RESEARCH ARTICLE

# Construction of the municipal ecological network based on morphological spatial pattern analysis (MSPA) model and ecological conservation importance evaluation

Li Hong*, Meiling Miao, Yuqi Fan, Xiaojing Yuan, Heya Zhao

College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, Heilongjiang, China.

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**For resource-based cities, it is especially pressing to mitigate ecological deficits and foster economic transition through the development of ecological networks. As exemplified by Hegang City, Heilongjiang, China, which faces the dual pressures of coal resource depletion and ecological degradation, optimizing its industrial and spatial layout *via* ecological networks has become imperative. This study selected the municipal area of Hegang City, Heilongjiang, China as the research region to comprehensively identify ecological sources by integrating morphological spatial pattern analysis (MSPA) with ecological conservation importance evaluation results through overlay analysis. A comprehensive resistance surface was constructed using seven resistance factors extracted based on the minimum cumulative resistance (MCR) model. Potential ecological corridors in the study area were hierarchically classified according to the gravity model, ultimately establishing the landscape ecological network of Hegang City. The results demonstrated that MSPA analysis revealed core areas occupied the highest proportion of 48.39% of Hegang's landscape and dominated by forest land and water bodies. Thirteen ecological sources were identified including 10 major and 3 minor sources. Gravity model analysis delineated 19 important potential ecological corridors and 59 general corridors. Existing corridors predominantly clustered in northern and southeastern Hegang, while ecological connectivity remained weak in central, northeastern, and southern regions, indicating that priority should be given to corridor construction between Luobei County and Suibin County. These findings enhanced the scientific rigor and structural integrity of Hegang's ecological network framework, providing critical references for future network optimization and ecological restoration initiatives.**

**Keywords:** ecological conservation; minimum cumulative resistance (MCR) model; morphological spatial pattern analysis (MSPA).

***Corresponding author:** Li Hong, College of Horticulture and Landscape Architecture, Northeast Agricultural University, Harbin, Heilongjiang 150030, China. Email: hongli@neau.edu.cn.

## Introduction

The rapid advancement of urbanization has intensified conflicts between urban development and environmental protection, severely disrupting the balance between natural transformation and ecological equilibrium. Establishing urban landscape ecological network systems through scientific approaches, restoring fragmented urban patches, and enhancing ecological network quality have emerged as one of the most pressing challenges demanding urgent resolution [1]. In the evolution of ecological network research, Europe and North America have adopted distinctly different approaches to its construction. In North America, research has centered on core areas including national parks, natural and cultural heritage sites, and nature reserves. Greenway networks are integrated with undeveloped land to develop greenway systems oriented toward recreational and aesthetic functions. In contrast, Europe prioritizes the construction of ecological network systems in highly developed regions with the aim of balancing economic vitality and ecological restoration. Through measures such as habitat corridor restoration and watershed ecological compensation, Europe pursues dual objectives of safeguarding the integrity of wildlife habitats and enhancing the ecological functions of river systems. Following long-term practice, both regions have established comprehensive technical frameworks covering planning, implementation, assessment, and dynamic maintenance [2]. Contemporary urban spaces increasingly confront challenges such as ecological patch fragmentation and intensifying heat island effects. Ecological corridor construction as an approach to organically link these fragmented patches can effectively enhance ecosystem self-regulatory capacity. As meso-scale implementation units, municipal ecological networks play a pivotal role in planning initiatives targeting the mitigation of urban ecological crises. As a typical resource-based city undergoing transformation in the cold region of Northeast China, Hegang City must adhere to the “mountains, rivers, forests, farmlands, lakes, grasslands, and deserts” community with a shared life as the fundamental principle for ecological network optimization. Guided by the territorial spatial development and protection pattern, and integrating regional ecological fundamentals with urban transformation needs, Hegang should build an ecological network defined by “strengthened core ecological sources, connected corridor systems, and integrated urban-rural spaces”.

“Dual evaluation” provides effective theoretical support and scientific guidance for the preparation of territorial spatial planning by assessing the carrying capacity of natural resources and the environment for human activities and the appropriateness of development [3]. As a fundamental component of the "dual assessment" framework, the assessment of the importance of ecological protection focuses primarily on evaluating the importance of ecosystem service functions and ecological vulnerability [4]. Building upon this assessment, further research on ecological space identification and ecological security pattern construction facilitates the scientific delineation of ecological spatial patterns, which holds significant reference value for delineating ecological conservation redlines and optimizing ecological space planning, providing critical guidance for maintaining regional ecological stability and sustainable development. Morphological spatial pattern analysis (MSPA), a mathematical morphology-based image processing method, employs erosion and dilation operations to extract geometric features of landscape elements. By converting raster data into binary classifications, MSPA quantifies landscape connectivity and fragmentation levels, categorizing landscapes into seven types of core areas (continuous habitats), edge areas (habitat transition zones), perforations (internal disturbance zones), among others [5]. While MSPA significantly enhances the accuracy and scientific rigor of ecological source identification, it fails to reflect the intrinsic ecological functions of these sources. Currently, the evaluation of ecological conservation importance is primarily conducted through the overlay evaluation method, which involves overlaying single-factor evaluation results of ecosystem service functions and ecological vulnerability to derive comprehensive ecological conservation importance outcomes. This approach delineates critical ecological conservation areas within the study region and reflects the stability and health status of ecosystem units, providing essential insights into the complexity and dynamic changes of ecological environments [6]. Wang *et al*. applied remote sensing (RS) and geographic information system (GIS) technology platforms and drew upon references of the $14^{th}$ Five-Year Plan for Ecological and Environmental Conservation of Heilongjiang Province and the

Ecological Conservation Red-Line Delineation Guide in addition to previous research findings to integrate MSPA with ecological conservation importance evaluation through overlay analysis for the identification of ecological sources in the research area [7]. In addition, the minimum cumulative resistance (MCR) model was used to construct a comprehensive resistance surface by calculating the least-cost paths for ecological flows during spatial diffusion, thereby identifying potential ecological corridors for the network. The combination of MSPA and MCR models enabled more scientifically grounded identification of ecological sources and construction of ecological corridor networks, which has now become a paradigm for landscape ecological network construction [8].

