.09	0.05	0.05	0.05	0.03	0.03	0.15	0.07	0.04	0.05	0.03	0.19	0.02	0.03
2		0.17	21.79	63.7	0.11	2.26	0.32	0.71	0.11	0.39	0.06	0.24	0.15	0.14	0.65	0.31	0.17	0.22	0.1	0.21	0.08	0.1
3			0.2	0.15	21.62	0.06	0.04	0.11	0.12	0.04	0.07	0.04	0.03	0.03	0.14	0.07	0.04	0.05	0.02	0.26	0.02	0.03
4				26.37	0.13	2.51	0.33	0.74	0.14	0.42	0.04	0.27	0.17	0.16	0.72	0.33	0.19	0.25	0.11	0.27	0.09	0.12
5					0.1	3.43	0.39	0.85	0.12	0.46	0.03	0.28	0.17	0.16	0.74	0.36	0.19	0.25	0.11	0.22	0.09	0.12
6						0.04	0.03	0.07	0.09	0.03	0.05	0.03	0.02	0.02	0.09	0.05	0.03	0.03	0.02	0.22	0.01	0.02
7							0.15	0.34	0.07	0.3	0.02	0.13	0.08	0.08	0.36	0.15	0.09	0.12	0.05	0.14	0.05	0.06
8								32.82	0.03	0.22	0.01	0.56	0.23	0.26	2.73	1.69	0.24	0.89	0.27	0.05	0.14	0.25
9									0.08	0.56	0.03	2.36	0.81	1.02	12.71	8.32	0.81	3.98	1.05	0.13	0.48	0.9
10										0.04	0.15	0.03	0.02	0.02	0.1	0.05	0.03	0.04	0.02	3.63	0.02	0.02
11											0.01	0.38	0.23	0.2	0.84	0.24	0.25	0.28	0.11	0.07	0.1	0.11
12												0.01	0.01	0.01	0.04	0.02	0.02	0.02	0.01	0.16	0.01	0.01
13													1.95	4.72	17.9	1.31	1.31	4.22	0.9	0.06	0.4	0.65
14														3.79	2.65	0.46	9.42	0.8	0.28	0.04	1.02	0.74
15															4.42	0.57	1.72	1.24	0.37	0.04	0.43	0.37
16																10.77	2.32	357.2	12.78	0.18	2.41	5.99
17																	0.49	3.72	0.88	0.08	0.4	0.75
18																		0.73	0.49	0.05	2.15	1.4
19																			3.09	0.06	0.77	1.88
20																				0.03	0.94	1.95
21																					0.03	0.04
22																						2.88

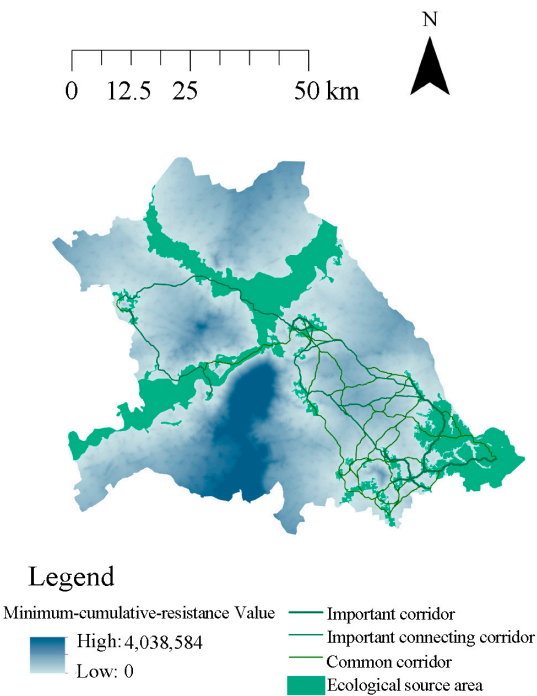


Figure 8. Classification and distribution of ecological corridors.

