Construction of Ecological Security Pattern in Southwest Mountainous Regions Based on Ecological Importance and Sensitivity: A Case Study of Dali Bai Autonomous Prefecture, Yunnan Province (Postprint)

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Abstract

Ecological security pattern construction is an effective approach to alleviate the contradiction between ecological protection and land development and ensure regional ecological security under the background of rapid urban expansion. Source areas and resistance surfaces are important foundations for ecological security pattern construction. Current resistance surface construction focuses mostly on ecological elements while neglecting the representation of ecological processes corresponding to regional typical ecological problems. Taking the southwestern mountainous region—Dali Bai Autonomous Prefecture, Yunnan Province—as the study area, this study selects ecosystem services such as biological resource protection, water resource security, and nutrient retention to assess ecological importance for identifying source areas, constructs an ecological resistance surface based on ecological sensitivity including geological hazards, soil erosion, and rocky desertification, and employs the minimum cumulative resistance model to identify group corridors and landscape corridors, thereby constructing a mountainous ecological security pattern. The research shows that the total area of ecological security source areas in Dali Prefecture is 14,416.64 km^2, accounting for 50.93% of the total land area of the prefecture; key ecological corridors are divided into two types—group corridors and landscape corridors—with lengths of 404.7 km and 208.4 km, respectively, exhibiting a dendritic radial distribution in the form of "one axis and three belts". The ecological source areas and corridors within the ecological security pattern should be designated as prohibited development zones in the development of gentle hill and slope land resources. The method of identifying source areas based on ecological importance and constructing resistance surfaces based on ecological sensitivity can provide new insights for ecological security pattern construction, and the

research results offer quantitative guidance for land use selection and spatial expansion in mountainous urban construction in Dali Prefecture.

Full Text

Building Ecological Security Patterns in Southwestern Mountainous Areas Based on Ecological Importance and Sensitivity: A Case Study of Dali Bai Autonomous Prefecture, Yunnan Province

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Abstract

Ecological security pattern construction represents an effective approach for reconciling conflicts between ecological conservation and land development amid rapid urban expansion, thereby ensuring regional ecological security. Source areas and resistance surfaces constitute critical foundations for ecological security pattern development. However, current resistance surface construction predominantly focuses on ecological elements while neglecting the representation of ecological processes corresponding to region-specific ecological problems. This study selected Dali Bai Autonomous Prefecture in Yunnan Province, a typical southwestern mountainous region, as the research area. We identified ecological source patches through comprehensive assessment of ecosystem service importance, including biological resource conservation, water resource security, and nutrient retention. We constructed an ecological resistance surface based on ecological sensitivity to geological disasters and rocky desertification, and employed the Minimum Cumulative Resistance model to identify cluster corridors and key ecological corridors, thereby establishing a mountainous ecological security pattern. The results demonstrate that the total area of ecological security sources in Dali Prefecture is 14,416.64 km^2, accounting for 50.93% of the prefecture' s total land area. Key ecological corridors span 613.1 km, comprising 404.7 km of cluster corridors and 208.4 km of landscape corridors. These corridors exhibit a dendritic radial distribution pattern forming "one axis and three belts." All identified ecological sources and corridors should be designated as prohibited development zones during low-slope hilly land resource development. The methodology of source identification based on ecological importance and resistance surface construction based on ecological sensitivity provides new insights for ecological security pattern development. The findings offer quantitative guidance for land use selection and spatial expansion of mountainous urban construction in Dali Prefecture.

Keywords: ecological security pattern; ecological importance; ecological sensitivity; key ecological corridors; Minimum Cumulative Resistance model; Dali Prefecture

1. Introduction

Rapid urbanization has intensified human disturbance to ecosystems, posing new challenges to sustainable development. Ecological Security Patterns (ESP) represent an effective pathway for achieving smart growth while supporting urban natural life systems and ensuring ecosystem integrity and normal function. ESP aims to evaluate the environmental effects of key natural processes and their impacts on ecological security, identifying points, patches, and corridors critical for maintaining regional ecosystem development to construct multi-level spatial optimization schemes. As an important research method for ecological security analysis and evaluation, ESP provides fundamental spatial safeguards for reconciling ecological conservation and land development conflicts.