By applying the MCR model and gravity model, this study identified potential ecological corridors within the research area. A gravity model matrix was constructed to screen and hierarchically classify these corridors, ultimately generating a potential ecological network structure map for Hegang City, Heilongjiang, China. Through analyzing the inherent challenges in Hegang's ecological network configuration, corresponding optimization strategies were proposed to enhance its structural integrity and functional connectivity, which provided a theoretical reference for studies on municipal ecological network construction at the same scale and held significant practical significance for promoting the dynamic balance between ecological protection and urban development.

## Materials and methods

### Overview of the study area

Hegang City, Heilongjiang, China is located in the transitional zone between the Lesser Khingan Mountains and the Sanjiang Plain with geographic coordinates of 129°39' to 132°31'E and 47°03' to 48°21'N. The city inclines from the northwest towards the south and boasts diverse landforms including low mountains, hills, undulating plains, valleys, and alluvial flats, covering an area of 146.8 $km^2$. The city has a typical northern temperate continental monsoon climate, with a long-term average annual precipitation of 649.3 mm, mainly concentrated in summer. The average annual temperature is 3.5°C. Winter is long and cold. Spring is dry with little rain, strong winds, and large temperature differences. Summer sees both high temperatures and rainfall peak simultaneously with precipitation unevenly distributed in time and space. Autumn is characterized by strong winds and large diurnal temperature variations. Due to its topography and climate, the region is susceptible to natural disasters such as soil erosion, drought, and floods.

### Data sources and pre-processing

The study integrated multiple national and remotely sensed datasets. Meteorological observations were obtained from the China Meteorological Data Service Center (http://data.cma.cn/), which included precipitation and temperature data from the China Climate Normal Value Dataset (1991 – 2020), evapotranspiration information from the Chinese Terrestrial Ecosystem Dataset that reported the transpiration-to-evapotranspiration ratio, while wind-speed records were drawn from the daily meteorological dataset of basic meteorological elements compiled from China's National Surface Weather Stations. Topographic and vegetation indices were acquired from the geospatial data cloud (https://www.gscloud.cn/) including digital elevation model (DEM) data and normalized difference vegetation index (NDVI) dataset, while annual net primary productivity (NPP) data for the period of 2000 - 2020 were also included. Soil-type distribution was sourced from the National Glacial Frozen Soil Desert Data Center (https://www.ncdc.ac.cn/portal/) using the China soil dataset based on the Harmonized World Soil Database (HWSD) v1.1. Land-use information was provided by the National Geomatics Center of China *via* the GlobeLand30 Dataset (2000 – 2020) ( http://globeland30.org/). Preprocessing steps were conducted by using ArcGIS 10.8 (https://www.arcgis.com/) including mosaic, reclassification, resampling, and coordinate system transformation with spatial resolution standardization to 30 m × 30 m.

**Identification of ecological sources**

**(1) Evaluation of ecological conservation importance**

Both the model method and the net primary productivity (NPP) quantitative index method were used to quantify the importance of ecological conservation in Hegang City [9, 10]. This approach has been confirmed to achieve satisfactory outcomes in the biodiversity maintenance function in provinces of Guangxi [11], Henan [12], and Heilongjiang [13], respectively. The evaluation was carried out from five perspectives including water conservation, soil conservation, biodiversity maintenance, soil erosion, and land desertification. Based on the ecological baseline conditions of Hegang City, water conservation capacity was designated as the core indicator for assessing the water conservation ecological function with the calculation as follows [14].

$$R = P - E - W \quad (1)$$

where $R$ was the regional water conservation volume. $P$, $E$, and $W$ were precipitation, evapotranspiration, and surface runoff, respectively. The revised universal soil loss equation (RUSLE) was adopted to compute the difference between potential and actual soil erosion, thus obtaining the evaluation results for the soil and water conservation function as below [15].

$$A_c = R \times K \times L \times S \times (1 - C) \quad (2)$$

where $A_c$ was soil conservation volume. $R$, $K$, $L$, $S$, and $C$ were rainfall erosivity, soil erodibility, slope length, slope gradient, and vegetation cover, respectively. Given the current scarcity of accurate multi-level species distribution data in Hegang City, this study employed the net primary productivity (NPP) quantitative index method to evaluate the biodiversity maintenance capacity of the city's ecosystems with the calculation below [16].

$$S_{bio} = NPP_{mean} \times F_{pre} \times F_{tem} \times F_{alt} \quad (3)$$

where $S_{bio}$ was the biodiversity maintenance capacity index. $NPP_{mean}$, $F_{pre}$, $F_{tem}$, $F_{alt}$ were average net primary productivity, average precipitation, average temperature, and altitude factors, respectively. A set of key indicators were selected to assess soil erosion sensitivity by drawing on the principles of the universal soil loss equation (USLE) as follows [17].

