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Spatiotemporal Evolution of Ecological Security Patterns in Longnan City Based on the MSPA-InVEST Model (Postprint)

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Abstract

Constructing ecological security patterns and accurately identifying key areas for ecological restoration constitute the prerequisite and guarantee for advancing territorial ecological restoration. As a national key water source conservation area and an ecological security barrier in the upper reaches of the Yangtze River, the ecological security of Longnan City is of paramount importance. This study employs the InVEST model to assess ecosystem service functions, and integrates the Morphological Spatial Pattern Analysis (MSPA) method and circuit theory to construct the ecological security pattern of Longnan City and analyze its evolutionary patterns. The results indicate: (1) From 2000 to 2022, the number of ecological sources increased, with significant increases observed in Kang County, Hui County, and Cheng County, displaying a spatial distribution pattern characterized by more in the south and fewer in the north. (2) The average resistance value exhibited a trend of initial decline followed by increase, while the length of ecological corridors showed an initial increase followed by decrease, with a net reduction of approximately 508.94 km, and a spatial shifting trend from the central region toward the southeast. (3) Ecological pinch points are primarily located in low-resistance areas, dominated by forestland, cropland, and grassland, with their area decreasing year by year, and a net reduction of approximately 144.84 km2 during the same period; both the number and area of ecological barrier points decreased, concentrating in Wudu District, Li County, and Dangchang County. The research findings can provide a scientific basis for formulating ecological restoration planning and promoting high-quality regional economic development in Longnan City.

Full Text

Spatiotemporal Evolution of Ecological Security Pattern in Longnan City Based on the MSPA-InVEST Model

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Abstract

Constructing ecological security patterns and accurately identifying key areas for ecological restoration are prerequisites for advancing territorial ecological restoration. As a nationally designated key water source conservation area and ecological security barrier in the upper reaches of the Yangtze River, Longnan City's ecological security is of paramount importance. This study employs the InVEST model to evaluate ecosystem services, combined with morphological spatial pattern analysis (MSPA) and circuit theory to construct and analyze the evolution of Longnan City's ecological security pattern. The results demonstrate that: (1) From 2000 to 2022, the area of ecological source patches increased, with significant expansion in Kang County, Hui County, and Cheng County, exhibiting a spatial distribution pattern of higher density in the south and lower in the north. (2) The average resistance value showed a trend of initial decline followed by increase, while ecological corridor length first increased then decreased, with a net reduction of approximately 508.94 km during the study period. (3) Ecological pinch points were primarily located in low-resistance areas dominated by forestland, cropland, and grassland, with their area decreasing annually and showing a spatial shift from central to southeastern regions, resulting in a net reduction of approximately 144.84 km^2. The number and area of ecological barrier points also decreased, concentrating in Wudu District, Li County, and Tanchang County. These findings provide a scientific basis for formulating ecological restoration plans and promoting high-quality regional economic development in Longnan City.

Keywords: ecosystem services; ecological security pattern; InVEST model; MSPA method; Longnan City

Introduction

Accelerated urbanization and large-scale infrastructure construction have intensified land development, leading to significant changes in ecological environments and landscape patterns, declining biodiversity, and reduced ecological stability. These challenges pose serious threats to the stability and sustainable development of regional ecosystems. The 20th National Congress of the Communist Party of China emphasized the unified protection and systematic governance of "mountains, rivers, forests, farmlands, lakes, grasslands, and deserts" to enhance ecosystem diversity, stability, and sustainability, while accelerating the implementation of major ecological protection and restoration projects. Scientific identification of key ecological restoration areas and targeted restoration measures can effectively mitigate environmental problems caused by rapid urbanization.