Over the past decade, Chinese scholars have devoted sustained attention to ESP research, with gradually maturing concepts, theoretical foundations, design principles, and methodologies. Beyond comprehensive overlay methods based on ecological constraint diagnosis, the application of the Minimum Cumulative Resistance (MCR) model according to landscape ecology and planning principles has become the mainstream paradigm. Source areas and resistance surfaces constitute important foundations for ESP construction. Source identification has been extensively explored, showing diversified approaches—either directly selecting nature reserves rich in biodiversity or identifying hotspots from ecosystem service perspectives through value equivalency assignment or comprehensive index system assessment, while considering both patch functional attributes and structural importance in landscape patterns.

However, resistance surface construction requires further research depth. Current approaches generally assign resistance coefficients based on ecological elements such as land cover type and slope, or refine spatial heterogeneity using impervious surface indices and nighttime light data. Nevertheless, studies focusing on regional ecological problems and interpreting ecological processes remain relatively rare. Southwestern mountainous regions feature fragile ecological environments, complex terrain, frequent geological disasters, and widespread rocky desertification, which disturb wildlife habitats and regional ecosystem services, threatening ecological security.

Dali Bai Autonomous Prefecture (hereafter Dali Prefecture) in northwestern

Yunnan Province exemplifies these challenges. The region boasts diverse ecosystem types and abundant flora and fauna resources but faces risks from geological disasters and plateau fault lake pollution. Recent intensified human activities have caused vegetation cover reduction and habitat quality degradation in localized areas. Implementing the "low hill gentle slope" development strategy, Dali confronts both opportunities for construction land expansion and challenges of regional ecosystem protection. This study identifies urban expansion constraints and key regional ecological problems, focusing on underlying ecosystem patterns and functions. We comprehensively evaluate ecological importance based on ecosystem services (biological resource conservation, water resource security, nutrient retention) to identify sources, and analyze ecological sensitivity to geological disasters and rocky desertification to construct resistance surfaces. Using the MCR model to identify key ecological corridors, we build an ecological security pattern to provide decision-making support for optimizing construction land and developing new low-slope mountainous towns while preserving ecological security.

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2. Study Area Overview

Dali Bai Autonomous Prefecture is located in western-central Yunnan Province (24°40 -26°42 N, 98°52 -101°03 E), at the junction of the Yunnan-Guizhou Plateau and Hengduan Mountains, covering a total area of 28,308.78 km^2. With over 90% mountainous terrain, it represents a typical southwestern mountainous region. The topography is complex and diverse, with elevations higher in the northwest and lower in the southeast. Under a subtropical low-latitude plateau monsoon climate influenced by unstable monsoon circulation and varying weather systems, the region experiences frequent meteorological disasters including frost. Geological hazards such as landslides and debris flows occur frequently, with severe rocky desertification and soil erosion in some areas, making the ecological environment relatively fragile.

Natural ecosystems constitute the landscape matrix in Dali Prefecture' s land use structure, with water bodies and wetlands accounting for 76.06% of the total area. Construction land occupies only 2.23%, while artificial or semi-artificial ecosystems represent a low proportion. As a biodiversity hotspot, the prefecture holds unique advantages for wildlife, plant, and germplasm resource conservation and development. Water resources are relatively abundant, with the Jinsha River system, over 160 rivers, and natural lakes including Erhai Lake providing irrigation and domestic water. However, water ecosystems face pollution risks from agriculture, tourism, and low-slope hilly development. The ecosystem's vulnerability and uniqueness make ESP construction both necessary and challenging.