$$SS_i = \sqrt[4]{R \times K \times LS \times C} \quad (4)$$

where $SS_i$ was the soil erosion sensitivity index. $R$, $K$, $L$, $S$, and $C$ were rainfall erosivity, soil erodibility, slope factor, and vegetation cover, respectively. In accordance with the interim regulations on ecological function zoning, the indicators of the number of sand-driving wind days, soil texture and vegetation coverage, and the aridity index were chosen with the calculation as follows [18].

$$D = \sqrt[4]{I \times W \times K \times C} \quad (5)$$

$$I_i = 0.16 \times \frac{Annual\ Accumulated\ Temperature \geq 10°C}{Annual\ Precipitation\ during\ the\ period\ of\ Temperature \geq 10°C} \quad (6)$$

where $D$ was the land desertification sensitivity index. $I$, $W$, $K$, and $C$ were aridity index, days with wind speed > 6 m/s, soil texture and vegetation cover, respectively. By using ArcGIS software, the importance of ecosystem service function and ecological vulnerability results were calculated. Through overlapping analysis, the level of importance of ecological conservation was determined [19]. The reclassification tool was employed to classify the level of importance from high to low as follows.

$$S_i = \max(M_i, N_i) \quad (7)$$

where $S_i$ was the ecosystem service level for the $i$-th spatial unit. $M_i$ was the importance of ecosystem service function. $N_i$ was the level of ecological vulnerability.

**(2) Morphological spatial pattern analysis (MSPA)**

The land use types of Hegang City were reclassified using ArcGIS software. Forest land and water bodies, representing habitats of optimal quality, were designated as foreground elements and assigned a value of 2, while other land use types were classified as background elements with a value of 1. MSPA was conducted using the Guidos Toolbox software (https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/), categorizing the landscape into seven distinct types including core, edge, perforations, islet, bridge, loop, and branch. Core patches characterized by larger area, lower fragmentation, and intact morphology were selected from the core areas as candidate ecological sources. The ecological conservation importance evaluation results were overlaid with the MSPA-derived core patches in ArcGIS to determine the spatial distribution of ecological sources within Hegang City.

**Construction of potential ecological corridors based on the MCR model**

MCR model was primarily employed to identify the least-cost paths between ecological sources, thereby extracting potential ecological corridors. By using ArcGIS software, the minimum cumulative resistance paths from each ecological source to other regions were calculated, serving as optimal routes for ecological corridors as follows [20].

$$MCR = f_{min} \sum_{j=n}^{i=m} D_{ij} \times R_i \tag{8}$$

where $f_{min}$ was the function reflecting the proportional relationship between MCR and variables $D_{ij}$ and $R_i$. $D_{ij}$ was spatial distance from source $j$ to spatial unit $i$. $R_i$ was resistance coefficient of spatial unit $i$. The resistance surface reflected the degree of hindrance posed by different land use types to ecological flows. The selection of resistance factors was based on a comprehensive consideration of three categories including landscape factors, natural factors, and anthropogenic factors (Table 1). Based on existing research and the physiographic conditions of the study area, single factors for constructing the resistance surface including land use type, slope, elevation, NDVI, and road networks were extracted. Each resistance factor was reclassified and assigned corresponding resistance values. The weights of resistance factors were determined through a combination of relevant studies and the analytic hierarchy process (AHP). According to the influence degree of each factor on species migration, resistance was categorized into five grades with resistance coefficients ranging from 1 to 5. Higher assigned values corresponded to stronger resistance to species dispersal. By using the weighted overlay tool, the resistance surfaces of individual factors were integrated to generate a comprehensive resistance surface [21].

**Ecological corridor simulation and hierarchical classification based on the gravity model**

In ecological corridor analysis, the gravity model quantified the interaction intensity between ecological sources. By analysing least-cost paths, the interaction force for each source pair was calculated to construct a gravity model matrix. Potential ecological corridors identified as least-cost paths between sources were classified into important and general corridors based on interaction intensity as below [22].

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{(\frac{1}{P_i} \times lnS_i)(\frac{1}{P_j} \times lnS_j)}{\left(\frac{L_{ij}}{L_{max}}\right)^2} = \frac{L_{max}^2 \ln(S_i S_j)}{L_{ij}^2 P_i P_j} \tag{9}$$

where $G_{ij}$ was the interaction intensity between patches $i$ and $j$. $N_i$ and $N_j$ were the weight values of patches $i$ and $j$, respectively. $D_{ij}$ was standardized resistance value of the potential ecological corridor between patches $i$ and $P_i$. $P_j$ was the ecological resistance values of patches $i$ and $j$. $S_i$ and $S_j$ were areas of patches $i$ and $j$. $L_{ij}$ was the cumulative resistance value of the potential ecological corridor between patches $i$ and $j$. $L_{max}$ was the maximum cumulative resistance value among all corridors in the study area.

**Table 1.** Classification of indicators for constructing the comprehensive resistance surface in Hegang City.

| Resistance indicator | Resistance factor | Weights | Resistance value | | | | |
|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 |
| Ecological factor | Altitude (m) | 0.189 | < 133 | 133 - 253 | 253 - 379 | 379 – 538 | > 538 |
| | Elevation (°) | 0.104 | < 3 | 3 - 7 | 7 - 11 | 11 - 16 | > 16 |
| | NDVI | 0.057 | > 0.8 | 0.6 - 0.8 | 0.4 - 0.6 | 0.2 - 0.4 | 0 - 0.2 |
| Human factor | Distance to water (m) | 0.223 | < 500 | 500 - 1,000 | 1,000 - 1,500 | 1,500 -2,000 | > 2,000 |
| | Distance from road (m) | 0.090 | > 2000 | 1,500 – 2,000 | 1,000 -1,500 | 500 -1,000 | < 500 |
| | Distance from residential area (m) | 0.037 | > 2000 | 1,500 – 2,000 | 1,000 -1,500 | 500 -1,000 | < 500 |
| Landscape factors | Land use type | 0.3 | Woodland | Waters, wetlands | Grasslands | Plow land | Building land, bare land |

