Post-print of Priority Area Identification for Ecological Conservation and Restoration in the Inner Mongolia Yellow River Basin

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Date: 2024-12-16T00:00:00+00:00

Abstract

How to scientifically identify priority areas for ecological protection and restoration and implement different ecological restoration strategies by zone is a major challenge facing current ecological protection and restoration efforts. This study takes the Yellow River Basin in Inner Mongolia as the research area, employs methods such as Spatial Principal Component Analysis (SPCA) and Morphological Spatial Pattern Analysis (MSPA) to conduct ecological security assessment, and identifies ecological protection and restoration areas based on landscape element matching degree. The results show that: (1) The study area is dominated by regions with medium ecological security level, accounting for 40.58% of the study area. (2) MSPA and Minimum Cumulative Resistance (MCR) model analysis reveal that there are 14 ecological source areas (accounting for 20.92% of the study area), 42 ecological corridors, and 78 ecological nodes in the study area. (3) Among the 62 sub-watersheds in the study area, there are 8 sub-watersheds with high landscape element matching grade, accounting for 23.34% of the area, and 38 sub-watersheds with low matching grade, accounting for 43.20% of the area. (4) The Level 3 ecological restoration priority zone has the largest area in the study area, accounting for 35.53%, while the Level 1 ecological restoration priority zone accounts for 18.63%. Based on the identification results of ecological protection and restoration priority areas, restoration strategies for different regions are discussed, which can provide a basis for ecological protection and high-quality development in the Yellow River Basin of Inner Mongolia.

Full Text

Abstract

How to scientifically identify priority areas for ecological protection and restoration and implement differentiated restoration strategies by zone represents a ma-

jor challenge facing current ecological conservation efforts. This study focuses on the Yellow River Basin in Inner Mongolia, employing Spatial Principal Component Analysis (SPCA) and Morphological Spatial Pattern Analysis (MSPA) to evaluate ecological security, and identifies ecological protection and restoration areas by combining the matching degree of landscape elements. The results indicate that: (1) the study area is dominated by regions with moderate ecological security levels, accounting for 40.58% of the total area; (2) MSPA analysis combined with the Minimum Cumulative Resistance (MCR) model identified 14 ecological sources (comprising 20.92% of the study area), 42 ecological corridors, and 78 ecological nodes; (3) among the 62 sub-watersheds, 8 exhibited high landscape element matching levels (23.34% of the total area), while 38 showed low matching levels (43.20% of the total area); and (4) third-level ecological restoration priority areas accounted for the largest proportion at 35.53%, while first-level priority areas represented 18.63%. Based on these identification results, restoration strategies tailored to different regions are discussed, providing a foundation for ecological protection and high-quality development in the Yellow River Basin of Inner Mongolia.

Keywords: priority areas for ecological protection and restoration; ecological security; landscape pattern; Yellow River Basin in Inner Mongolia

Introduction

Scientific identification of priority areas for ecological restoration and the implementation of zonal restoration strategies constitute a critical challenge in current ecological restoration practice. The Yellow River Basin serves as a vital ecological barrier in northern China, forming an ecological corridor connecting the Tibetan Plateau, Loess Plateau, and northern sand prevention belt within the national "Two Screens and Three Belts" ecological security strategic pattern. Due to its complex and fragile natural environment and close relationship with human activities, the ecological security of the Yellow River Basin has attracted widespread concern, with its diverse ecological problems seriously threatening regional ecosystem security and stability. Consequently, the Yellow River Basin has remained a focal region for ecological protection and construction in China, and establishing an ecological security model for areas along the Yellow River represents an essential pathway for achieving sustainable regional development.

In response to prominent ecological issues in the basin, China has successively implemented ecological projects such as returning farmland to forests and grasslands, soil and water conservation, and the "Three Norths" shelterbelt program, as well as establishing nature reserves including the Three-River-Source and Yellow River wetlands. The national strategy of ecological protection and high-quality development in the Yellow River Basin has elevated the importance and urgency of ecological protection and restoration efforts, a fact recognized by numerous researchers. In recent years, intensified climate change and human activities have dramatically altered the landscape pattern of the Yellow River Basin in Inner Mongolia, leading to declining ecosystem service capacity, biodiversity loss, and other problems. Although enhanced ecological protection and governance efforts have achieved positive results in desertification control through the "Kubuqi Model," saline-land management in the Hetao irrigation area, and comprehensive water pollution control in Wuliangsuhai, the basin remains a typical ecologically fragile zone where ecosystems are prone to degradation with difficult and slow recovery. Current ecological challenges include the decline of forests, grasslands, and wetlands, as well as desertification, soil salinization, soil erosion, and reduced biodiversity. Therefore, targeted identification of priority areas for ecological protection and restoration in the Yellow River Basin of Inner Mongolia is particularly crucial.