Ecological nodes are an important part of the ecological network, when organisms move in the corridors, ecological nodes can be used as stepping stones and turning points for organisms to migrate and can provide good resting places for species that migrate long distances. Sixty-one first-level ecological nodes were obtained by intersecting the ecological corridors with the resistance surface ridgelines. Sixty-five secondary ecological nodes were obtained by intersecting the corridors with other corridors.

3.4. Ecological Security Pattern Construction and Optimization

3.4.1. Ecological Security Pattern Construction

The ecological security pattern of the urban central district of Harbin is a superposition of source areas, corridors, nodes, and ecological security areas, as shown in Figure 9. Ecological security areas were categorized into five levels; the high level accounted for 45.75%, the higher level accounted for 28.34%, the medium level accounted for 18.09%, the lower level accounted for 5.95%, and the low level accounted for 1.87%, as shown in Table 8. A total of 84.09% of high- and higher-level ecological security areas indicate that the ecological condition of the study area is good. The low-level ecological security area is mainly the urban built-up area, which is located in the south-central part of the study area. There is a lack of source areas, and this prevents the formation of corridor connections between other source areas.

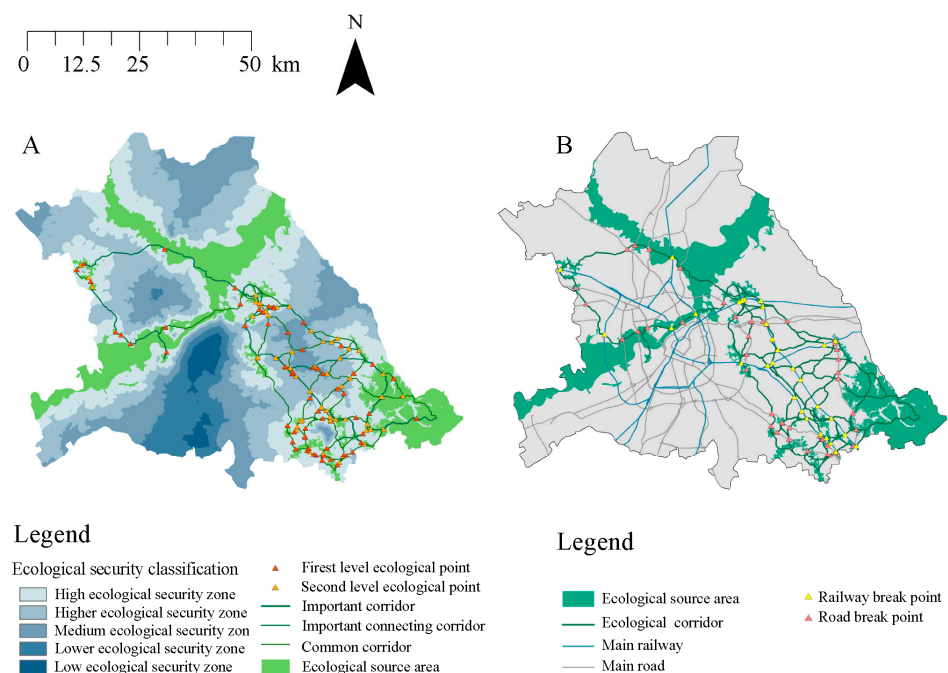


Figure 9. (A) Ecological security pattern of the urban central district of Harbin; (B) distribution of important roads and ecological breakpoints.

Table 8. Area and proportion of ecological safety areas.

Classification of Ecological Safety Areas	Percentage (%)	Area (km ²)
High	45.75	1976.37
Higher	28.34	1224.38
Medium	18.09	781.37
Lower	5.95	257.05
Low	1.87	80.84

Intersecting the corridor with railroads and highways yielded a total of 75 ecological breakpoints, as shown in Figure 9B. Of these, 31 are located on railroads and 44 are located

on highways. There are 15 breakpoints distributed in six corridors on the north bank of the Songhua River and 60 breakpoints distributed in the remaining 42 corridors. The connectivity function of the corridors is easily hindered at breakpoints, where green spaces should be constructed such as biologically passable bridges and underpasses to provide access for species dispersal.

