Landscape Ecological Risk Assessment and Optimization of Ecological Security Patterns in Yinchuan City (Postprint)

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Abstract

Ecological protection and high-quality development in Yinchuan City have become integral components of sustainable development in the Yellow River Basin, necessitating the optimization of regional ecological security patterns. Taking Yinchuan City as the study area, this research integrates an ecological risk assessment model and a minimum cumulative resistance model to analyze the spatiotemporal differentiation characteristics of landscape ecological risk in Yinchuan, construct an ecological security pattern, and propose ecological security protection strategies. The results indicate that: (1) The landscape ecological risk in Yinchuan exhibits a spatial distribution pattern characterized by high risk in the central-northern region and low risk in the southern region. The average landscape ecological risk indices for 2000, 2010, and 2020 are 0.2155, 0.2145, and 0.2130, respectively, demonstrating an overall declining trend in ecological risk, with risk levels generally transitioning from high to low grades. (2) A total of 22 ecological corridors and 52 ecological nodes were identified and optimized for Yinchuan, with a cumulative corridor length of approximately 511.23 km, distributed in a reticular pattern roughly oriented from northwest to southeast, sparse in the north and dense in the south. Six key corridors traverse the north-south axis, distributed along the Helan Mountain National Nature Reserve—Yellow River—Baijitan National Nature Reserve belt, forming a spatial distribution pattern characterized by "three verticals." (3) The optimized ecological security pattern for Yinchuan comprises 819.56 km^2 of ecological sources, 22 ecological corridors, and 52 ecological nodes, with targeted ecological security protection strategies proposed for the sources, corridors, and nodes, aiming to provide theoretical reference and basis for landscape ecological risk assessment and the enhancement of ecological security levels in Yinchuan City.

Full Text

Landscape Ecological Risk Assessment and Ecological Security Pattern Optimization in Yinchuan City

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Abstract: Ecological protection and high-quality development in Yinchuan City have become integral components of sustainable development in the Yellow River Basin, necessitating urgent optimization of the regional ecological security pattern. This study employs land use data from 2000, 2010, and 2020 to analyze the spatiotemporal variation characteristics of landscape ecological risk and investigate the ecological risk evolution patterns across different land use types. Using the landscape ecological risk index (ERI) and the minimal cumulative resistance (MCR) model, we propose an ecological security pattern and corresponding protection strategies. To reflect the magnitude of resistance encountered during species migration, we identified core ecological sources with areas exceeding 10 km^2, primarily distributed in natural protected areas such as Helan Mountain and Baijitan National Nature Reserve. Six resistance factors were selected, including landscape ERI, vegetation coverage, elevation, slope, distance from roads, and distance from water bodies, to calculate resistance values. Based on these ecological sources and resistance surfaces, minimal cumulative resistance values were obtained through the MCR model to preliminarily identify ecological corridors and nodes. The preliminary ecological security pattern was then optimized by integrating the 2020 land use map and MCR values, and ecological security strategies were proposed. The results demonstrate that: (1) Landscape ecological risk in Yinchuan City exhibits a spatial distribution pattern characterized by high risk in the central-northern region and low risk in the southern region. The average ERIs for 2000, 2010, and 2020 are 0.2155, 0.2145, and 0.2130, respectively, indicating an overall downward trend in landscape ecological risk over the past two decades, with risk levels transitioning from high to low grades. (2) Twenty-two ecological corridors and 52 ecological nodes were identified, with a cumulative corridor length of 511.23 km. The corridors display a net-like distribution oriented in a northwest-southeast direction, sparse in the north and dense in the south. Six key ecological corridors traverse the north-south axis, distributed along the Helan Mountain National Nature Reserve—Yellow River—Baijitan National Nature Reserve belt, forming a "three vertical lines" spatial pattern. (3) An optimized ecological security pattern for Yinchuan City was constructed, comprising 819.56 km^2 of ecological sources, 22 ecological corridors, and 52 ecological nodes. Targeted ecological security protection strategies were proposed based on this pattern, providing theoretical references and a foundation for landscape ecological risk assessment and ecological security enhancement in Yinchuan City.