The identification of priority areas for ecological protection and restoration serves as a prerequisite for constructing regional ecological security patterns, maintaining ecosystem stability, and implementing conservation and restoration work. Previous studies have primarily determined priority restoration areas based on ecological security evaluation or landscape element identification. Commonly used ecological security evaluation models include the "Pressure-State-Response" (PSR) model, "Driving Force-Pressure-State-Impact-Response" (DPSIR) model, "Driving Force-Pressure-State-Exposure-Effect-Action" (DPSEEA) model, and "Driving Force-Pressure-State-Exposure-Response" (DPSER) model, often combined with spatial analysis methods. However, few studies have integrated landscape pattern analysis, making it difficult to reflect the spatial distribution patterns of regional ecological security. Since ecosystems are controlled by natural environmental elements, biological elements, and human activities, evaluation factors should reflect the mechanisms through which natural and anthropogenic factors affect complex ecosystems. As urban natural ecosystems and socio-economic systems increasingly influence each other, regional landscape patterns have undergone dramatic spatiotemporal evolution, with originally complete and homogeneous natural ecosystems gradually developing into complex and heterogeneous patterns. Such changes may reduce ecosystem service levels, thereby affecting regional ecological security.

This study addresses the Yellow River Basin in Inner Mongolia from the perspective of "environmental foundation-landscape pattern" to investigate ecological security issues. A three-dimensional framework for ecological protection and restoration evaluation was constructed, incorporating natural factors, human society factors, and landscape pattern factors. Spatial Principal Component Analysis (SPCA) was employed to evaluate the ecological security level of the study area, with the results serving as resistance surfaces. Morphological Spatial Pattern Analysis (MSPA) and the Minimum Cumulative Resistance (MCR) model were then used to identify landscape elements. By comprehensively considering ecosystem security and the matching degree of landscape elements, priority areas for ecological restoration were determined and targeted protection and restoration strategies were proposed. This research can enrich the theoretical and technical framework of watershed ecosystem security evaluation, improve the ecological security assessment system for the Yellow River Basin, and provide references for regional ecological security evaluation.

1.1 Study Area Overview

The Yellow River Basin in Inner Mongolia is located in western Inner Mongolia Autonomous Region. The Yellow River enters at Dusitu River Estuary on the Ningxia-Inner Mongolia border and exits at Magan Township in Zhungeer Banner, flowing for 843.50 km through the Ulan Buh Desert, Kubuqi Desert, Mu Us Sandy Land, Hetao irrigation area, and Tumochuan Plain, forming a "Ji" character bend between the southern foothills of the Yinshan Mountains and the Ordos Plateau. The basin spans seven leagues and cities: Alxa, Wuhai, Bayannur, Baotou, Ordos, Hohhot, and Ulanqab, covering a total area of 15.19$×10ˆ{4}$ km^2. Temperature decreases from northeast to southwest, while precipitation decreases from east to west, with more rainfall in the southeast and arid conditions in the northwest.

1.2 Data Sources

This study primarily utilized Digital Elevation Model (DEM), Normalized Difference Vegetation Index (NDVI), soil type, land use data, road data, Shannon's evenness index (SHEI), and contagion index (CONTAG) data. DEM data was used to extract slope, while land use data was used to extract water bodies, urban land, residential areas, and industrial land. ArcGIS software calculated distances to water bodies, urban land, residential areas, industrial land, and roads. Nighttime light data employed China nighttime light data. Shannon's evenness index (SHEI) and contagion index (CONTAG) were calculated using Fragstats software with a moving window method for spatial processing. The base map was produced using the standard map of the Ministry of Natural Resources (approval number GS(2019)1822), with no modifications to boundary lines. All data were unified to the WGS 1984 coordinate system and preprocessed, with raster data resampled to 30 m$×$30 m resolution. Data source details are provided in .