Current research widely adopts integrated approaches combining ecosystem service evaluation with ecological security pattern construction to identify key restoration areas. The conventional framework involves identifying ecological sources, constructing resistance surfaces, and extracting ecological corridors. Ecological sources, defined as habitat patches with robust ecological functions and high ecosystem service value, are typically identified through morphological spatial pattern analysis (MSPA), landscape connectivity evaluation, and other methods. Resistance surface construction requires comprehensive consideration of both natural processes and human disturbance intensity. Ecological corridors serve as critical linkages for material transfer and energy flow, playing a vital role in alleviating landscape fragmentation. Extraction methods include the minimum cumulative resistance model and circuit theory, with the latter employing the random movement characteristics of electric current through resistors to simulate species migration, providing valuable references for identifying key restoration areas.

Despite abundant research achievements on ecological security pattern construction, several limitations persist. First, most studies focus on economically developed cities and urban agglomerations, with relatively limited research on ecologically fragile, economically underdeveloped mountainous regions in western China such as the Qinba Mountains. Second, previous research has primarily concentrated on static assessments of regional ecological security patterns, neglecting dynamic ecosystem changes and the complex internal conditions, making it difficult to comprehensively reflect regional ecological characteristics.

Longnan City is located at the intersection of the Qinba Mountains, Loess Plateau, and Tibetan Plateau, serving as a crucial water source conservation area and ecological security barrier in the upper Yangtze River basin. The region hosts one national nature reserve and four provincial nature reserves, representing a key water and soil conservation area in the upper Yangtze, an important ecological barrier on the eastern edge of the Tibetan Plateau, and a priority area for biodiversity conservation. Despite its favorable environmental baseline, Longnan's ecosystems remain fragile, facing dual pressures from human activities and natural disasters. The complex terrain characterized by high mountains and deep valleys, combined with a monsoon climate, frequently triggers droughts, rainstorms, landslides, and other geological disasters, making it one of the most severely affected areas by landslides and debris flows in China and the most ecologically vulnerable region in the upper Yangtze basin. Therefore, comprehensive ecosystem service assessment and ecological security pattern construction are urgently needed to formulate targeted ecological restoration strategies.

This study integrates the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model with MSPA and circuit theory to identify ecological restoration elements, construct Longnan City's ecological security pattern, and analyze its evolution. The research aims to provide scientific support for implementing ecological restoration projects and rationally allocating restoration spaces in Longnan City, thereby facilitating rural revitalization and high-quality regional economic development.

1.1 Study Area

Longnan City is situated in southeastern Gansu Province (104°01 –106°35 E, 32°35 –34°32 N), characterized by a terrain that is higher in the northwest and lower in the southeast, with an average elevation of approximately 1,000 m. The region lies at the intersection of the Qinba Mountains, Loess Plateau, and Tibetan Plateau, featuring a landscape dominated by high mountains, deep valleys, hills, and basins. Influenced by a subtropical continental monsoon climate, the annual average temperature ranges from 2–14 °C, with annual precipitation of 400–1,000 mm. The area contains over 700 rivers including the Jialing River and Bailong River, forming a critical water system in the upper Yangtze basin.

1.2 Data Sources

Considering the study area's actual conditions and data availability, this research utilized six periods of land cover type data (2000, 2005, 2010, 2015, 2020, 2022), remote sensing imagery, meteorological data (precipitation, potential evapotranspiration), vector data for major transportation networks (railways, highways), water systems, residential points, and nature reserve boundaries from 2000 to 2022, as well as soil data. To ensure data consistency and validity, all raster data were resampled to a 30 m resolution and uniformly projected to WGS 1984. Specific data sources are detailed in .

1.3 Research Methods

1.3.1 InVEST Model for Ecosystem Service Assessment Ecological sources typically refer to areas with relatively complete ecosystem functions and high ecosystem service value, exhibiting strong ecological stability and expandability. Identifying ecological sources is fundamental to constructing ecological security patterns. This study employed the InVEST model to assess four key ecosystem services in Longnan City: water conservation, biodiversity, soil retention, and carbon storage. Based on the assessed importance, areas classified as "important" or "relatively important" were selected as potential ecological sources.

1.3.2 Morphological Spatial Pattern Analysis (MSPA) Based on Longnan's natural and socioeconomic characteristics, forestland, shrubland, grassland, and water bodies were selected as foreground classes for MSPA analysis, with other land use types as background. Using the Guidos Toolbox software, we performed morphological spatial pattern analysis to identify seven landscape types: core areas, edges, branches, islets, bridges, loops, and perforations. Core patches larger than 30 km^2 were selected as potential ecological sources.