Keywords: landscape ecological risk; ecological security pattern; minimal cumulative resistance model; Yinchuan City

1. Introduction

Since the reform and opening-up policy, rapid economic development has been accompanied by irrational exploitation of natural resources, leading to ecological and environmental problems such as biodiversity loss, soil erosion, land desertification, and water resource shortages, which pose significant challenges to sustainable socioeconomic development. In response, governments at all levels have actively implemented the important thought of ecological civilization construction, optimizing ecological security barriers and promoting the continuous and healthy development of regional ecological environmental quality. Consequently, conducting landscape ecological risk assessment and constructing optimized regional ecological security patterns in ecologically fragile areas have become critically necessary.

Landscape pattern and ecological processes are closely related. Adverse effects caused by human or natural factors lead to landscape ecological risk, which impacts landscape composition, structure, and function. Landscape ecological risk assessment comprehensively considers human and natural influences, employing landscape ecology methods based on landscape spatial patterns and ecological processes to reflect regional risk spatial distribution and variation characteristics. Evaluation methods primarily include risk source-sink approaches and landscape pattern-based approaches. The former inherits traditional ecological assessment models, conducting receptor analysis and exposure hazard assessment based on identified risk sources, as employed by researchers such as Li Qingpu et al. and Wang Hui et al. The latter focuses on land use/cover changes, emphasizing the impact of landscape elements on ecological risk, as utilized by scholars including Peng Jian et al., Chen Xinyi et al., and Gao Binpin et al.

Landscape ecological risk assessment and landscape pattern optimization are closely interconnected. Risk assessment provides direction for landscape optimization, while landscape optimization can enhance regional ecological security levels by optimizing the allocation of ecosystem elements, which is crucial for stabilizing ecological environments and promoting harmonious human-nature development. Primary methods for landscape pattern optimization include the minimal cumulative resistance (MCR) model, ecosystem service assessment, landscape ecological security index, and mathematical morphology. The MCR model demonstrates excellent applicability and extensibility in landscape pattern optimization, with numerous scholars employing it to identify ecological sources, corridors, and nodes to construct and optimize regional ecological security patterns.

Yinchuan City serves as an important water source conservation area and national key ecological function zone in the Yellow River Basin, featuring numerous lakes and unique wetland resources that confer significant ecological security status. However, rapid urbanization has substantially increased the frequency and intensity of human activity interference, intensifying contradictions between ecological environment and socioeconomic development, damaging regional landscape ecological functions, and increasing ecological risks. Maintaining and promoting sustainable economic, social, and ecological development in Yinchuan is crucial for ecological security in Ningxia and the entire Yellow River Basin. Therefore, this study employs land use data from 2000, 2010, and 2020 to construct a landscape ecological risk assessment model based on landscape ecology principles and MCR, exploring the spatiotemporal differentiation patterns of landscape ecological risk in Yinchuan from 2000 to 2020. Using the MCR model, we identify key landscape pattern elements, construct multilevel ecological networks, and optimize regional landscape patterns to provide decision-making basis and scientific references for landscape resource protection and ecological risk prevention in Yinchuan.

2. Study Area and Methods

2.1 Study Area

Yinchuan City is located in the central part of the Ningxia Plain, administratively comprising Xingqing District, Jinfeng District, Xixia District, Yongning County, Helan County, and Lingwu City, covering an area of approximately 9025.38 km^2. Geographically situated between 105°49 -106°35 E and 38°08 -38°53 N, the terrain slopes from high in the west to low in the east, with elevations ranging from 1100 to 1200 m and dominated by mountainous and plain landforms. The climate is temperate continental, characterized by scarce precipitation and strong evaporation, with an average annual precipitation of about 250 mm. Benefiting from the Yellow River, Yinchuan possesses nearly 200 natural lakes and marsh wetlands, earning the reputation of "Seventy-two Connected Lakes" with a wetland area of 5.31$\times10^{4}$ hm^2. Since the "13th Five-Year Plan" period, Yinchuan has pursued a development strategy of "ecology-based city, industry-strong city" to promote ecological protection and high-quality development in the Yellow River Basin and construct a northwestern ecological security barrier. However, rapid economic development has caused tremendous changes in land use structure, with various landscape elements becoming increasingly fragmented and heterogeneous, leading to ecosystem structure imbalance and dramatically increased ecological risks.

2.2 Data Sources and Processing

The primary data used in this study include land use data from 2000, 2010, and 2020; Landsat 8 remote sensing imagery; Digital Elevation Model (DEM) data; and various socioeconomic datasets. All spatial data were resampled to 30 m resolution. Remote sensing images underwent radiometric calibration, atmospheric correction, mosaicking, and cropping using ENVI 5.3 software. Data sources and descriptions are detailed in .

