Construction and Zoning Optimization of Territorial Spatial Ecological Security Pattern in the Liupan Mountain Area: Postprint

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Abstract

The construction of ecological security patterns is an important pathway for safeguarding human well-being and healthy development, and a concrete measure for implementing the concept of life community of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts. Selecting the Liupan Mountain area of Ningxia, which holds significant ecological status and barrier functions, this study fully integrates the advantages of the InVEST model for ecosystem service assessment and the Circuitscape circuit theory landscape model for corridor identification, and adopts the "source-corridor-node" research paradigm to conduct ecological security pattern construction and ecological restoration zoning in the Liupan Mountain area. The results show that: the Liupan Mountain area contains 75 ecological sources, accounting for 21.8% of the total study area, exhibiting characteristics of mountain system patterns and county-level expansion; there are 47 critical ecological corridors with a total length of 211.6 km; pinch points and barrier points requiring priority protection and restoration number 547 and 217 respectively, with areas of 626.9 km2 and 893.9 km2 respectively; the ecological barrier zone accounts for 17.4% of the area, requiring the implementation of the strictest ecological protection measures; the conservation zone, restoration and enhancement zone, and control and regulation zone account for 6.5%, 38.2%, and 37.9% of the area respectively, requiring strengthened ecological monitoring and implementation of differentiated restoration measures, and scientifically demarcating the three zones and three lines and comprehensively coordinating the development-protection relationship. The research results can provide references for territorial ecological protection and restoration, policy formulation, and project layout in the Liupan Mountain area.

Full Text

Preamble

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Construction of an Ecological Security Pattern and Zoning Optimization for Territorial Space in the Liupan Mountain Area

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Abstract

Ecological security pattern construction represents a vital pathway for safeguarding human well-being and healthy development, and constitutes a concrete measure for implementing the “life community” concept of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts. This study selected the Liupan Mountain area in Ningxia, a region of significant ecological status and barrier function, and integrated the ecological service evaluation advantages of the InVEST model with the corridor identification strengths of the Circuitscape theoretical landscape model. Adopting the “source-corridor-node” research paradigm, we constructed an ecological security pattern and developed ecological restoration zoning for the Liupan Mountain area. The results indicate that the region contains 75 ecological sources, covering 21.8% of the total study area and exhibiting characteristics of mountain system patterns and county-level expansion. A total of 47 key ecological corridors were identified, spanning 211.6 km and representing 17.6% of all corridors. Priority protection and restoration should focus on 547 ecological pinch points and 217 ecological barriers, covering areas of 626.9 km^2 and 893.9 km^2, respectively. The ecological barrier zone accounts for 17.4% of the total area and requires the strictest ecological protection measures. Conservation areas, restoration and enhancement zones, and control and regulation zones occupy 6.5%, 38.2%, and 37.9% of the area, respectively, necessitating strengthened ecological monitoring and differentiated restoration measures, scientifically demarcated three zones and three control lines, and comprehensive coordination of development and protection relationships. These findings provide a reference for territorial space ecological protection and restoration, policy formulation, and engineering layout in the Liupan Mountain area.

Keywords: territorial space ecological restoration; ecological security pattern; circuit theory; InVEST model; Liupan Mountain

Introduction

The forward march of human society and economic development inevitably drives high-intensity human activities such as urban expansion, infrastructure construction, industrial mining, and agricultural development. These activities alter land use patterns and spatial configurations, lead to overexploitation of natural resources, cause landscape fragmentation and habitat area reduction, and trigger global issues threatening wildlife and human survival, including declining ecosystem service capacity, biodiversity loss, and climate change. Since the 21st century, the concept of sustainable development and building a harmonious coexistence between humans and nature has gradually taken root. Optimizing and balancing the relationships among ecosystem management, protection, and development has become an important issue for both government and academia.