1.3.3 Landscape Connectivity Evaluation Building upon the potential ecological sources identified through ecosystem service assessment and MSPA, we employed landscape connectivity evaluation to determine final ecological sources. Using Conefor software, we calculated probability of connectivity (PC), integral index of connectivity (IIC), and patch importance (dI) indices for potential ecological sources. A connectivity probability of 0.5 and a distance threshold of 1,500 m were applied for core patch analysis, with final ecological sources determined based on patch importance rankings.

1.3.4 Ecological Resistance Surface Construction Ecological resistance surface construction quantifies the resistance encountered by organisms during migration or dispersal under the influence of natural environmental and socioeconomic conditions. More complete ecosystem services and lower landscape fragmentation result in lower resistance for species migration, while more frequent human activities increase resistance. Drawing on existing research and considering Longnan's ecological baseline and socioeconomic conditions, we selected ten resistance factors encompassing natural elements (land cover type, vegetation coverage, elevation, slope, terrain relief) and socioeconomic elements (distance to roads, residential points, and water bodies) to construct a comprehensive ecological resistance surface.

1.3.5 Ecological Corridor Extraction and Node Identification Based on Circuit Theory **Ecological Corridor Extraction.** Ecological corridors are channels connecting different landscape units that effectively facilitate species migration, population exchange, and gene flow, playing a positive role in enhancing biodiversity and representing key ecological components for improving overall ecosystem connectivity. We used the Centrality Mapper Tool to extract minimum cost paths between different ecological sources, which were classified as ecological corridors. The natural breaks method was applied to categorize corridors into primary, secondary, and tertiary levels.

Ecological Pinch Point Identification. Ecological pinch points are special locations along ecological corridors with relatively vulnerable ecological functions and high current density in ecological networks. Degradation or fragmentation of these pinch points can impact biodiversity and ecosystem stability. Therefore, pinch points should be prioritized in restoration efforts. We used the Pinchpoint Mapper tool to identify pinch points, with a corridor cost-weighted distance set at 60 km.

Ecological Barrier Point Identification. Ecological barrier points are areas along ecological corridors that impede species migration, population exchange, and gene flow, characterized by high cumulative current recovery values in ecological networks. Using the Barrier Mapper tool's moving window search method, we conducted iterative searches and selected 300 m as the most reasonable search range based on actual analysis results.

2.1 Ecological Source Identification and Spatiotemporal Changes

Based on ecosystem service importance evaluation results, Longnan City's ecosystem services were dominated by "important" and "relatively important" areas from 2000 to 2022. The total area of ecological sources showed an overall increasing trend, primarily distributed in peripheral regions with forestland as the dominant land cover type. Areas classified as "important" and "relatively important" were selected as potential ecological sources. MSPA analysis revealed that core area in Longnan City exhibited continuous growth over the past two decades, with marginal areas also increasing slightly. Core patches were relatively concentrated, mostly distributed in peripheral regions and largely overlapping with ecosystem service important areas.

The total area of ecological sources in Longnan City increased during the study period, with significant expansion in Kang County, Hui County, and Cheng County, showing a spatial pattern of higher density in the south and lower in the north. Wen County had the largest ecological source area, accounting for approximately 30% of Longnan's total, while Li County had the smallest at only 0.75%. Notable area increases in Kang, Hui, and Cheng counties likely reflect the city's active implementation of national "returning farmland to forest" policies, which increased forestland area and enhanced ecosystem stability , [Figure 2: see original paper].

2.2 Spatiotemporal Changes in Ecological Resistance Surface

From 2000 to 2022, Longnan City's average resistance value showed a slow overall decline, with a net reduction of 0.03, characterized by higher values in the east and lower in the west. High-value areas were mainly distributed in densely populated regions such as Kang County, while low-value areas were concentrated in the southern part of the study area (Bailong River Nature Reserve) dominated by forestland [Figure 3: see original paper].