1.3.1 Ecological Security Evaluation

This study constructed an ecological security evaluation index system from the perspective of "environmental foundation-landscape pattern." Based on literature experience and actual conditions in the study area, the natural breakpoint method was used to classify each indicator factor into five ecological security levels: low, medium-low, medium, medium-high, and high. Spatial Principal Component Analysis was employed to obtain statistically significant principal components (cumulative contribution rate exceeding 85%), along with eigenvalues, variance contribution rates, cumulative contribution rates, and spatial loading matrices for each component. The comprehensive ecological security index was defined as the weighted sum of multiple principal components, with weights represented by the variance contribution rates of each component. The formula is:

$$ESI = \sum_{i=1}^{n} a_{ij} \times F_j$$

where ESI is the comprehensive ecological security evaluation result; a_{ij} is the loading of the i-th grid cell on the j-th principal component; F_j is the variance contribution rate of the j-th principal component; and n and m represent the number of grid cells and principal components, respectively.

1.3.2 Landscape Element Identification

Reclassified binary raster files were processed using the eight-neighborhood rule in GuidosToolbox to identify core areas as ecological sources. The probability of connectivity index (PC) is widely used to evaluate landscape connectivity, with patch importance index (dPC) calculated using Conefor 2.6 software. The formula is:

$$PC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i \times a_j \times P_{ij}^*}{AL^2}$$

$$dPC = \frac{PC - PC_{remove}}{PC} \times 100$$

where PC is the possible connectivity index of ecological patches; a_i and a_j are the areas of patches i and j (km^2); n is the number of patches in the landscape; P_{ij}^* is the maximum probability of species fusion between patches i and j; AL is the total landscape area (km^2); and PC_{remove} represents the connectivity index after removing an ecological patch.

The ecological security evaluation results served as resistance surfaces, and ecological corridors were identified based on the Minimum Cumulative Resistance model (MCR). The formula is:

$$MCR = f \min \sum_{j=1}^{n} (D_{ij} \times R_i)$$

where MCR is the minimum cumulative resistance value for ecological source patch j spreading to a certain point in space; f is the function of MCR and the product of variables $(D_{ij} \times R_i)$; D_{ij} is the spatial distance from target source patch j to other source patch i; and R_i is the diffusion resistance coefficient of source patch i in a certain direction in space.

The gravity model was used to generate interaction forces between ecological sources:

$$G_{ij} = \frac{S_i \times S_j}{L_{ij}^2} \times \frac{P_{iP}j}{\max(L_{ij}^2)}$$

where G_{ij} is the interaction force between ecological sources i and j; L_{ij}^2 is the squared cumulative resistance value of the ecological corridor between sources i and j; S_i and S_j are the areas of ecological sources i and j (km^2); and $P_{iP}j$ is the shape index between ecological sources i and j.

1.3.3 Identification of Ecological Protection and Restoration Priority Areas

Using the hydrological analysis tools in ArcGIS and DEM data for the study area, the region was divided into 62 sub-watersheds. The spatial characteristics of landscape elements in each ecological source sub-watershed were represented by the Landscape Shape Index (LSI). The weights of landscape element quantity and spatial characteristics were determined using an equal weight method, and the matching level of landscape elements was calculated using a comprehensive weighted index method:

$$R_m = 0.5 \times \sum_{i=1}^{s} Z_{mi} \times W_{mi} + 0.5 \times \sum_{j=1}^{n} Z_{mj} \times W_{mj}$$

where R_m is the matching degree of landscape elements in the m-th sub-watershed; s is the sum of important and general ecological sources in the sub-watershed; Z_{mi} is the standardized value of the landscape shape index of the i-th ecological source in the m-th sub-watershed; W_{mi} is the weight of the shape index of the i-th ecological source in the m-th sub-watershed; n is the number of landscape elements; Z_{mj} is the standardized value of the j-th landscape element in the m-th sub-watershed; and W_{mj} is the weight of the j-th landscape element in the m-th sub-watershed.