Ecological security pattern construction serves as a crucial approach for ensuring human well-being and healthy development, and provides an important pathway for identifying key biological conservation sources, ecosystem service spaces, and ecosystem corridor patterns. The field has evolved from early qualitative landscape analysis and planning and quantitative ecological pattern analysis to rapid development in spatiotemporal pattern scenario decision-making, dynamic simulation, and trend analysis that incorporate numerous ecological theories and models. Research methods have progressed from single land use pattern analysis to enriched scenario simulation and decision analysis approaches including landscape pattern indices, minimum cumulative resistance models, InVEST models, and circuit theory landscape models, significantly improving the reliability of ecological security pattern construction and territorial space ecological restoration zoning. For instance, scholars such as Chen Xin et al. [], Wu Jiansheng et al. [], and Fu Fengjie et al. [] have conducted ecological security pattern construction and ecological restoration research in Guangdong, the Pearl River Delta, and Guangxi based on frameworks of “importance-sensitivity-connectivity,” ecosystem services and gravity models, and the general paradigm of “source identification-resistance surface construction-corridor extraction,” achieving good decision-support results.

Currently, the theories, models, and methods for ecological security pattern construction continue to improve with technological innovation, but the “source-corridor-node” paradigm remains one of the mainstream research methods in this field. Through extensive research practice, the circuit theory landscape model (Circuitscape) developed by The Nature Conservancy, which leverages the similarity between electric current and ecological flow, demonstrates theoretical and methodological advantages in corridor construction. Meanwhile, the InVEST ecosystem service supply and demand trade-off model, jointly developed by The Nature Conservancy and Stanford University, offers theoretical and methodological strengths in ecological source identification. Integrating both methods into ecological security pattern construction can leverage their respective advantages and significantly improve simulation reliability, making it one of the preferred methods in current research [**?**, **?**].

With ecological civilization construction elevated to a national strategy [], deeply implementing the concept of “systematic governance of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts as a life community,” scientifically identifying key areas for territorial space ecological protection and restoration, efficiently diagnosing ecological source, node, and corridor restoration systems, transforming ecological restoration management scales and intensities, and systematically constructing regional ecological security patterns with high quality and systematic approaches are both practical needs and hot topics []. This study takes the Liupan Mountain area in Ningxia as the research area, adopts the “source-corridor-node” ecological security pattern research paradigm [**?**, **?**], and simultaneously introduces the InVEST model and circuit theory landscape model (Circuitscape) to identify ecological sources, corridors, and ecological barrier points. On this basis, we conduct ecological security pattern construction and territorial space ecological protection and restoration zoning, providing important references for integrated, systematic, and systematic ecological restoration, policy formulation, and engineering layout in the region, while also supporting the construction of the Yellow River Basin ecological protection and high-quality development pilot zone.

1.1 Study Area Overview

The Liupan Mountain area is located in the loess hilly and gully region of southern Ningxia, with elevations ranging from 1150 to 2900 m. The terrain is fragmented with crisscrossing gullies and severe soil erosion. The Liupan Mountains sit at the southern tip of Ningxia, extending northward in two parallel columns that form the Liupan Mountain-Xihua Mountain system and the Liupan Mountain-Yunwu Mountain system. The region has a temperate semi-humid and semi-arid monsoon climate with obvious south-north humidity gradients, receiving approximately 700 mm of annual precipitation. The vegetation pattern is dominated by grassland, with forests, shrubs, and grasses distributed along the mountains []. As a major water source conservation area for first- and second-level tributaries of the Yellow River, the region has an average annual runoff of 7.28$×10^{8}$ m^3 and is known as the “wet island” on the Loess Plateau. The area hosts extremely rich flora and fauna resources, including 788 species of wild vascular plants and 291 species of wild vertebrates, accounting for 76.8% of Ningxia’s total species and earning it the title of “germplasm resource gene bank” of northwest China [].

1.2 Data Sources

The primary data requirements include ecological importance evaluation factors and ecological resistance surface construction indicators. Specific data sources are as follows: Landsat 8 OLI data were obtained free of charge from the Geospatial Data Cloud Platform (http://www.gscloud.cn). Land use data (2019) with 30 m spatial resolution were derived from the Ningxia thematic survey data of the National Ecological Environment Remote Sensing Survey. Nighttime light factor data were sourced from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn) with VIIRS model data at 1250 m spatial resolution. Normalized Difference Vegetation Index (NDVI) was extracted by inversion using ENVI remote sensing software from Landsat 8 OLI data at 30 m resolution for grain supply service calculations. Precipitation and soil data were obtained from the China Meteorological Data Network (http://date.cma.cn) and the National Forestry and Grassland Science Data Center (http://www.forestdata.cn), respectively, for water yield service simulation. Rainfall erosivity factor, soil erodibility factor, and potential evapotranspiration data were sourced from the National Earth System Science Data Center (http://www.geodata.cn, 2015) for soil conservation and water yield service simulation. Net Primary Productivity (NPP) model calculations at 250 m spatial resolution (2019) were used for carbon sequestration service simulation. Basic geographic data were collected from relevant local units and processed through projection conversion and standardization for ecological resistance surface construction.