## Results

### Analysis of land use type

Eight types of land use including woodland, shrubland, grass land, construction land, bare land, cropland, water body, and wetland were identified in this study (Figure 1). The results indicated that, from 2000 to 2020, woodland in Hegang City exhibited a significant upward trend, covering 45.86% of the total area and reaching 6,732.24 km², which was mainly distributed in the northern and western mountainous areas. Cropland occupied roughly 6,541.41 km² or 44.56% of the total area, mainly concentrated in the transitional plain of southeastern Hegang City. Open water area consisted of the major river system of Heilongjiang and Songhua rivers and 142 medium and small rivers with the total amount of water resources being 31 billion $m^3$. The city's forest coverage rate stood at a remarkable 43.22%, enriched by abundant wildlife resources. Hegang boasted three national forest parks, two national wetland parks, and several provincial nature reserves, forming a geographical pattern of "a city surrounded by mountains and rivers with forests in between". This spatial layout significantly contributed to the city's sustainable development and biodiversity conservation.

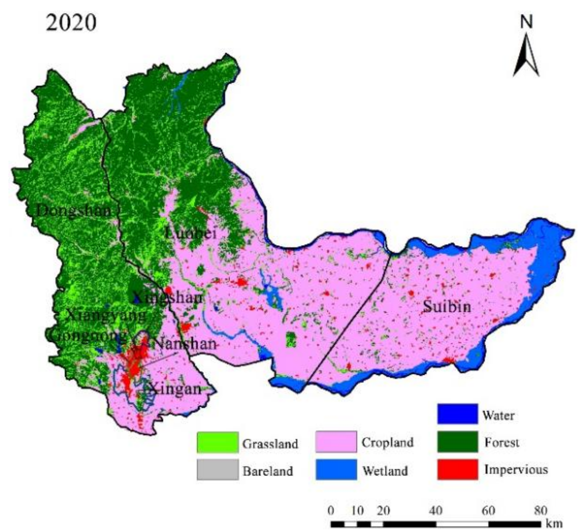


**Figure 1.** Analysis of land use type of Hegang City.

### Identification of ecological sources based on MSPA and ecological conservation importance evaluation

**(1) Analysis of landscape types using MSPA**

The ecological structure of Hegang City was dominated by core areas, which accounted for 48.39% of the total area. These core areas were concentrated in the northern and southeastern regions, forming large-scale continuous natural habitats with relatively low overall fragmentation risk. However, localized "hollowing-out" phenomena caused by perforations (0.52%) and islets (0.09%) necessitated strict development controls and restoration of degraded zones. Other landscape types collectively constituted less than 5%, indicating significant land cover homogenization and heavy reliance on core areas for ecosystem services. Regarding transitional zone characteristics, the combined proportion of edge areas (1.55%), islets, and perforations totalled 2.15%, reflecting narrow transitional

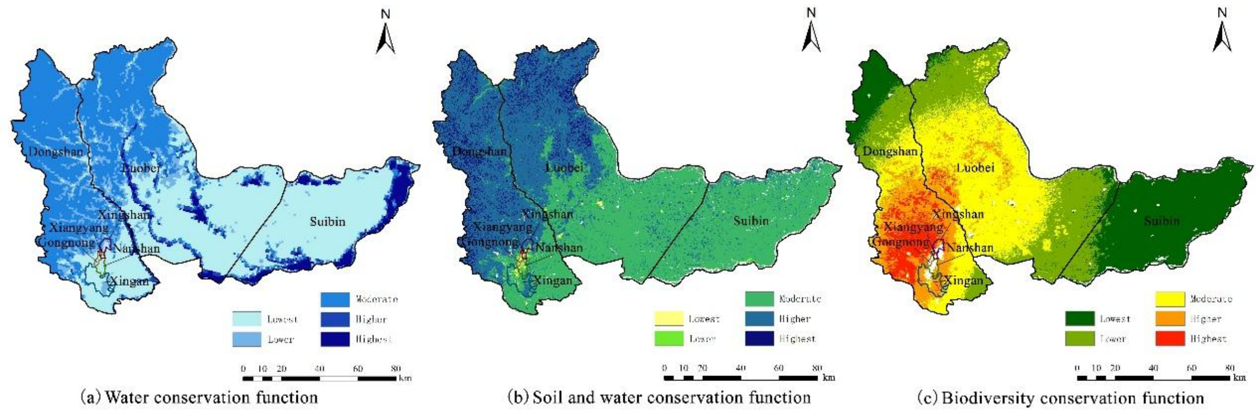


**Figure 2.** Single-layer evaluation results of the importance of ecosystem service function in Hegang City.

zones between core areas and the background matrix. This spatial configuration might hinder species dispersal due to localized habitat fragmentation, underscoring the need for buffer zone establishment to curb urban expansion. In terms of ecological connectivity, bridge zones, branches, and loops collectively occupied only 0.3%, appearing as scattered point-line structures (Table 2). The lack of effective corridor connections between core areas resulted in an "isolated island" pattern within the ecological network. Based on relevant studies and Hegang's physiographic conditions, core patches larger than 30 km² were selected as critical ecological sources for the city.