Based on the degree of ecological environmental damage, the overall restoration priority was determined, and ecological restoration priority areas were classified into three levels [20-21], as shown in .

2.1 Ecological Security Evaluation of the Yellow River Basin in Inner Mongolia

Based on the natural geographical conditions and landscape ecological status of the Yellow River Basin in Inner Mongolia, and combining relevant research findings, 14 evaluation indicators were selected across three dimensions for ecological security evaluation (), following principles of systematicity, scientificity, typicality, and operability.

In terms of natural factors, elevation and slope are primary topographic factors affecting the spatial distribution and utilization of land resources, with potential impacts on soil erosion processes and natural disasters such as landslides and collapses. Therefore, elevation and slope were selected as topographic indicators. Soil type directly influences plant production, biodiversity conservation, pollutant accumulation, and ecosystem stability. NDVI represents vegetation distribution extent, with higher vegetation coverage indicating more concentrated vegetation distribution and higher ecological security levels. Water sources provide ecosystem services for habitat improvement and maintenance; proximity to water sources indicates higher ecological security levels and facilitates ecological source expansion.

Regarding human society factors, distance to urban land reflects the impact of urban expansion on ecological security. Residential construction alters original land cover and landscape composition, with distance to residential areas indicating the intensity of human disturbance on ecosystems. Distance to industrial land reflects the impact of industrial production activities on landscape patterns. Transportation roads influence surrounding land use, causing changes in land use structure. Nighttime light data were selected to reflect the intensity of human activity impacts.

For landscape pattern factors, Shannon's evenness index (SHEI) represents the maximum possible diversity for a given landscape richness, with higher landscape richness typically indicating more stable ecosystems. The contagion index (CONTAG) reflects the aggregation degree or extension trend of different landscape composition type patches; higher values indicate good connectivity of dominant landscape types, while lower values suggest higher landscape fragmentation.

The 14 evaluation factors were weighted and overlaid in the raster calculator, and the natural breakpoint method was used to classify the ecological security evaluation results into five levels: low, medium-low, medium, medium-high, and high. Principal component analysis was performed, generating six principal components () that captured 87.82% of the information from the 14 original variables. The variance contribution rates were 43.47%, 16.44%, 10.65%, 8.15%, 5.73%, and 3.38%, respectively, indicating that these six principal components effectively explain the ecological security patterns in the study area.

Analysis of loading values revealed that among natural factors, soil type showed the highest loading (0.85) on the third principal component, while NDVI and distance to water bodies showed the highest loadings (0.81 and 0.78, respectively) on the sixth principal component. Elevation and slope exhibited relatively low loadings, indicating that soil type significantly influences ecological security in the study area, with NDVI and distance to water bodies having substantial impacts, while elevation and slope have minimal effects. Among human society factors, distance to urban land, distance to residential areas, and nighttime light index showed the highest loadings (0.83, 0.79, and 0.77, respectively) on the fifth principal component, while distance to industrial land showed the highest loading (0.71) on the third principal component, and distance to roads had relatively low loading. These results demonstrate that human activities significantly impact ecological security in the study area. Regarding landscape pattern factors, CONTAG showed the highest loading (0.86) on the first principal component, while SHEI showed the highest loading (0.82) on the fourth principal component, indicating that both landscape unit diversity and connectivity importantly influence regional ecological security, with connectivity having a greater impact.

The medium ecological security level covered the largest area (61,664.00 km^2, 40.58% of the total), with land use primarily consisting of grassland and cultivated land and relatively high vegetation coverage. Future ecological restoration measures could enhance landscape ecological security stability in these areas. Low ecological security level areas covered 6,764.90 km^2 (4.45% of the total), characterized by wasteland with sparse vegetation and poor ecological conditions, necessitating feasible restoration strategies based on comprehensive evaluation. Medium-low ecological security level areas covered 41,024.69 km^2 (27.00% of the total), with land use dominated by wasteland and grassland where ecological security could be improved through ecological corridor construction and rational utilization of ecological resources. Overall, the study area exhibited medium ecological security levels. Low ecological security areas showed relatively low connectivity, 不利于 regional ecosystem sustainable development. Therefore, more active protection measures should be implemented alongside economic development to prevent ecological deterioration and meet future development needs.