1.3.1 Ecological Source Identification

We selected five importance evaluation factors—water yield service, habitat maintenance, soil conservation, carbon sequestration service, and grain supply—to identify ecological sources. Carbon sequestration service was calculated using the CASA model [], while soil conservation, water yield service, and habitat maintenance were calculated using the InVEST Sediment Delivery Ratio model, Water Yield model, and Habitat Quality model, respectively (Table 1). Grain supply was calculated by spatial interpolation of county crop yields from statistical yearbooks using the 2019 maximum NDVI values. The fuzzy membership function was employed for data standardization, and the Analytic Hierarchy Process (AHP) was used for weight analysis based on literature review and expert scoring [**?**, **?**], ultimately obtaining a comprehensive ecological importance evaluation index. The 95th percentile method was applied for importance classification using ArcGIS. Extremely important areas were selected, aggregated for patches smaller than 2 km, and fragmented patches smaller than 250 m were removed. Existing nature reserves were overlaid to finally identify ecological sources.

The fuzzy membership function calculation method is as follows:

$$\text{Standardized Value} = \frac{c_i - \min}{\max - \min}$$

where the standardized value is dimensionless between 0 and 1; max and min are the actual maximum and minimum values of each evaluation factor; and c_i

is the actual value of each evaluation factor [].

AHP is a practical method combining qualitative and quantitative multi-objective decision-making that completes weight calculation through establishing a systematic hierarchical structure, constructing judgment matrices, and conducting consistency tests []. The consistency test method is as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1}, \quad \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}$$

where CI is the consistency index; $\lambda_{\max}$ is the maximum eigenvalue of the matrix; n is the number of indicators; RI is the average random consistency index; and CR is the consistency ratio. When $\mathrm{CR} < 0.1$, the judgment matrix has satisfactory consistency. For this ecological service factor weight calculation, $\lambda_{\max} = 5.156$, $\mathrm{CI} = 0.039$, $\mathrm{RI} = 1.120$, and $\mathrm{CR} = 0.035$, passing the consistency test.

1.3.2 Ecological Resistance Surface Construction

The resistance surface indicates the accessibility of species movement among landscape patches, with resistance values influenced by human activity stress, landscape fragmentation, and ecological quality conditions. We selected six natural environmental factors (land use type, vegetation coverage, distance to water bodies, drought index, slope, and soil erosion sensitivity) and four socioeconomic factors (distance to residential areas, distance to mining points, distance to roads and railways, and nighttime light factor). Based on literature review and expert scoring [**?**, **?**], AHP was used to calculate factor weights ($\lambda_{\max} = 10.261$, $\mathrm{CI} = 0.025$, $\mathrm{RI} = 1.490$, $\mathrm{CR} = 0.029$, passing consistency test). The resistance surface was constructed through spatial overlay analysis (Table 2).

1.3.4 Ecological Security Pattern Construction and Zoning

Aiming to maintain regional ecological process stability and pattern security, and based on ecological importance evaluation and resistance surface construction, we used spatial overlay analysis and the circuit theory landscape model to identify key elements of the ecological security pattern, including ecological sources, corridors, barrier points, and pinch points. ArcGIS natural breaks method was employed to divide the ecological resistance surface into high, medium, and low value zones. From the perspective of regional territorial space integrity, completeness, and continuity, and guided by a “function-problem” orientation, we completed ecological security pattern construction and ecological restoration zoning based on spatial zoning combinations of pattern elements and resistance thresholds, proposing point, line, and area optimization strategies.