**Table 2.** Analysis of MSPA results in Hegang City area.

| Landscape type | Area (km²) | Proportions (%) |
|---|---|---|
| Core | 7,095.48 | 48.39 |
| Islet | 12.47 | 0.09 |
| Perforation | 75.77 | 0.52 |
| Edge | 226.89 | 1.55 |
| Loop | 4.94 | 0.03 |
| Bridge | 10.60 | 0.07 |
| Branch | 29.00 | 0.20 |

**(2) ArcGIS-based evaluation of ecological conservation diversity in municipal areas**

Soil and water conservation was a key indicator in the single-layer evaluation of the importance of ecosystem service function in Hegang City. Areas with the strongest capability of water conservation account for 4.6% of the study area, primarily distributed along the riverbanks in Suibin County and the central river areas of Luobei County. Areas with relatively strong capability of water conservation took up 469.76 km², representing 3.2% of the total area, and were mainly located in the high-altitude mountainous areas of northern Luobei County and northern Dongshan District, where there were dense forest and low evapotranspiration (Figure 2a). Areas with the strongest capability of soil conservation covered a total of 1,086.32 km², accounting for 7.4% of the study area. They were scattered across the northwestern and northeastern mountainous areas of Luobei County, as well as the northwestern foothill of Dongshan District. Areas with relatively strong capability of soil conservation covered 6,092.2 km², making up 41.5% of the total area, and were concentrated in the northern part of Luobei County and Dongshan District. These areas featured dense vegetation coverage and undulating terrain (Figure 2b). Areas with the strongest capability of biodiversity maintenance encompassed 785.38 km², representing 5.35% of the total area, and were concentrated in the northwestern part of Xingan District and the central part of Dongshan District. Areas with relatively strong capability of biodiversity maintenance covered 1,751.32 km² or 11.93% of the total, mainly distributed in the central and western part of Dongshan District, Xingan

District, and the mid-western areas of Luobei County (Figure 2c). These areas usually had high forest coverage and abundant water resources, which naturally formed a sound environment for local biodiversity. The quantitative results demonstrated that areas that held significant ecosystem service function in Hegang City covered 2,099.24 km², accounting for 14.3% of the total city area. These areas were predominantly concentrated along the riverbanks in Suibin County and the northern, central, and northern mountainous areas of Luobei County and Dongshan District. Areas that held significant ecosystem service function spanned 952.73 km², representing 6.49% of the study area, and were primarily found along the riverbanks in Suibin County and the central riverine areas of Luobei County. Areas that held basic ecosystem service function took up 1,146.51 km², making up 7.81% of the total, and were concentrated in the northern part of Luobei County and the northern mountainous areas of Dongshan District (Figure 3). These areas featured high forest coverage and low evaporation rate with little human disturbance.

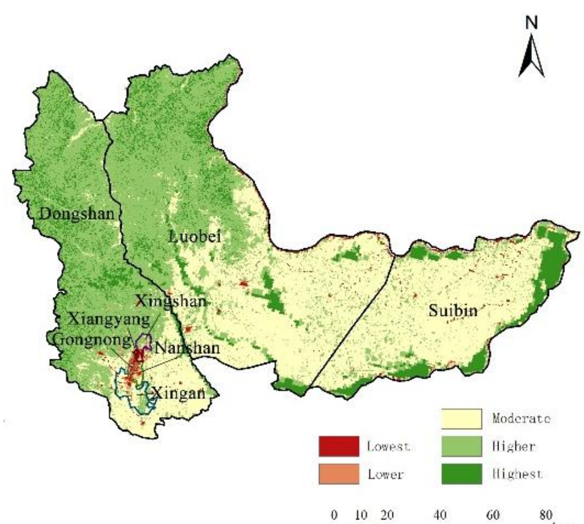


**Figure 3.** Quantitative evaluation of the importance of ecosystem service function in Hegang City.

It was known from the single-layer evaluation results of ecological vulnerability that, in Hegang City, few areas covering 5.92% of the study area were highly susceptible to soil erosion and were predominantly distributed in the western and northern foothill of Luobei County as well as the western mountainous areas of Dongshan District (Figure 4a). These areas were usually undulating, suffered from great erosion of soil, and surrounded by numerous gullies and valleys. Areas that were susceptible to soil erosion spanned 2,257.78 km², accounting for 15.38% of the total area, and were mainly located in the central and northern part of Luobei County, northern Dongshan District. Some were scattered throughout the southeastern Luobei County and the western and northeastern part of Suibin County. Land desertification was one of the key factors influencing the ecological vulnerability (Figure 4b). Areas that were most sensitive to land desertification covered 2,072.82 km², representing 14.12% of the study area, and were concentrated in the central and eastern cultivated land of Suibin County. The areas that were moderately sensitive to soil erosion encompassed 2,171.17 km², making up 14.79% of the total area, and were mainly distributed in the eastern part of Luobei County and the western part of Suibin County, where herbaceous plants were the main type of vegetation due to frequent sandy and windy days. The comprehensive evaluation results of ecological vulnerability in Hegang City showed that the city was occupied by generally and moderately vulnerable areas. Areas with extreme ecological vulnerability covered 2,916.92 km², accounting for 19.87% of the total city area. These areas were primarily concentrated in the eastern part of Suibin County, where there was flat terrain for agricultural planting. The winter there was cold and dry and there were numerous windy days all year round. Some areas with extreme vulnerability were scattered in the northern part of Luobei County and the northwestern mountainous areas of Dongshan District. Areas with moderate ecological vulnerability spanned 4,035.53 km², making up 27.49% of the total area, and were primarily distributed in the southeastern part of Luobei County and the western part of Suibin County (Figure 5).