For convenience in developing ecological protection and restoration strategies, the grid-scale ecological security evaluation results were transformed to watershed-scale ecological security patterns. The ecological security level representing the largest proportion of sub-watershed area was assigned to characterize the entire sub-watershed's ecological security level [26], classifying each sub-watershed into low, medium, or high ecological security levels ([Figure 3: see original paper]). This classification showed 基本一致 consistency with the grid-scale distribution and could generally represent the study area's ecological security conditions, providing a foundation for watershed-scale identification of ecological restoration priority areas.

2.2.1 Identification of Ecological Sources

The MSPA analysis revealed that core areas were relatively large, mainly distributed in the southwestern and northern parts of the study area, while core areas in the eastern and central parts were small and fragmented ([Figure 4: see original paper]). The reclassified core patches were imported into Conefor 2.6 software for landscape connectivity analysis. Based on landscape connectivity and spatial distribution characteristics, 14 core patches were selected as ecological sources. According to the dPC calculation results and ecological source area, patches with $dPC > 50$ km were identified as important ecological sources, with the remainder classified as general ecological sources.

Ecological sources covered an area of 31,780.86 km^2 (20.92% of the study area), with important ecological sources accounting for 30,900.97 km^2. Land use in ecological sources was primarily grassland, concentrated in the southwestern and northern parts of the study area, mostly surrounded by water systems with good ecological connectivity. This distribution pattern arises because the northern part of the study area lies at the northernmost point of the Yellow River's "Ji" character bend, with favorable water resource conditions and high vegetation coverage, while the southwestern part consists of large, continuously distributed grasslands with minimal human disturbance. In contrast, the central and eastern parts of the study area are dominated by cultivated land and wasteland, representing major human activity centers with low vegetation coverage. Consequently, ecological sources in these areas are small, fragmented, and suffer from severe landscape fragmentation.

2.2.2 Identification of Ecological Corridors and Ecological Nodes

Based on the MCR model, the minimum cumulative cost distance between each ecological source patch and other ecological source patches was calculated, and these paths were overlaid to form ecological corridors in the Yellow River Basin of Inner Mongolia ([Figure 5: see original paper]). A total of 42 ecological corridors were identified, with a total length of 4,774.20 km. Using the gravity model, corridors with interaction strength > 50 between ecological sources were identified as important ecological corridors, yielding 17 important corridors with a total length of 1,271.37 km (26.63% of all ecological corridors).

The interaction strength between ecological sources in the study area showed significant differences. The strongest interaction occurred between ecological source 1 and ecological source 2 (interaction strength of 89.34), primarily due to the relatively short distance between these sources and low landscape resistance, making animal migration more likely. The weakest interaction occurred between ecological source 13 and ecological source 14 (interaction strength of 12.67), related to the long distance and high resistance values between these sources. Each ecological source was extracted as an important ecological node, and corridor intersection points were designated as general ecological nodes, yielding 16 ecological nodes (8 important and 8 general).

2.3 Landscape Element Matching Level in the Yellow River Basin of Inner Mongolia

The landscape element matching level is illustrated in [Figure 6: see original paper]. The study area contained 8 sub-watersheds with high matching levels, covering 35,464.58 km^2 (23.34% of the study area), including sub-watersheds in the northern and southwestern parts. There were 21 sub-watersheds with medium matching levels, covering 50,840.63 km^2 (33.46% of the total area), including sub-watersheds in the northern, southwestern, and southeastern parts. Low matching level sub-watersheds numbered 33, covering 65,631.53 km^2 (43.20% of the total area), primarily distributed in the central and eastern parts. Overall, the landscape element matching level in the study area was relatively low, significantly impacting watershed ecological security.

2.4 Ecological Restoration Priority Areas and Strategies

Priority levels for ecological restoration were determined by setting sub-watershed ecological security level as the primary criterion, followed by landscape element matching level (), resulting in three levels of ecological restoration priority areas ([Figure 7: see original paper]). Targeted restoration strategies were proposed for each region based on actual conditions, following principles of ecological priority, protection priority, and natural restoration as the main approach.