Between 2000 and 2010, the average resistance value declined, indicating significant achievements in ecological protection during this period. Implementation of ecological restoration projects reduced human disturbance, leading to slowly decreasing average resistance values. Enhanced protection in ecologically sensitive areas like the Bailong River Nature Reserve contributed to reduced resistance. However, from 2010 to 2022, Longnan City experienced rapid economic development with substantial construction land expansion. Particularly after the full operation of the Lan-Yu Railway in 2017, the increasingly dense transportation network accelerated urbanization, causing average resistance values to rise rapidly with an increase of 0.08. At the county level, smaller resistance value changes occurred in Wen County, Tanchang County, and Kang County, with average resistance increases of 0.02, 0.01, and 0.01, respectively.

2.3.1 Ecological Corridors

During the study period, ecological corridors showed an overall decreasing trend with a net reduction of approximately 508.94 km. From 2000 to 2010, corridor length increased slowly with a net increase of about 224.14 km. After 2010, total corridor length decreased rapidly, with primary corridors showing a net reduction of 445.78 km, mainly distributed in eastern regions (Cheng County, Hui County, and Wudu District). Secondary corridors were widely distributed in northern regions (Xihe County, Li County, and Wudu District), while tertiary corridors were located in peripheral areas. Severe degradation of ecological sources in Li County caused corridors to shift southward, weakening landscape connectivity in northern Longnan [Figure 4: see original paper].

2.3.2 Ecological Pinch Points

The total area of ecological pinch points in Longnan City decreased annually by 144.84 km^2 during the study period. In 2000, pinch points were mainly located in western regions, but by 2022 they had shifted to central and eastern areas, mostly distributed along key and important ecological corridors. Land cover analysis revealed that pinch points were dominated by forestland, cropland, and grassland. Resistance surface analysis showed that pinch points were located in relatively low-resistance areas where biological migration occurs more easily, facilitating energy exchange and gene flow [Figure 5: see original paper].

2.3.3 Ecological Barrier Points

Based on circuit theory, we identified ecological barrier points by selecting high-value areas of cumulative current recovery using the natural breaks method. In 2000, Longnan City had 63 barrier points covering 63.21 km^2, which decreased to 51 points covering 51.38 km^2 by 2022, indicating reductions in both number and area. Spatially, barrier points were most frequent in Wudu District, followed by Li County and Tanchang County, with lower frequencies in Hui County and Liangdang County . Analysis of the resistance surface and land cover types revealed that larger barrier points were mostly located in construction land or areas with frequent human activity (near residential points and roads), where high resistance values impede species migration, energy exchange, and gene flow between ecological sources [Figure 6: see original paper].

Discussion

Regarding ecological source identification, this study combined InVEST and MSPA methods to identify potential ecological sources, then applied landscape connectivity evaluation to consider patch structural attributes, making the determination of ecological sources more scientifically robust. The identified ecological sources in Longnan City showed increased area and high overlap with high-quality ecosystems such as forestland and grassland, consistent with findings by Li Yue et al. This increase likely stems from national and provincial ecological civilization initiatives implemented since 2000, including the Natural Forest Protection Project and Returning Farmland to Forest and Grassland Program, which directly promoted forestland and ecological source expansion, particularly in eastern and southern counties like Hui, Kang, Wen, and Wudu. Furthermore, as a key component of Gansu Province's ecological barrier, Longnan's ecological functions have been incorporated into national and provincial planning documents such as the "Gansu Province Ecological Function Zoning" and "Longnan City Ecological Protection and Construction Plan," which explicitly define protection and expansion measures for ecological sources.

In resistance surface construction and resistance value changes, this study considered the impact of major transportation infrastructure on corridor fragmentation by incorporating roads (railways and highways) as resistance factors, reflecting infrastructure effects on regional ecological security patterns. The resistance value decline from 2000–2010 demonstrates significant ecological protection achievements, with restoration projects reducing human disturbance. Enhanced protection in ecologically sensitive areas like the Bailong River Nature Reserve lowered resistance values. However, the resistance increase after 2010 likely resulted from major projects such as the Lan-Yu Railway, Wujiu Highway, and Chengxian Airport, which intensified human disturbance, particularly in urban core areas like Wudu District, exerting pressure on ecosystems and increasing resistance values.