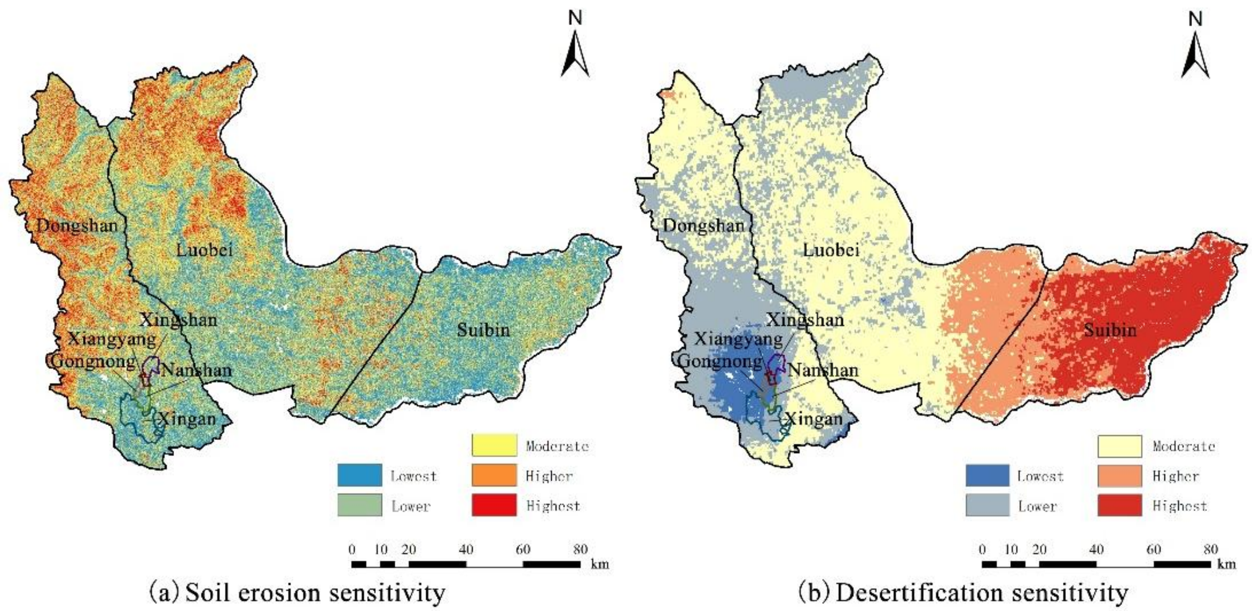


**Figure 4.** Single-layer evaluation results of ecological vulnerability in Hegang City.

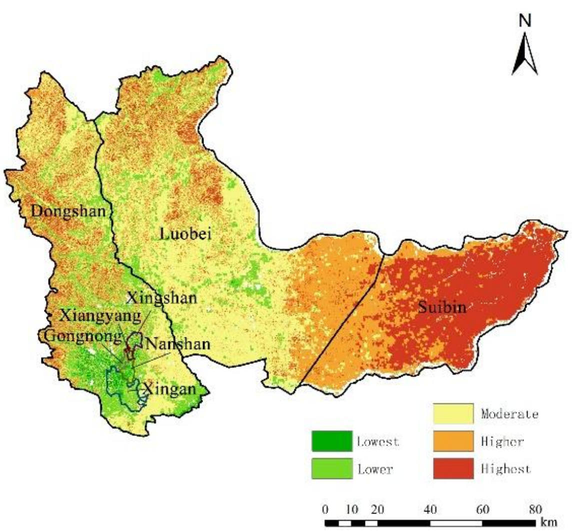


**Figure 5.** Comprehensive evaluation results of ecological vulnerability in Hegang City.

The importance of ecosystem conservation showed that areas that were extremely important for ecological conservation in Hegang City encompassed 27.36% of the total city area and were predominantly distributed in the eastern plains of Suibin County. Some were scattered in the central and northern mountainous areas of Luobei County, as well as the northern part of Dongshan District. Areas deemed moderately important for ecological conservation covered 50.79% of the total area and were mainly found in the northern part of Dongshan District, the northern and southeastern part of Luobei County, and the western part of Suibin County (Figure 6). Such distribution indicated a close relationship between the importance of ecological conservation and the geographic location of Hegang City. The northwestern part of Hegang City was mountainous, featured by dense forests, numerous mountain ranges, and undulating terrain. In contrast, the southeastern part was a transitional zone of the Sanjiang Plain with an average slope of 8°, making it susceptible to soil erosion and water loss. Therefore, these areas should be prioritized when delineating ecological conservation red lines. Specific ecological planning and management strategies should be formulated for these areas to improve ecological conservation. Through the spatial overlay analysis between core patches and the comprehensive ecological conservation importance evaluation, 10 major ecological sources and 3 minor ecological sources were identified in Hegang City (Figure 7).