3.4.2. Strategy for Optimizing Ecological Security Pattern

Based on the identified ecological source areas, corridors, and nodes, the structure of the ecological security pattern optimization of “two axes, two belts and four areas” is proposed through the analysis of the characteristics and problems of the study area, as shown in Figure 10.

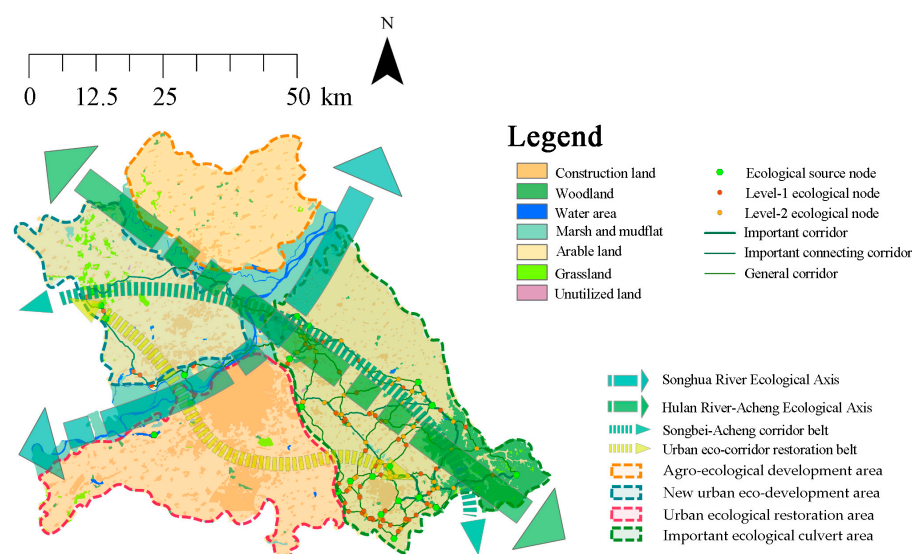


Figure 10. Optimization of the ecological security pattern in the urban central district of Harbin.

Two Axes

(1) Songhua River ecological axis.

The Songhua River ecological axis runs east–west through the study area, within the largest ecological source area in the study area, and plays an important role in transmitting information, energy, and material flows between ecological regions in the study area. Within it exist important ecological areas such as the Sun Island National Wetland Park, Qunli Bund Wetland, and Alejin National Wetland Park. The ecological corridors in the study area separated by this axis show a clear difference in north–south distribution.

(2) Hulan River–A-cheng ecological axis.

The Hulan River–A-cheng ecological axis runs north–south through the study area. This part of the Hulan River exists within the largest ecological source area in the study area, with important ecological areas such as the Hulan Estuary Wetland and the Whitefish Bubble Wetland. This part of A-cheng is located in the second-largest ecological source area in the study area, close to the Changshou Mountain National Forest Park and Jinlong Mountain National Forest Park, and the whole axis needs to be focused on as it covers a large number of ecological corridors. The western part of this axis is the vast majority of the built-up area, while the eastern part is the arable land area.

Two Belts

(1) Songbei–A-cheng corridor belt.

The Songbei–A-cheng corridor belt consists of ecological corridors on the north and south sides of the Songhua River, spanning a long distance. The northern corridor is narrow

and monolithic and needs to focus on solving the problem of breakpoints and consolidating the level-1 and level-2 ecological nodes.

(2) Urban eco-corridor restoration belt

The urban eco-corridor restoration belt is an ecological corridor that connects the north and south areas in another direction, and a narrow and monolithic corridor also exists in its northern part, which is treated in the same way as above. At the same time, its midway area is the saddle of the resistance surface of the city built-up area, which is an easier part to build new ecological corridors and can focus on the construction of new ecological source areas to increase connectivity.