** Data sources of the study area**

Data Type	Data Source
Land use data	Resource and Environment Science Data Center, Chinese Academy of Sciences
Landsat 8 remote sensing imagery	Geospatial Data Cloud
Digital Elevation Model (DEM)	Geospatial Data Cloud
Socioeconomic data	Yinchuan Statistical Yearbook and "National Master Plan for Major Ecosystem Protection and Restoration Projects (2021-2035)"

Land use data were obtained from the Resource and Environment Science Data Center, Chinese Academy of Sciences, with comprehensive evaluation accuracy exceeding 90% for first-level land use types. Land use classification followed the national "Current Land Use Classification Standard" (GB/T 21010-2017), combined with the ecological environment status of the study area, dividing land into six categories: cultivated land, forestland, grassland, water bodies, construction land, and unused land for landscape ecological risk assessment in Yinchuan.

2.3 Division of Landscape Ecological Risk Units

To reasonably express the spatial heterogeneity of landscape patterns and visualize regional landscape ecological risk indices spatially, the study area was divided into risk evaluation units. Using GIS 10.6 software and referencing previous studies, grain sizes of 3 km, 5 km, and 10 km were tested for dividing the study area. After comparative analysis and considering patch sizes, watershed area, and computational workload, a 5 km$×$5 km square grid was selected for systematic sampling, yielding 361 landscape ecological risk evaluation units ([Figure 1: see original paper]). The landscape ecological risk index was calculated for each unit and assigned to the unit' s center point.

[Figure 1: see original paper] Division of ecological risk evaluation districts of the study area

2.4 Construction of Landscape Ecological Risk Model

Referencing existing research and considering the landscape pattern characteristics of the study area, we selected landscape disturbance index (Si), landscape vulnerability index (Fi), and landscape loss index (Ri) to construct the landscape ecological risk assessment model for Yinchuan. The Si index comprises landscape fragmentation index (Ci), landscape separation index (Ni), and landscape dominance index (Ki). Using Fragstats 4.2 software, we calculated landscape indices for Yinchuan from 2000 to 2020. For the weights of Ci, Ni, and Ki, we employed the expert scoring method based on previous research findings and the actual situation of the study area, assigning values of 0.5, 0.3, and 0.2, respectively. Calculation formulas and detailed meanings are provided in the literature.

The landscape ecological risk index calculation formula is:

$$Si = 0.5Ci + 0.3Ni + 0.2Ki$$

$$Ri = Si \times Fi$$

$$ERI_k = \sum_{i=1}^{n} \left(\frac{A_{ki}}{A_k} \times Ri \right)$$

where Si, Ci, Ni, Ki, Ri, and Fi represent the landscape disturbance index, landscape fragmentation index, landscape separation index, landscape dominance index, landscape loss index, and landscape vulnerability index for landscape type i, respectively; ERI_k is the landscape ecological risk index for risk evaluation unit k; A_{ki} is the area of landscape type i in unit k (km^2); and A_k is the total area of unit k (km^2).

2.5 MCR Model

The MCR model was initially applied by Knaapen et al. to landscape planning, species diffusion, and conservation biology. The widely used modified version by Yu Kongjian is expressed as:

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

where MCR is the minimal cumulative resistance value; f is a function positively correlated with the ecological process; D_{ij} is the distance from source j to target source i; and W_i is the resistance of target source i to biological migration.

3. Results

3.1 Landscape Pattern Index Changes

Landscape index results indicate significant changes in the number of patches for various landscape types in Yinchuan from 2000 to 2020, leading to notable variations in landscape dominance index, landscape disturbance index, and landscape loss index. Cultivated land, grassland, construction land, and unused land exhibited relatively high landscape dominance indices. Specifically, the dominance index of cultivated land showed a decreasing trend, while those of grassland, construction land, and unused land increased. Forestland and water bodies had smaller distribution areas and correspondingly lower dominance indices. The landscape fragmentation and separation indices of construction land gradually decreased while its area continuously increased, indicating that construction land patches became increasingly connected, developing toward contiguous patterns with enhanced aggregation and internal stability. Regarding landscape disturbance indices, construction land showed significantly higher values than other landscape types, with the most pronounced changes gradually decreasing over time, while other landscape types exhibited insignificant changes. Furthermore, landscape loss indices revealed significant changes in construction land and unused land. The loss index of construction land decreased due to continuous expansion, enhanced connectivity, and improved anti-interference capacity, while unused land showed high and increasing loss indices due to rising landscape fragmentation and separation.