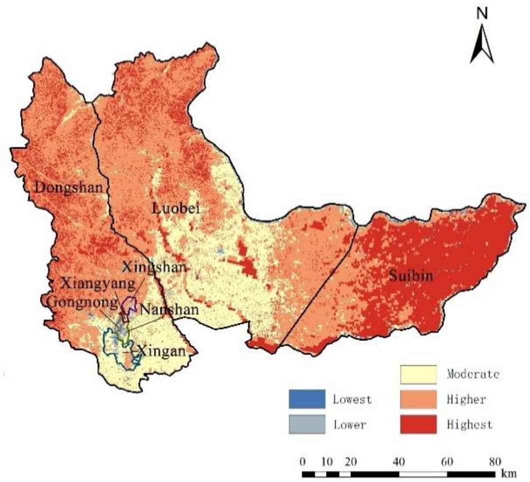


**Figure 6.** Comprehensive evaluation of ecological conservation function importance in Hegang City.

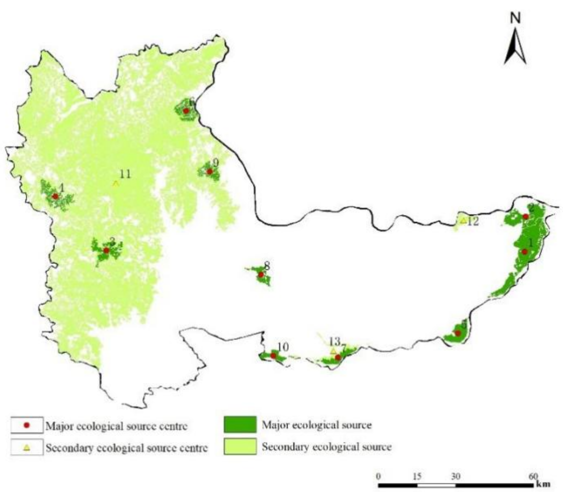


**Figure 7.** Spatial distribution of ecological sources in Hegang City.

**Resistance surface construction and potential ecological corridor identification**

The comprehensive resistance surface of Hegang City was generated by overlaying individual resistance factors. The resistance surface exhibited a "central high, peripheral low" spatial pattern. High-resistance zones were concentrated in the centrally urbanized and southwestern mining-intensive areas, characterized by dense populations and significant infrastructure fragmentation. In contrast, low-resistance zones predominantly occurred in northern forested areas, southeastern wetlands, and river corridors, where natural habitats remained intact, and ecological connectivity was robust (Figure 8).

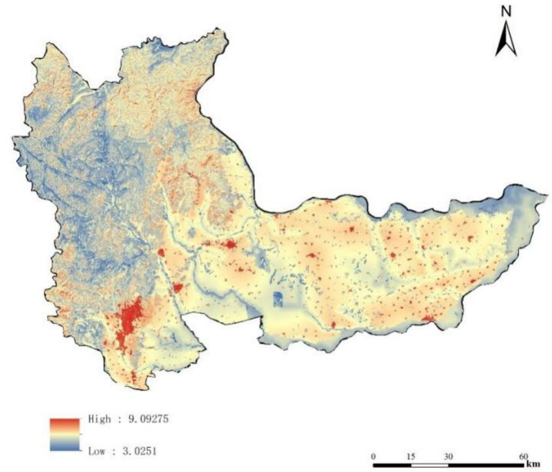


**Figure 8.** Comprehensive resistance surface of Hegang City.

Based on the 13 ecological sources and the MCR model, 78 potential ecological corridors were identified. By using the gravity model, 19 critical corridors with interaction forces exceeding 150 were prioritized, primarily connecting northern core patch clusters (Table 3). The remaining 59 general corridors were delineated to form the potential ecological network structure of Hegang City (Figure 9).

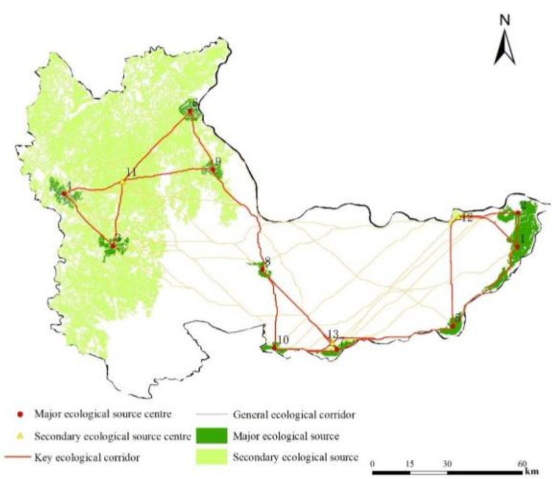


**Figure 9.** Ecological potential ecological network structure of Hegang City area.

**Table 3.** Gravity model matrix.

| Patch | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 20.34 | 24.27 | 16.62 | 13.11 | 2,170.33 | 609.87 | 17.07 | 30.20 | 238.50 | 70.78 | 34.90 | 55.60 |
| 2 | | | 19.14 | 28.20 | 17.82 | 11.94 | 996.60 | 18.61 | 34.10 | 146.82 | 61.86 | 33.16 | 47.99 |
| 3 | | | | 105.40 | 142.10 | 585.42 | 529.43 | 21.04 | 83.86 | 19.50 | 55.35 | 67.27 | 39.94 |
| 4 | | | | | 120.20 | 97.96 | 912.96 | 17.71 | 46.62 | 14.78 | 36.50 | 40.27 | 26.73 |
| 5 | | | | | | 14.88 | 25.41 | 18.55 | 141.43 | 56.29 | 217.17 | 76.90 | 173.08 |
| 6 | | | | | | | 422.37 | 248.20 | 16.40 | 66.83 | 37.03 | 32.31 | 26.95 |
| 7 | | | | | | | | 56.91 | 28.04 | 67.34 | 298.82 | 32,523.74 | 627.65 |
| 8 | | | | | | | | | 165.59 | 92.39 | 79.04 | 300.18 | 411.01 |
| 9 | | | | | | | | | | 235.75 | 38.08 | 48.56 | 54.24 |
| 10 | | | | | | | | | | | 68.18 | 43.52 | 632.44 |
| 11 | | | | | | | | | | | | 28.05 | 46.67 |
| 12 | | | | | | | | | | | | | 69.31 |