First-level restoration areas include 8 sub-watersheds covering 28,307.15 km^2 (18.63% of the total area). These areas generally exhibit high landscape element matching levels but low ecological security levels, which weaken the positive effects of landscape elements on ecosystems to some extent. Therefore, improving ecological security levels represents the primary focus in these 8 sub-watersheds, with restoration and remediation as key priorities. Although regional development has its geographical and historical characteristics, first-level restoration areas generally feature high urbanization levels and rapid economic growth, indicating that ecological security is affected by economic development, particularly grassland desertification, cultivated land degradation, and urban pollution—largely resulting from decades of prioritizing economic growth over ecological construction. For degraded grassland areas such as sub-watershed 2, the pace of returning farmland to pasture should be accelerated, and grazing management practices adjusted to restore stable grassland ecosystems. In mountainous areas with steep slopes such as sub-watershed 5, afforestation quality should be improved to create water conservation areas and natural green barriers. For resource-based cities like Ordos (sub-watershed 6), measures such as returning farmland to forests and vegetation restoration on unused land should be implemented to enhance ecosystem service values, ensuring that positive ecological construction impacts outweigh negative impacts from urban construction land expansion. At the northernmost latitude of the Yellow River Basin in Bayannur (sub-watershed 8), priority should focus on safety issues during the ice jam period, considering restoration of old Yellow River channels to divert water and improve the ecological environment of Wuliangsuhai and the Ulan Buh Desert.

Second-level restoration areas include 11 sub-watersheds covering 11,657.71 km^2 (7.67% of the total area), concentrated in the central part of the study area, with both low landscape element matching levels and low ecological security levels. In plain areas such as sub-watershed 15, soil salinization control should be strengthened to gradually restore soil fertility. In loess hilly areas such as sub-watershed 22, restoration should focus on terracing and greening to reduce soil erosion and reconstruct damaged landscapes. For typical arid desert areas such as sub-watershed 29, a development policy of “protection and construction with equal emphasis, protection priority” should be adopted, along with forestry sand control measures of "mainly shrubs, combining trees, shrubs, and grasses."

Third-level restoration areas include 43 sub-watersheds covering 53,973.82 km^2 (35.53% of the total area), concentrated in the eastern part of the study area, with low landscape element matching levels but medium-high ecological security levels. Therefore, landscape pattern optimization forms the basis for improving ecological security levels, requiring increased area of different landscape patch types and ensuring their sustainable development. In areas with ecological sources such as sub-watershed 35, core source boundaries should be delineated to avoid unnecessary development and destruction, strengthening connections between surrounding areas and core sources to further enhance ecological source security levels. In areas with ecological corridors and nodes such as sub-watershed 44, important corridors should be optimized, eliminating construction land encroachment on ecological corridor spaces, increasing corridor width, and planning and constructing surrounding greenways. For areas without landscape element distribution such as sub-watershed 58, future ecological restoration should focus on adjusting landscape patterns based on natural community layouts, achieving reconstruction and optimization of landscape elements through natural restoration, artificial afforestation, and grass planting to meet basic watershed ecological security requirements.

Discussion

Using spatial principal component analysis to evaluate the ecological security pattern of the Yellow River Basin in Inner Mongolia revealed that soil type, nighttime light index, and landscape connectivity have the greatest impact on regional ecological security. NDVI, distance to water bodies, distance to industrial land, distance to urban land, distance to residential areas, and landscape diversity have widespread effects, while elevation, slope, and distance to roads have insignificant impacts. The medium ecological security level covers the largest area in the study region, concentrated in the central part. This pattern occurs because sub-watersheds 9, 10, and 11 are economically developed with concentrated populations, resources, and industries, and rapid industrial growth. Cultivated land reclamation in the Hetao irrigation area and urban construction along both banks of the Yellow River have caused severe landscape fragmentation in these regions. Desert ecosystems are extremely fragile, and sub-watersheds 30, 31, and 32 exhibit low ecological security levels. High ecological security levels are mainly distributed in the western part of the study area, particularly in Ordos City (sub-watersheds 1 and 2), where grassland is the dominant land use type. These conclusions are generally consistent with findings by Yao Linjie [15], Liu Wei et al. [19], and Wang Aiqiong [24].