3.2 Spatiotemporal Changes in Ecological Risk

The landscape ecological risk index for each risk evaluation unit was calculated using the aforementioned formula, with the entire study area’ s risk distribution obtained through Kriging interpolation. Using the equal interval method, risk levels were classified into five grades: low ecological risk (0-0.1], lower ecological risk (0.1-0.2], medium ecological risk (0.2-0.3], higher ecological risk (0.3-0.4], and high ecological risk (0.4-1.0] ([Figure 2: see original paper]).

[Figure 2: see original paper] Spatial distributions of landscape ecological risk in Yinchuan City in 2000, 2010 and 2020

The results reveal that landscape ecological risk in Yinchuan City displays a spatial distribution pattern of “high in the central-northern region and low in the southern region.” High ecological risk areas are primarily distributed in the southeastern part of Yinchuan, northeastern Helan County, and the piedmont region of Helan Mountain, where land use types are mainly cultivated land and unused land with substantial human disturbance, resulting in poor landscape connectivity and integrity and weak ecosystem anti-interference capacity. Medium and higher ecological risk areas are distributed in the central and northern parts of the study area, while low and lower ecological risk areas are mainly located in the southern part, northeastern Lingwu City, and parts of Helan Mountain.

From 2000 to 2010, low ecological risk areas in the southern part of the study area decreased significantly, with the proportion dropping by 11.15%. Lower and medium ecological risk areas continued to increase, with proportions rising by 6.39% and 7.67%, respectively. High ecological risk areas experienced a decline, with the proportion decreasing by 3.29%. From 2010 to 2020, low and higher ecological risk areas tended to decrease, while lower and medium ecological risk areas increased. High ecological risk areas showed a pattern of initial increase followed by decrease, with the proportion of medium ecological risk areas being the largest in all three years. The average landscape ecological risk indices for 2000, 2010, and 2020 were 0.2155, 0.2145, and 0.2130, respectively, indicating an overall declining trend in ecological risk across the study area.

Regarding ecological risk changes across different land use types, cultivated land is mainly distributed in higher and medium ecological risk areas, but its proportion in higher risk areas continuously decreased from 49.06% to 26.07%. Forestland and grassland are primarily distributed in lower and low ecological risk areas. Construction land is mainly found in medium and higher ecological risk areas, with its proportion in medium risk areas showing a significant increasing trend while decreasing markedly in higher risk areas. This shift occurs because urban expansion transforms construction land from dispersed to orderly, regular patterns with enhanced connectivity and anti-interference capacity, reducing loss and risk levels. Unused land is mainly distributed in medium and higher ecological risk areas, with proportions in higher and high risk areas increasing to some extent. This land type exhibits high vulnerability and loss, with loss indices increasing over time, leading to continuously rising risk levels that necessitate strengthened protection.

3.3 Analysis of Landscape Ecological Risk Level Transitions

A transition matrix of landscape ecological risk levels from 2000 to 2020 was calculated in GIS 10.6 (). The results show that areas with increasing risk levels accounted for approximately 25.82% of the total area, primarily transitioning from low to lower, lower to medium, and medium to higher risk. Areas with decreasing risk levels accounted for about 28.91% of the total area, mainly transitioning from medium to lower, higher to medium, and high to higher risk. The decreasing area was approximately 1.12 times the increasing area, indicating an overall transition from high to low ecological risk grades in Yinchuan. Despite rapid economic development, population growth, and intensified urbanization causing unreasonable land use and ecological deterioration in some areas, the implementation of policies such as returning farmland to forest and grassland and the "ecology-based city" strategy have improved the overall ecological environment, with landscape ecological risk levels generally trending downward.

** Transfer matrix of landscape ecological risk classes from 2000 to 2020**

3.4 Determination of Ecological Sources

Considering habitat patch size, spatial distribution characteristics, and biodiversity in Yinchuan, and referencing relevant literature, we identified and extracted natural protected areas, forestland patches larger than 10 km^2, and spatially continuous rivers, lakes, and wetlands as core ecological sources. Areas smaller than 10 km^2 were designated as other ecological sources, scattered in the central and southern parts of the study area. Core ecological sources are mainly distributed in the Helan Mountain National Nature Reserve in the north, the Lingwu Baijitan National Nature Reserve in the south, and relatively dispersed rivers, lakes, and wetlands in the central region, with a total area of approximately 819.56 km^2.