The circuit theory landscape model (Circuitscape) developed by McRae et al. [] was used for ecological corridor identification. The model includes Linkage Mapper, Barrier Mapper, Pinchpoint Mapper, and Centrality Mapper modules for identifying ecological corridors, ecological barrier points, ecological pinch points, and core ecological sources. The model treats ecological sources as voltage, ecological corridors as current paths, and ecological barrier areas as resistance. The specific calculation methods are as follows:

$$I_{lp} = \frac{U_{cm}}{R_{bm}}$$

where I_{lp}, U_{cm}, and R_{bm} represent current, voltage, and effective resistance, respectively. In ecological terms, R_{bm} reflects landscape fragmentation degree and blocking effects between nodes, representing habitat suitability of natural environmental factors and disturbance intensity of human activities; I_{lp} represents probability paths of species migration and movement among landscapes, identifying potential ecological corridors and key nodes based on current intensity; and U_{cm} represents core ecological sources that play key radiating or driving roles in positive ecological process succession.

2.1 Ecological Importance Evaluation and Source Identification

According to the quantile classification method used in the "Technical Guidelines for Delimiting National Ecological Protection Redlines (Trial)," single ecological importance factors and comprehensive evaluation indices were divided into five levels: extremely important, highly important, moderately important, relatively important, and generally important. Extremely important areas are key regions for maintaining ecosystem stability and security, with irreplaceable and priority protection needs.

Habitat quality extremely important areas account for 25.4% of the study area, mainly distributed north-south along the "Liupan Mountain-Nanhua Mountain" range (Fig. 2a), subject to strict spatial control by nature reserves and ecological protection redlines, forming an important regional biodiversity conservation corridor. Water yield service extremely important areas account for 32.8%, concentrated in the main Liupan Mountain area of Pengyang, Jingyuan, and Longde counties (Fig. 2b), presenting a mountain system pattern and county expansion characteristic. Soil conservation extremely important areas account for 23.9%, concentrated in the high vegetation coverage zone of "Liupan Mountain-Nanhua Mountain" and the soil and water conservation management area of Pengyang County (Fig. 2c). Carbon sequestration service extremely important areas account for 27.7%, showing a "forest-farmland" vegetation pattern and forming the "Liupan Mountain-Nanhua Mountain" forest carbon sequestration belt and the farmland carbon sequestration belt along the Qingshui River corridor (Fig. 2d). Grain supply extremely important areas account for 29.5%, mainly in Xiji County and the Qingshui River corridor (Fig. 2e).

Through spatial overlay analysis, comprehensive ecological service function extremely important areas account for 49.1% of the study area, maintaining the spatial pattern characteristics of mountain system patterns and county expansion. Ecological sources were extracted from these areas by overlaying protected areas and removing fragmented patches, yielding 75 sources covering 21.8% of the study area. The sources are dominated by natural vegetation, with grassland, shrubland, and forest accounting for 30.8%, 25.2%, and 24.3%, respectively. From a county perspective, Jingyuan and Pengyang counties have the most concentrated ecological sources, accounting for 25.2% and 24.3% of the area, respectively. Jingyuan forms the strategic core of the ecological barrier with two high-integrity patches, while Pengyang becomes the strategic core of soil and water conservation functions with 10 high-concentration patches. Using natural breaks method to set source current density thresholds, we identified 10 core ecological sources (15.0% area) at the northern and southern edges of the Liupan Mountain area, playing strategic ecological radiation roles; 22 important ecological sources (38.2% area) located in the eastern and western important buffer zones, serving as important nodes in the ecological network and security pattern; and 43 general ecological sources (46.8% area) dispersed between core and important sources, playing important buffering and transitional roles (Fig. 3, Tables 4-5).

2.2 Resistance Surface Construction and Ecological Corridor Identification

Guided by a “problem-function-stress” orientation, we selected 10 indicators from natural environment and socioeconomic factors to construct the ecological resistance surface, which not only simulates potential ecological corridor paths but also characterizes regional ecological pressure and quality conditions. Using spatial overlay and natural breaks method to set resistance thresholds, the ecological resistance surface was divided into low, medium, and high value zones, accounting for 23.4%, 44.2%, and 32.4% of the area, respectively, presenting a “two belts and two corridors” spatial pattern (Fig. 4). The two belts are the “Liupan Mountain-Nanhua Mountain” low-resistance ecological barrier belt and the “Liupan Mountain-Yunwu Mountain” low-resistance ecological barrier belt. The two corridors are the high-resistance stress corridor along the Qingshui River and the “Yuanzhou-Haiyuan” high-resistance stress corridor, forming the basic skeleton of ecological security patterns and protection-restoration efforts.