The ecological corridors in Hegang city presented the spatial characteristics of “northern agglomeration - southeastern extension”. The northern forest and river confluence area formed a high-density corridor network, and the important corridors along the water system built a “Z”-shaped main skeleton, and through the north-south longitudinal corridors connecting the mountainous and plains ecosystems. The southeast wetland core area and the eastern hilly area formed the secondary network nodes, and the ecological hubs were mostly distributed in the gently sloping areas of river valleys. The central city and the southwestern industrial-mining-agricultural zone were ecologically broken due to the expansion of construction land, and only scattered general corridors existed. The central transition zone presented a medium-density network structure, and the intertwined areas of farmland and woodland formed a complex habitat interface. It was suggested to take the “Z”-shaped main corridor as the axis, implant stepping-stone patches in the southwestern fracture zone, optimize the habitat heterogeneity of the hilly transition zone, and construct a multi-level ecological network system.

## Discussion

### Identification of ecological sources and extraction of ecological corridors in the study area

This study identified ecological sources in the research area by integrating MSPA and ecological conservation importance evaluation. The results indicated that core habitats in Hegang City were well-preserved with core areas of ecological sources accounting for 48.39% of the total area. These core areas were predominantly distributed in regions with relatively intact ecosystems such as the northern foothills of the Lesser Khingan Mountains and southeastern wetlands and water bodies including national forest parks and national wetland reserves. These zones formed large-scale continuous habitat patches with low fragmentation risks. However, other landscape types occupied minimal proportions (< 5%), resulting in severely insufficient ecological connectivity and heightened risks of habitat islandization and marginalization. The sparse distribution of bridge zones, branches, and loops (collectively 0.3%) exacerbated the "isolated island" pattern of the ecological network, particularly in central urban and southwestern mining-agricultural zones. Among the 78 ecological corridors extracted by the gravity model matrix, several important corridors relied on areas with high vegetation coverage to connect the northern forests and southeastern wetlands, providing continuous habitats for species. However, they lacked alternative routes and were vulnerable to natural disasters. General ecological corridors were mainly located in the urban-rural transition zones and were of medium quality. General ecological corridors were mainly distributed in the transition zone between urban and rural areas with medium habitat quality, which could provide basic connectivity for the ecological network and mitigate the adverse effects of ecological isolation. It was recommended that the ecological network should be optimized through the construction of stepping stone patches and corridors to enhance the migration function of species.

**Recommendations for optimizing the municipal ecological network**

**(1) Supplementing ecological sources**

The ecological sources in Hegang City were predominantly distributed in the northern and southeastern regions, while central and southwestern areas exhibited significant gaps, leading to an uneven distribution of ecological sources and poor internal connectivity. To address this issue, qualified ecological source patches should be selected in the central farmland-forest mosaic zones and southwestern industrial-mining transition zones as supplementary sources. Priority should be given to restoring vegetation in abandoned mining areas and rehabilitating degraded wetlands. Establishing a "core-secondary source hierarchical system" would enhance the structural redundancy of the network and refine the current ecological spatial configuration.

**(2) Introducing stepping-stone patches**

Given the high fragmentation of habitat patches in Hegang City, stepping-stone patches should be strategically added in ecologically vulnerable zones such as urban-rural transitional areas and agricultural intensification zones following the principle of stepping-stone supplementation. These patches should be selected along major ecological corridors to fill connectivity gaps, thereby improving patch connectivity. By optimizing patch density, dispersal resistance could be reduced, and the capacity for material and energy exchange between isolated habitat patches could be enhanced.

**(3) Supplementing ecological corridors**

The ecological corridors in Hegang City exhibited a “sparse west-dense east” distribution pattern. Severe corridor deficiencies in the southwestern region had hindered material and energy flows across the municipal area. To address this issue, supplementary ecological corridors should be constructed by integrating newly identified ecological sources with existing ones, which would optimize the current ecological corridor network, alleviate resistance to species migration, and enrich biodiversity within Hegang City.

**(4) Priority on establishing an ecological framework in the central urban area**

Priority should be placed on establishing a "three cores, four corridors, multiple nodes" ecological framework in the central urban area. By using existing large ecological patches, three major ecological cores of the northern Xiaoxing'anling forest core, eastern Dulu River wetland core, and western New City green core could be developed, and core area ecological integrity could be strictly preserved through demarcation of ecological protection red lines. Going forward, optimizing Hegang's ecological network must focus on core contradictions, adopt hierarchical, categorized ecological restoration strategies, and ultimately develop an ecologically resilient network defined by “wetlands as the ecological core, forests and grasslands as green barriers, and corridors connecting urban and rural areas”, which would drive Hegang's transition from a “coal-based black city” to a “cold-region ecological green core” and offer a replicable paradigm for the sustainable development of resource-based cities.

**Limitations and future studies**

In cold regions, seasonal variations are significant, and climatic factors such as temperature, sunlight, and precipitation exhibit large fluctuations across different seasons, which exerts a remarkable impact on vegetation growth and NPP. If only the annual average NPP is used to evaluate the biodiversity maintenance function, the potential impact of such seasonal dynamic changes on biodiversity may be obscured. Biodiversity maintenance is not solely dependent on NPP. It also involves other key functions and processes of the ecosystem such as nutrient cycling and soil and water conservation. Under the background of cold climate, there may be complex interactive effects between these functions and NPP. Future studies should fully consider the regulatory effect of climate change on NPP and combine supplementary indicators such as species distribution patterns and soil physical and chemical properties to conduct a more systematic and comprehensive assessment of the biodiversity maintenance function of the ecosystem in Hegang City.

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