3.5 Construction of Resistance Surface

Based on Yinchuan' s actual conditions and data availability, and referencing Yu Jing et al.' s research, we constructed an ecological resistance surface evaluation index system. Six indicators were selected: landscape ecological risk index, vegetation coverage, elevation, slope, distance from roads, and distance from water bodies, each divided into five levels assigned values of 1, 2, 3, 4, and 5 to reflect comprehensive resistance to species migration and biological function flow (). The Analytic Hierarchy Process was used to determine the weights of the six resistance factors, with a consistency test result of CR=0.0197 (<0.1), meeting the consistency requirement. Using the raster calculator in ArcGIS 10.6 spatial analysis tools, these factors were overlaid to obtain the ecological resistance surface ([Figure 3: see original paper]).

** Evaluation index system of ecological resistance surface**

[Figure 3: see original paper] Spatial distributions of ecological resistance surface and minimum cumulative resistance value in Yinchuan City

High resistance values are mainly distributed in the Helan Mountain area in the northwest and eastern Lingwu City, while low resistance values are concentrated in the central and southern parts of the study area, showing an overall spatial pattern of high resistance in the east-west direction and low resistance in the central-southern region.

3.6 Identification and Optimization of Ecological Corridors

After determining the "core ecological sources" and ecological resistance surface, the distance tool in ArcGIS 10.6 was used to calculate the spatial distribution of minimal cumulative resistance values. Combining core ecological sources with the minimal cumulative resistance surface, the hydrology tool was employed to identify ecological corridors. Ecological nodes were determined as intersection points between "ridge lines" of high resistance value distribution and ecological corridors based on the minimal cumulative resistance surface. The preliminary landscape ecological network was then optimized by integrating the 2020 land use map and minimal cumulative resistance surface to avoid construction land and connect ecological sources such as nature reserves.

The results identified 22 ecological corridors with a cumulative length of 511.23 km, including 6 key corridors (with more than 10 ecological nodes) and 16 auxiliary corridors. Key corridors total 299.45 km, accounting for 58.57% of the total corridor length, while auxiliary corridors total 211.78 km, accounting for 41.43%. Overlaying ecological corridors with the 2020 land use map reveals that main corridors are mostly distributed in cultivated land areas, while secondary corridors are primarily in southern grassland types, with 4 main corridors passing through construction land. The northern ecological function weak area cannot form effective network coverage with ecological source areas, reducing landscape connectivity and impeding effective species flow, thus necessitating further optimization of the landscape ecological network.

Spatially, ecological corridors display a net-like distribution oriented in a northwest-southeast direction, sparse in the north and dense in the south. Six key corridors traverse the north-south axis along the Helan Mountain National Nature Reserve—Yellow River—Baijitan National Nature Reserve belt, forming a "three vertical lines" spatial pattern. Auxiliary corridors are mainly distributed in the southern Baijitan National Nature Reserve. Ecological nodes show a spatial pattern of "few in the north, many in the south," with 28 nodes distributed on key corridors and 24 on auxiliary corridors ([Figure 4: see original paper]).

[Figure 4: see original paper] Spatial distributions of ecological corridors and ecological nodes in Yinchuan City

3.7 Ecological Security Protection Strategies

As an important ecological barrier in western China, Yinchuan holds significant ecological position. The region faces long-term threats from wind-sand invasion due to its location between the Mu Us Desert and Tengger Desert, with serious desertification and salinization problems in some areas. The ecological environment remains fragile due to extensive production modes and unreasonable industrial structures, threatening overall ecological security. Land use change is a crucial factor affecting regional ecological security patterns. From 2000 to 2020, cultivated land, forestland, and unused land areas decreased, while construction land and grassland areas increased. In the northern plain area dominated by cultivated land, continuous construction land expansion has reduced cultivated land area and its capacity to resist external interference, making ecological security vulnerable. Therefore, existing cultivated land should be actively protected, urban land appropriately increased, and occupation of ecological land reduced.

The 22 ecological corridors form a northwest-southeast oriented network, sparse in the north and dense in the south, connecting core ecological sources in northern and southern Yinchuan and serving as important channels for regional ecological flow migration. Efforts should focus on increasing tree and grass species along corridors, improving vegetation quality and biodiversity, optimizing land use around corridors, ensuring connectivity, reducing resistance values, and promoting flow between ecological sources. Special attention should be paid to the 52 ecological nodes, where ecological dynamic monitoring and restoration should be combined with territorial spatial planning and ecological restoration planning, implementing appropriate engineering and biological measures to reduce regional ecological risk and ensure ecological security.