Simulation identified 120 ecological corridors totaling 1203.7 km, including 47 key ecological corridors (211.6 km, 17.6%) distributed in the “two belts” region (Fig. 5), connecting core ecological sources and forming high-density material, energy, and information exchange channels with irreplaceable roles in maintaining ecological unit continuity, integrity, and security. Important ecological corridors span 413.1 km (34.3%), mainly connecting peripheral ecological sources (Fig. 5), playing vital roles in maintaining ecosystem virtuous cycles and balance while reducing isolation of protected areas, habitat fragmentation, and degradation. General ecological corridors cover 579.0 km (48.1%), mainly connecting scattered ecological sources in the northern mountainous area (Fig. 5), crucial for reducing ecological degradation risks and enhancing ecological resilience.

Ecological pinch points and barrier points were identified based on current and resistance thresholds. Ecological corridors are squeezed into narrow areas such as natural vegetation or rivers by farmland, urban areas, or linear infrastructure, forming "pinch points" that are critical for the virtuous cycle of the ecological network system and maintenance of ecological pattern security. A total of 547 ecological pinch points were identified, with 83.2% smaller than 1 km^2, mainly distributed in the "two belts" and concentrated in Pengyang, Jingyuan, and Xiji counties (Fig. 5). Pinch points larger than 5 km^2 are fewer but have larger patch areas, mainly in the north-central arid desert belt where comprehensive stress from land desertification, soil erosion, and human activities compresses ecological corridors, making restoration of pinch points and corridor expansion an urgent need to control ecological degradation risks.

A total of 217 ecological barrier points were identified, with 67.3% smaller than 1 km^2, mainly in the south-central region with good ecosystems (Fig. 5). Barrier point types are sequentially farmland, vegetation degradation points, and towns/villages. Points larger than 5 km^2 account for 96.5%, mainly in the north-central arid desert belt where land desertification, vegetation degradation, agricultural activities, and urban construction cause barrier points to expand outward with larger patch areas. Protecting and restoring "barrier points" and "pinch points" and reducing human activity stress should be prioritized tasks in constructing regional ecological security patterns (Table 7).

2.3 Ecological Security Pattern Construction and Zoning Strategy

Through ecological resistance zoning and spatial combination of elements, the study area formed an ecological security pattern characterized by "two barriers, two corridors, and four zones." Ecological sources and nature reserves are high current density areas playing strategic ecological point and node roles. Core ecological sources and key ecological corridors constitute the ecological barrier belt, which covers 3248.7 km^2 (17.4% of the area) and requires the strictest ecological protection measures to maximize regional ecological radiation effects. Conservation areas, composed of core sources and other sources, cover 1227.8 km^2 (6.5%), dominated by high-coverage natural vegetation distributed in the eastern and northern desert areas of Pengyang County, playing important soil and water conservation and windbreak/sand fixation functions. These areas should focus on ecosystem structure optimization and function enhancement, consolidating existing ecological construction achievements and controlling ecological degradation risks through closed-slope prohibition of grazing, effectiveness monitoring, and comprehensive implementation of grassland ecology, slope-to-terrace conversion, and soil and water conservation forest construction projects.

Priority restoration areas, covering other ecological corridors beyond key corridors, total 3449.2 km^2 (18.5%). Due to ecological degradation, urban/village construction, agricultural activities, and infrastructure development, numerous "pinch points" and "barrier points" have formed, requiring differentiated measures such as withdrawal from sandy land, ecological farmland retirement, restoration of abandoned land, ecological relocation, and creation of biological corridors to ensure healthy and stable ecological network cycles. Restoration and enhancement areas are low-resistance zones covering 3676.9 km^2 (19.7%), distributed in a dispersed pattern, requiring strengthened ecological monitoring and problem diagnosis, moderate restriction of human activities, and focused restoration of degraded areas to increase forest and grass coverage and enhance the ecological buffer zone effect.