Regarding ecological security pattern construction, landscape elements are influenced by both natural environmental changes and socioeconomic development, with their spatial patterns continuously evolving. While previous studies often adopted static perspectives, this research employed long-term time series data to construct multi-period ecological security patterns, analyze evolution patterns, and propose optimization suggestions, thereby enriching ecological security pattern research. However, this study focused only on corridor length and location; future research should examine corridor width to support Longnan's ecological corridor network construction. Ecological security patterns are dynamically influenced by natural environments and human activities, with precipitation, temperature, population, and land use confirmed as important driving factors. Elucidating these driving mechanisms represents a future research priority.

4.1 Conclusions

This study reveals three key findings: (1) From 2000 to 2022, Longnan City's ecological sources were dominated by forestland, with increases concentrated in eastern and southern counties including Kang, Hui, Wen, and Wudu. The net increase in ecological source area was 1,630.31 km^2, with particularly significant growth in Kang, Hui, and Cheng counties. (2) During the study period, average resistance values first decreased then increased, showing an east-high, west-low pattern before 2010. After 2010, rapid urban expansion caused resistance values to rise quickly. Ecological corridor length decreased overall by approximately 508.94 km, with primary corridors showing the most significant reduction. Primary corridors, which were widely distributed in central regions with strong centrality, decreased by 445.78 km after 2010, mainly in eastern areas. The southward shift of ecological corridors weakened landscape connectivity in northern Longnan. (3) Ecological pinch point area decreased by 144.84 km^2 from 2000 to 2022, with spatial distribution shifting from west to central and eastern regions. Land cover types were primarily forestland, cropland, and grassland. Both the number and area of ecological barrier points decreased, concentrating in Wudu District, Li County, and Tanchang County, with fewer distributions in Hui County and Liangdang County.

4.2 Recommendations

Longnan City is a critical water conservation and biodiversity ecological function area in the upper Yangtze River's "Two Rivers and One Water" basin and an important component of the southern Qinba Mountain ecological barrier zone in Gansu Province. Based on these findings and actual ecological issues, we propose the following recommendations:

First, protect and cultivate new ecological sources. As core areas of ecological security patterns and important habitats for biological reproduction, ecological sources require strict protection measures to reduce human disturbance. During the study period, while total ecological source area increased, some areas like Li County experienced source shrinkage. Future efforts should strictly implement ecological protection measures, employing afforestation and returning farmland to forest when necessary. The construction of nature reserves such as Li County Xiangshan Provincial Nature Reserve, Giant Panda National Park Bailong River Section, and Chengxian Jifeng Mountain Provincial Nature Reserve should be advanced, appropriately expanding their scope to enhance ecological barrier functions.

Second, rely on natural ecological corridors to improve connectivity between nature reserves. The southward migration of ecological corridors and weakened connectivity in northern Longnan necessitate protection of valuable natural landscapes along rivers and mountains. Key corridor nodes should be secured to reduce landscape fragmentation and ensure unobstructed animal movement and migration pathways. Artificial corridors should be constructed to complement natural river channels, facilitating biological migration. Northern corridor construction should be strengthened with buffer zones to prevent encroachment by urban construction land, maintaining balanced and stable regional ecological resources.

Third, protect ecological pinch point areas and restore barrier zones. Pinch points facilitate biological migration and diffusion; strengthening their protection and construction can improve corridor functions. The study period witnessed uneven pinch point reduction across regions, requiring attention to areas with declining pinch points, analysis of underlying causes, and enhanced protection. Additionally, Wudu District, Li County, and Tanchang County exhibited numerous barrier points that should be designated as priority restoration areas for implementing ecological protection and restoration projects to promptly restore corridor functions and improve ecological network connectivity.

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