Core ecological sources are mainly distributed in Helan Mountain National Nature Reserve, the Yellow River vicinity, and Baijitan National Nature Reserve, which constitute core areas of Ningxia' s ecological protection red line and natural reserves and serve as important regional ecological barriers. Therefore, priority should be given to protecting and constructing Helan Mountain and Baijitan National Nature Reserves to maintain the stability and ecological security of these sources. The ecological corridor along the eastern foothills of Helan Mountain should be secured to build a green ecological corridor along the Yellow River, constructing a rationally distributed, functionally complete, and aesthetically pleasing plain oasis ecosystem in the Yellow River irrigation area to form a northwestern ecological security barrier.

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4. Discussion

Constructing landscape ecological risk indices based on land use is an important method for landscape ecological risk assessment, widely used by scholars to study spatial characteristics and internal formation mechanisms of ecological risk. This study, focusing on Yinchuan City, integrates ecological risk assessment models and the MCR model for the first time to analyze landscape ecological risk and optimize ecological security patterns. The results show a declining trend in landscape ecological risk from 2000 to 2020, with improved regional ecological security, consistent with findings by Wang Bo et al. Regarding risk level classification, Kang Ziwei et al. found that using the natural breaks method to classify landscape ecological risk levels yields relatively small proportions of high-risk areas in arid oasis regions, mainly distributed in areas with frequent human activities or high inherent vulnerability. Their reported high-risk area proportions of 3.79% in 2000, 5.67% in 2010, and 4.14% in 2020, primarily comprising construction land, cultivated land, and unused land, align well with our results.

Based on landscape ecological risk assessment, this study identified ecological sources, constructed resistance surfaces, and optimized ecological security patterns. Researchers typically designate nature reserves, wetlands, major rivers, or cultivated land, forestland, and grassland as ecological sources, while resistance surfaces often consider terrain factors or ecosystem service value equivalents of different land use types as evaluation elements. This study considers terrain factors while incorporating landscape ecological risk assessment results as the basis for resistance assignment, comprehensively accounting for natural conditions, human activities, and landscape pattern factors to ensure comprehensive and objective resistance values. However, when identifying ecological corridors and nodes, basing the analysis solely on ArcGIS 10.6 results may introduce errors from the actual security pattern, creating uncertainties in practical application that require further research.

5. Conclusions

1) Landscape ecological risk in Yinchuan City exhibits a spatial distribution pattern of "high in the central-northern region and low in the southern region." From 2000 to 2020, low and higher ecological risk areas decreased by 11.15% and 9.51%, respectively, while lower and medium ecological risk areas increased by 6.39% and 7.67%, respectively. High ecological risk areas showed a pattern of initial increase followed by decrease, with minimal overall change. The average landscape ecological risk indices for 2000, 2010, and 2020 were 0.2155, 0.2145, and 0.2130, respectively, indicating an overall declining trend in ecological risk across the study area, with risk levels transitioning from high to low grades.

2) An optimized ecological security pattern for Yinchuan City was constructed, comprising 819.56 km^2 of ecological sources, 22 ecological corridors (cumulative length of 511.23 km), and 52 ecological nodes. Six key corridors, totaling 299.45 km (58.57% of total corridor length), traverse the north-south axis along the Helan Mountain National Nature Reserve—Yellow River—Baijitan National Nature Reserve belt, forming a "three vertical lines" spatial pattern. Auxiliary corridors (16 corridors, 211.78 km) are mainly distributed in the southern Baijitan National Nature Reserve. Ecological nodes display a spatial pattern of "few in the north, many in the south," with 28 nodes on key corridors and 24 on auxiliary corridors.

3) Targeted ecological security protection strategies were proposed based on the optimized ecological security pattern. Priority should be given to protecting and constructing Helan Mountain and Baijitan National Nature Reserves to maintain source stability and ecological security. Efforts should focus on increasing tree and grass species along corridors, optimizing surrounding land use, reducing resistance values, and ensuring connectivity. Special attention should be paid to the 52 ecological nodes, implementing appropriate engineering and biological measures to reduce regional ecological risk and ensure ecological security.

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Note: Figure translations are in progress. See original paper for figures.