[Figure 1: see original paper] Location of the study area

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3. Data Sources and Preprocessing

This study utilized multiple datasets: land use data, vegetation type data, digital elevation model (DEM), geological disaster data, soil data, karst terrain data, water source protection zones, river systems, and precipitation data. Land use data were derived from 30m-resolution Landsat imagery interpretation. DEM data (30m resolution) were obtained from the Geographic Spatial Data Cloud of the Chinese Academy of Sciences to generate slope data. Vegetation types came from the Yunnan Province vegetation atlas compiled by the Institute of Ecology and Geobotany at Yunnan University and forest resource data from the Forestry Science Data Center. Geological disaster hazard locations and tectonic distribution were vectorized from Dali Prefecture geological disaster prevention maps. Soil and karst terrain data were vectorized from soil type and geomorphology maps. Water source protection zones and river systems were vectorized from river distribution maps. Precipitation data (1981–2010 daily values) came from the China Meteorological Data Sharing Network, interpolated using thin-plate spline functions after multi-year averaging. NDVI data were obtained from MOD13Q1 products (250m resolution) from the Geographic Spatial Data Cloud, with annual averages calculated. The basic spatial unit for this study is a 30m-resolution grid cell.

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4. Ecological Importance Assessment

Ecological importance assessment measures ecosystem service provision and process maintenance based on ecosystem characteristics to identify critical areas for conservation. In fragile southwestern mountainous environments, stable ecosystem structure and function are particularly vital for regional ecological security. Referencing similar cases and considering Dali' s characteristics—diverse water resources, abundant flora and fauna, and frequent flooding—we conducted a comprehensive evaluation from three dimensions: biological resource conservation, water resource security, and nutrient retention importance.

Biological Resource Conservation Importance: Based on source-sink landscape theory and biodiversity conservation, we evaluated the role of specific ecosystems in maintaining biodiversity. From a structural perspective, land use types with minimal human disturbance and intact ecological space (e.g., forests, grasslands) facilitate species exchange and ecosystem service transfer, receiving the highest importance rating. From a functional perspective, we calculated biodiversity service equivalents for different land use types based on Xie et al.' s methodology, assigning habitat importance coefficients accordingly.

Water Resource Security Importance: This was analyzed from flood safety and water resource protection perspectives. The former used river buffer distances and flood regulation zones for classification, while the latter focused on forest water conservation capacity and water source protection zones.

Nutrient Retention Importance: This addressed potential non-point source pollution from nutrient loss and lake eutrophication consequences. Based on river system maps, we classified important and general lake-wetland areas, then evaluated nutrient retention importance according to lake significance, river order, and location within river systems.

All three dimensions used the natural breaks method for classification (extremely important=4, important=3, moderately important=2, generally important=1). The comprehensive ecological importance result was obtained through weighted overlay (biological resource conservation weight=0.5, water resource security=0.3, nutrient retention=0.2) and reclassification.

Index system for assessing ecological importance

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5. Ecological Sensitivity Analysis

Ecological sensitivity reflects ecosystem response to environmental changes from internal and external factors, indicating the likelihood of ecological imbalance and environmental problems. Southwestern China experiences strong tectonic activity, variable climate conditions, and frequent earthquakes and secondary geological disasters that disturb wildlife habitats and ecosystem services. Karst areas suffer severe soil erosion and widespread rocky desertification, exacerbating ecological fragility.

Based on literature review and the National Ecological Function Zoning, Dali Prefecture's ecological sensitivity analysis focused on geological disaster sensitivity, soil erosion sensitivity, and rocky desertification sensitivity. Each dimension was classified into five levels (higher values indicate greater sensitivity). Following the "short board effect" principle, the final comprehensive sensitivity result adopted the highest value among the three influencing factors.

Geological Disaster Sensitivity: This indicates potential disaster impacts. Within hazard point influence ranges, we calculated sensitivity using the formula: $DE = P \times T \times \beta$, where DE represents disaster potential impact/sensitivity, P is disaster probability, T is impact intensity, and β is the distance decay coefficient. Influence ranges were determined based on disaster type (landslide, collapse, debris flow, ground fissure, ground collapse, unstable slope), with varying impact radii and intensities.