Integrating ecological security evaluation with landscape element identification can effectively determine ecological restoration priority areas [3,15-16,20], demonstrating strong applicability in this study region and enriching the theoretical and technical system of ecological security evaluation for the Yellow River Basin. As a critical component of the middle and upper Yellow River, the ecological issues in the Yellow River Basin of Inner Mongolia affect not only local development but also the sustainable development of downstream areas. Given the region's rich cultural heritage and tourism resources, conflicts and imbalanced development between ecological protection and economic growth are inevitable. The comprehensive evaluation index system incorporating natural and human society factors, combined with landscape patterns, provides prerequisite conditions for identifying priority areas for ecological protection and restoration.

Conclusions

As landscape ecology develops, landscape ecological security evaluation and ecological security pattern construction have increasingly attracted scholarly attention as manifestations of pattern-process feedback effects. However, most related research focuses on the entire Yellow River Basin, with few studies targeting the Yellow River Basin in Inner Mongolia specifically. This study identifies ecological protection and restoration priority areas at the sub-watershed scale in the Yellow River Basin of Inner Mongolia, laying the foundation for subsequent refined and targeted ecological restoration management. The main conclusions are:

(1) The ecological security level in the Yellow River Basin of Inner Mongolia is predominantly medium, with soil type, nighttime light index, and landscape connectivity exerting significant influence. Low ecological security areas account for 4.45% of the total area, characterized by wasteland with sparse vegetation and low connectivity between sub-watersheds, which is unfavorable for sustainable regional ecosystem development. Medium-low ecological security areas account for 27.00% of the total area, with land use dominated by wasteland and grassland. Medium ecological security areas account for 40.58% of the total area. Medium-high ecological security areas account for 23.46% of the total area. High ecological security areas account for 4.50% of the total area, mainly distributed in the western part with grassland as the primary land use type.

(2) Ecological sources in the Yellow River Basin of Inner Mongolia exhibit a distribution pattern of being abundant in the north and west, scarce in the center, and fragmented in the east, mostly surrounded by water systems with good ecological connectivity. Northern ecological sources are located at the northernmost point of the Yellow River's "Ji" character bend with favorable water conditions and high vegetation coverage. Southwestern ecological sources consist of large, continuously distributed grasslands with minimal human disturbance. Central and eastern ecological sources are dominated by cultivated land and wasteland, being small and fragmented. Longer ecological corridors are mainly distributed between northern and southern ecological sources, while shorter corridors are primarily found among eastern sources. Interaction strength between ecological sources shows significant variation due to distance and resistance values.

(3) Landscape element matching levels in the study area are relatively low, substantially impacting watershed ecological security. Sub-watersheds with high matching levels account for 23.34% of the total area, mainly in the western part with dense ecological corridors and abundant nodes. Sub-watersheds with medium matching levels account for 33.46% of the total area, distributed in the western and northeastern parts, where urbanization, mining, fenced breeding, and grassland degradation have fragmented habitats and reduced matching levels. Sub-watersheds with low matching levels account for 43.20% of the total area, concentrated in the central and eastern parts, related to poor environmental conditions and the development model of resource-based cities.

(4) First-level restoration areas are mainly distributed in the north, accounting for 18.63% of the total area, representing the most problematic sub-watersheds requiring priority restoration and management. These areas should focus on improving ecological security levels through restoration and remediation, accelerating the pace of returning farmland to pasture, adjusting grazing management practices, and implementing vegetation restoration on unused land. Second-level restoration areas are mainly distributed in the central part, accounting for 7.67% of the total area, where both ecological security levels and landscape element matching levels should be improved through spatial pattern and form-guided restoration of damaged landscapes. Third-level restoration areas are mainly distributed in the eastern part, accounting for 35.53% of the total area, where landscape pattern optimization forms the basis for improving ecological security, requiring increased landscape patch area, adjusted landscape patterns, and enhanced landscape diversity.

Overall, ecological restoration priority areas in the Yellow River Basin of Inner Mongolia are dominated by third-level restoration areas, followed by first-level restoration areas, with second-level restoration areas comprising the smallest proportion. Based on these findings, returning farmland to forests and pastures can be implemented in sub-watersheds 2, 5, and 6, scattered ecological sources in eastern Ordos (sub-watersheds 35 and 44) can be integrated, and ecological restoration projects can be prioritized in first-level restoration areas to improve the integrity of natural ecological units [27].

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