Four Areas

(1) Argo-ecological development area.

This area is distributed in Hulan District in the northern part of the study area, which is a key area for the construction of basic farmland. The main land-use type in the region is arable land, resulting in a lack of ecological source area. Protective forest belts can be established to protect arable land and build new basic corridors.

(2) New urban eco-development area.

This area is distributed in Songbei District in the northwestern part of the study area, with a small amount of new built-up areas and a small number of narrow and monolithic corridors present. The ecology of this area has not yet been seriously damaged by urban development, but there are only a few ecological source areas and corridors. The size of the ecological source area could be expanded based on the grassland area near the Duiqingshan town, and additional protective forests could be added near the built-up area. This approach can build the corridor network in the region and increase ecological corridor stability.

(3) Urban ecological restoration area.

This area is mainly the built-up urban area on the south bank of the Songhua River, which is in poor ecological condition and lacks basic ecological source areas. Small-scale ecological projects can be planned at multiple points as a solution, such as establishing road greenery to improve the surrounding environment. The route in the direction of Changling Lake Tourist Area to Heilongjiang Forestry Botanical Garden is the resistance saddle of the area, which can be used as the main route for the restoration corridor construction.

(4) Important ecological culvert area.

This area is distributed in the Daowai and A-cheng Districts in the southeastern portion of the study area, and there are widely distributed ecological source areas, high habitat quality, and low ecological resistance. Eco-strategic points are mainly located in this area and need to be maintained with emphasis. There are also lots of ecological breakpoints, and a lot of green space needs to be built to help species spread.

4. Discussion

Building the ecological security pattern of the city can effectively maintain the stable regional ecosystem. In addition, it can guide means of ecological restoration such as the designation of protected areas and the construction of corridors [54]. The research sequence in this paper is to firstly identify the source areas, secondly construct the resistance surfaces, thirdly extract the corridors and nodes, and finally construct and optimize the ESP. However, there is no standardized research methodology for the individual steps. Based on the strengths and weaknesses of some of these method selections and applications, we discuss them as follows.

(1) To identify ecological source areas, a combination of ecological sensitivity assessment and MSPA analysis was chosen. Prior research approaches have employed methods such as ecosystem-service-value-based valuation and subjective selection of patches with

higher habitat quality [44]. However, this study adopts a comprehensive approach, blending qualitative and quantitative methods, thus offering a more scientifically rigorous and persuasive evaluation that takes into account both spatial and functional characteristics specific to the study area. It is worth noting that there is currently no universally standardized framework for evaluating ecological sensitivity in the academic sphere. In this research, eleven evaluation indicators were selected, categorized under topography and geomorphology, soil safety, vegetation and water system, and human activities. These indicators provide an accurate and intuitive representation of the ecological environment in the study area. Nevertheless, it is important to acknowledge that data collection has its limitations, as certain factors such as geological hazards and species distribution were not considered in this study. In the future, the indicator system could be further refined, and more objective allocation methods, such as the variation coefficient method and the entropy method, could be incorporated to determine the weighting of indicators, reducing reliance on subjective expert decisions. In MSPA analysis, the selection of prospects lacks a standardized criterion and should be tailored to the specific context and research objectives of the region. In this paper, the selection process extends beyond forest land and grassland to encompass mudflats, marshes, and areas with high ecological sensitivity, facilitating a more comprehensive extraction of ecological source areas. However, in the assessment of landscape connectivity using Conefor 2.6 software, the evaluation predominantly focuses on larger patches, possibly overlooking smaller yet high-quality source areas. Future investigations may consider exploring source areas at finer spatial resolutions. Regarding the selection of distance thresholds, this study opted for 2500 m, typically used at a moderate scale. Future research could conduct comparative studies using different thresholds to yield diverse results.