Control and regulation areas are medium-high resistance zones covering 7083.8 km^2 (37.9%), presenting patterns along the Qingshui River and "Yuanzhou-Haiyuan" corridors. These areas face prominent ecological environmental problems including land desertification, soil erosion, and low vegetation coverage, with strong ecological stress from agricultural activities, urban construction, and high population density. The contradiction between territorial space development and protection is acute, requiring strengthened territorial space comprehensive management and restoration, scientifically demarcated three zones and three control lines, controlled disorderly expansion of construction land, improved land conservation and intensive use levels, accelerated exploration of "two mountains" transformation paths, and active seeking of sustainable development models (Fig. 6, Table 8).

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3 Discussion

The Liupan Mountain area is extremely rich in animal and plant resources, serving as an important regional "germplasm resource gene bank," a vital water source conservation area in the Yellow River Basin, and an important component of the national "two barriers and three belts" pattern, with extremely important ecological status and critical ecological security. Against this background, this study introduced the InVEST and Circuitscape models from the perspective of integrated, systematic, and systematic ecological restoration to construct ecological security patterns and zoning optimization, providing spatial guidance for macro-scale territorial space pattern shaping and ecological restoration in the region.

The establishment of resistance surfaces and scientific identification of corridors and ecological sources are key factors in ecological security pattern construction. Currently, there is no unified understanding of ecological resistance surface indicator system construction and scoring weighting, and the scientificity and rationality of determining resistance values for each factor are still under exploration. The resistance value determination and weight analysis in this study were also based on literature and expert consultation. Although the semi-quantitative AHP method was adopted, it is inevitably influenced by expert experience and methodological limitations. Ecological corridor construction methods mainly focus on numerous method models supported by "cost-distance" theory. The Circuitscape model has been increasingly applied due to its good correspondence between current, voltage, and resistance and ecological corridors, sources, and barrier areas, but its simulation accuracy and scientificity are also affected by resistance surface establishment. Additionally, corridor construction reliability is influenced by the accuracy of ecological source identification, as corridors start and end at ecological sources and simulate optimal paths through cost-distance theory and circuit theory. Currently, ecological source identification mainly uses comprehensive factor evaluation methods, while factor types, scales, weights, accuracy, patch processing, or researchers' own experience and understanding of the study area can all influence identification results.

In summary, due to current common issues such as models, methods, and indicator system construction, the reliability of this study's results at local scales needs further improvement. However, at the macro scale, the results can provide important references for ecological protection and restoration, scientific ecological management, policy formulation, and engineering spatial layout in the Liupan Mountain area.

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4 Conclusion

Using the "source-corridor-node" research paradigm, we quantitatively identified key elements including ecological sources, corridors, barrier points, and pinch points, and completed ecological security pattern construction and restoration zoning combined with resistance surface spatial analysis. This provides spatial guidance for promoting comprehensive, full-element, and full-process systematic restoration and pattern shaping of the mountain-river-forest-farmland-lake-grassland-desert life community in the Liupan Mountain area. The main conclusions are:

1) The study area contains 75 ecological sources covering 4075.1 km^2 (21.8% of the study area), exhibiting mountain system patterns and county expansion characteristics, serving as ecological strategic points and nodes for ecological security pattern construction.

2) The study area contains 120 ecological corridors totaling 1203.7 km, including 47 key ecological corridors spanning 211.6 km (17.6% of total corridor length), playing crucial roles in interconnecting ecological sources and

building ecological networks. A total of 547 ecological pinch points and 217 ecological barrier points were identified, providing specific engineering targets for ecological corridor restoration.

3) Ecological barrier belts, conservation areas, restoration and enhancement zones, and control and regulation zones account for 17.4%, 6.5%, 38.2%, and 37.9% of the area, respectively. Ecological barrier belts require the strictest ecological protection to enhance regional ecological radiation effects. Conservation areas need strengthened closed-slope monitoring and vegetation restoration to control ecological degradation risks. Restoration and enhancement zones should implement differentiated measures to improve ecological quality, maintain healthy and stable ecological network cycles, and leverage ecological buffer zone effects. Control and regulation zones require scientifically demarcated three zones and three control lines, improved land conservation and intensive use levels, and comprehensive, coordinated, and sustainable development.

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