Soil Erosion Sensitivity: This reflects erosion likelihood under comprehensive natural conditions. We calculated erosion quantity using the RUSLE model, with higher erosion corresponding to greater sensitivity, classified using thresholds of 10, 25, 80, and 150 $t \cdot ha^{-1} \cdot yr^{-1}$.

Rocky Desertification Sensitivity: This evaluated slope (15°, 25°, 35° thresholds), vegetation canopy density (20%, 50%, 70% thresholds), and karst presence, assigning the highest factor value as the final sensitivity grade.

Index system for assessing ecological sensitivity
Reach and impact of geo-hazard points in Dali Prefecture

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6. Ecological Security Pattern Construction

The core steps include ecological source identification, resistance surface construction, and key ecological corridor extraction.

Ecological Sources: These are starting points for species or ecological events to diffuse outward, promoting ecological processes and ensuring regional ecological security. Based on ecological importance assessment and considering total area and land use distribution, we extracted patches with high ecological value and importance as source patches to ensure process integrity and service continuity.

Ecological Resistance Surface: Following Yu Kongjian's definition, more sensitive ecosystems exhibit greater likelihood of ecological problems and stronger resistance to ecological function flow. Based on Dali' s typical ecological problems, we comprehensively evaluated geological disaster, rocky desertification, and soil erosion sensitivities to assign resistance coefficients to each grid cell.

Key Ecological Corridors: Using the MCR model and ArcGIS 10.2 cost distance tools, we identified corridors between source patches. Taking each source patch center as a node, we calculated minimum cost paths to all other nodes, generating n paths per node (where n is total node count). These minimum cumulative cost paths were defined as cluster corridors, connecting nodes within groups. To connect all sources across the prefecture into a network, we then identified secondary minimum cost paths between disconnected nodes, defined as landscape corridors. Together, these form the key ecological corridors.

Resistance coefficient associated with ecological sensitivity

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7. Source Identification Based on Ecological Importance

Weighted overlay of the three importance dimensions produced Dali Prefecture' s ecological importance spatial pattern, classified using natural breaks into extremely important, important, moderately important, and generally important areas.

- **Extremely important areas** total 7,086.34 km^2 (25.03% of prefecture area), are mainly distributed along the Lancang River, Nujiang River, and major lakes and wetlands such as Erhai Lake and Cibi Lake, ensuring water resource security.
- **Important areas** total 7,330.30 km^2 (25.89%), distributed mainly along edges of extremely important areas.

- **Moderately important areas** total 9,843.56 km^2 (34.79%), concentrated in eastern Dali.
- **Generally important areas** total 4,048.59 km^2 (14.30%), with Xiangyun and Yongping counties as main regions.

[Figure 2: see original paper] Spatial distribution of ecological importance in Dali Prefecture

Extremely important and important patches were selected as ecological security sources, totaling 14,416.64 km^2 (50.92% of prefecture area), aligning with Dali' s ecological baseline and conservation planning requirements. By landscape component: forests dominate (84.55% of source area), followed by cultivated land (12.36%), water bodies (2.58%), and grassland (1.51%). By distribution: Yunlong County has the largest source area (17.39% of prefecture sources), while Midu has the smallest (4.94%). All counties except Xiangyun and Yongping show forest-dominated sources exceeding 90% of their source area.

[Figure 3: see original paper] Distribution and composition of ecological sources in Dali Prefecture

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8. Key Corridor Identification and Ecological Security Pattern Construction

Based on the highest sensitivity values among the three factors, we obtained Dali Prefecture' s comprehensive ecological sensitivity classification: extremely sensitive, highly sensitive, moderately sensitive, lightly sensitive, and insensitive.

- **Extremely sensitive areas** (317.31 km^2, 1.12% of prefecture) are mainly geological disaster-prone zones in southern Yunlong and central Nanjian.
- **Highly sensitive areas** (1,108.98 km^2, 3.92%) distribute along edges of extremely sensitive zones, also including northeastern Yangbi.
- **Moderately sensitive areas** (3,598.29 km^2, 12.71%) lie at edges of highly sensitive zones, concentrated in Midu and Yangbi.
- **Lightly sensitive areas** (5,291.77 km^2, 18.70%) have extensive coverage.
- **Insensitive areas** are most widespread (17,992.43 km^2, 63.55%).