(2) In the process of constructing the MCR surface, this study demonstrates a scientific approach by considering both natural conditions like fraction vegetation coverage (FVC) and land-use type, as well as anthropogenic factors such as proximity to roads and settlements. However, it is important to acknowledge that certain crucial factors, such as species distribution patterns and variations in species' resource-finding abilities, were not incorporated due to data limitations. Furthermore, akin to the ecological sensitivity evaluation, the process of constructing resistance surfaces relies on empirically driven assessments of scores and weights. To enhance objectivity in future research, additional, more objective methods should be integrated.

(3) The use of connectivity indices to select important corridors is intuitive and scientific. However, the size of the source area heavily influences the evaluation results in the calculation of the connectivity index, leading to the possibility that high-quality corridors connecting smaller source areas may be missed. In the future, high-quality corridors can be preserved by artificially selecting to retain small areas of high ecological value based on source areas attributes. Furthermore, we can explore the adoption of other advanced methodologies for identifying ecological corridors, including circuit theory [7] and ant colony [57] optimization, to enhance our analytical framework.

(4) In terms of data selection for the study, the 30 m precision correlation data used in this study meets the needs of the research process. However, more detailed and valid results would be obtained if more precise land-use data were used. Meanwhile, based on the results of the current experiment, areas with better habitat quality can be further selected to be added to the source area, thus improving the ecological network. In this way, the dilemma of the lack of source areas and corridors in some areas can be solved.

(5) The ecological security pattern for the central urban area of Harbin constructed in this study aligns with the "multi-corridor, multi-core" requirements specified in the public draft of the "Master Plan for Territorial Space of Harbin City (2021–2035)" [58]. It is situated along the Songhua River and its tributary corridors, adhering closely to the actual planning. This is in accordance with the government's guiding principle of prioritizing ecological protection. Based on our research findings, a more detailed spatial planning for the central urban area can be achieved, contributing to the enhancement of ecological conservation

and management of the Songhua River and important lakes and wetlands, and improving the quality and stability of the ecosystem.

(6) In light of the observation that the ecological component within the methodology and analysis of our study could be further emphasized, we propose to enhance the ecological dimension in future research. This enhancement would involve integrating biodiversity indices and ecosystem service evaluations into our data sources. Additionally, we advocate for the inclusion of field-based ecological surveys that focus on specific flora and fauna to assess biodiversity thoroughly.

5. Conclusions

In this study, ecological sensitivity and the MSPA-MCR model were used to construct the ecological security pattern, in the urban central district of Harbin. The results are as follows:

(1) Highly sensitive areas mainly exist in the southeastern mountainous and forested regions, constituting a small portion of only 3.71% of the total study area. In contrast, the majority of the area exhibits moderate and low ecological sensitivity, indicating overall ecological stability is stable.

(2) The study identified 23 ecological source areas through MSPA calculations and landscape connectivity assessments, encompassing 21.23% of the total study area. Additionally, 48 ecological corridors were delineated, with a total length of 807.17 km. Among these, 10 important corridors spanning 82.55 km and 8 vital connecting corridors covering 195.26 km were identified. A total of 126 ecological nodes were pinpointed, including 61 first-level nodes and 65 second-level nodes. Furthermore, 75 ecological breakpoints were identified, consisting of 31 railroad breakpoints and 44 road breakpoints.

(3) Based on the resistance values present in the composite resistance surface, the study categorized ecological safety areas into five levels. The highest percentage was occupied by high-level ecological safety areas, amounting to 45.75% of the total study area.

(4) The proposed layout for optimizing the ecological security pattern (ESP), known as the “two axes, two belts, and four areas,” serves as a valuable guideline for ecological restoration within Harbin’s urban central district. Additionally, the process of constructing the ecological security evaluation system outlined in this study can be used as a reference and learning resource for similar studies focused on ESPs in urban areas.

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