[Figure 4: see original paper] Spatial distribution of ecological sensitivity in Dali Prefecture

Ecological corridors connect sources as carriers for energy and material flow, maintaining ecological flow continuity. Using the sensitivity-based resistance surface, we identified 9 cluster corridors (404.7 km total) and 5 landscape corridors (208.4 km total). Cluster corridors connect nodes within groups, while landscape corridors achieve landscape-scale connectivity. The corridors exhibit a dendritic radial distribution forming "one axis and three belts," primarily distributed across Cangshan in Dali City, northeastern Yangbi, western Yongping, southern Nanjian, and central Yunlong. Major rivers like the Lancang and Heihui flow through the area, providing crucial protection for biological resources, water security, and nutrient retention.

[Figure 5: see original paper] Key ecological corridors and ecological security sources in Dali Prefecture

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9. Discussion

Overlaying nature reserves with the ecological security pattern reveals high consistency. All 8 nature reserves fall within ecological sources, including Dali Cangshan-Erhai National Nature Reserve and Jianchuan Jianhu Wetland Provincial Nature Reserve. Seven reserves show >50% overlap with sources, with 4 exceeding 70.78% overlap. The 94.01% overall coincidence rate validates the reliability of our ESP construction.

The ESP provides control basis for mountainous urban construction land selection. Sources and corridors should be designated as prohibited construction zones. Future urban development should center on Cangshan-Erhai as the core, protecting surrounding mountains like Zijinshan and Luoguoshan, strengthening control over river systems and wetlands, and maintaining key ecological barriers to achieve an ecologically friendly, aesthetically pleasing mountainous urban pattern.

ESP construction typically ends with pattern component description, but validation remains crucial. Alternative validation methods include examining whether existing control measures protect important source patches, assessing sustainability in spatial planning, and using landscape metrics to adjust green infrastructure systems. Dynamic monitoring of source attributes and dual assessment of pattern quantity and quality represent future evaluation directions. Integrating ESP into urban planning, construction land suitability assessment, and urban ecological zoning requires further theoretical and practical exploration.

Regarding corridor width, theoretical studies show width directly affects ecological function, influencing species diversity patterns. However, considering regional species diversity and practical constraints, this study did not specify corridor widths, focusing instead on identifying spatial locations suitable for ecological flow transmission based on ecological processes.

[Figure 6: see original paper] Distribution of nature reserves in Dali Prefecture
[Figure 7: see original paper] Area ratio of nature reserves covered by ecological sources

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10. Conclusion

This study applied landscape ecology principles to Dali Prefecture, focusing on urban expansion constraints and typical ecological protection issues. By evaluating ecological importance for source identification, analyzing ecological sensitivity for resistance surface construction, and applying the MCR model for corridor identification, we enhanced ecological security safeguards for mountainous urban development.

Key findings: - Ecological security sources total approximately 14,416.64 km^2 (50.93% of prefecture area), distributed mainly in Cangshan (Dali City), northeastern Yangbi, western Yongping, southern Nanjian, and central Yunlong. - Key ecological corridors (613.1 km total) comprise cluster corridors (404.7 km) and landscape corridors (208.4 km), showing dendritic radial distribution. - During low-slope hilly development, sources and corridors must be strictly protected as prohibited construction zones.

ESP construction aims to identify spatial domains maintaining ecosystem structure, function, and process integrity, forming a rigid pattern for urban natural life support systems. For Dali Prefecture, ESP implementation should focus on pollution control, ecological restoration, intensified Erhai watershed management, protection of ecological public welfare forests and soil conservation forests, comprehensive pollution control in nature reserves and scenic areas, and visitor number control in low-environmental-capacity areas. Ecological compensation mechanisms should be improved to enhance stakeholder enthusiasm for ecosystem maintenance, comprehensively supporting sustainable mountainous urban development.

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