

Construction of Ecological Security Pattern in Urumqi City Based on Multi-temporal Remote Sensing Data (Postprint)

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Abstract

The construction of ecological security patterns can facilitate regional ecological development and is particularly crucial for environmental improvement in ecologically fragile areas. Based on land use data for three periods (2000, 2010, and 2020) in Urumqi City, ecological sources were identified through assessments of ecosystem service importance and ecological sensitivity, ecological corridors were extracted using the Minimum Cumulative Resistance (MCR) model, ecological pinch points were determined using circuit theory, and ecological security spaces were constructed and high-alert restoration areas were identified using the resistance threshold method. The results indicate that: (1) Over the past two decades, the area of ecological sources exhibited an increasing trend, with a total increase of 445.63 km² and a proportion increase of 3.19%. New ecological sources were mainly distributed in Urumqi County and Dabancheng District in the southwestern and eastern parts of the study area. (2) The total numbers of ecological corridors identified in the three periods were 27, 30, and 40, respectively, with total lengths of 870.42 km, 1115.83 km, and 1277.12 km, respectively. (3) Over the past two decades, the spatial distribution of five-grade ecological security spaces in the study area exhibited unevenness. High ecological security spaces were concentrated in the northeastern and southwestern parts of the study area, while relatively high ecological security spaces were concentrated around the periphery of high ecological security spaces and relatively concentrated in the central region, with both showing a continuous expansion trend. Medium ecological security spaces exhibited a northwest-southeast oriented band pattern, relatively low ecological security spaces were concentrated in the northwestern and southeastern parts of the study area, and low ecological security spaces were mainly concentrated in the northern part with fewer distributions in the southern part, all three showing a continuous decreasing trend. (4) The study area contained 7 ecological pinch points, high-alert restoration

areas of 188.17 km², and the maximum cumulative current after restoration decreased from 4.75 A to 3.82 A.

Full Text

Construction of Ecological Security Pattern in Urumqi Based on Multi-Temporal Remote Sensing Data

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Abstract

An ecological security pattern can promote regional ecological development and be highly beneficial for preserving ecologically fragile areas. Urumqi of Xinjiang, China, is a typical oasis city in an arid area. In an era of rapid development of industrialization and urbanization, because of the topographical and geological limitations and uneven spatial distribution of water and soil resources, the trade-off between regional agricultural development, ecological protection, and urbanization development is a concern. Therefore, the development of an effective method for the analysis of the temporal and spatial evolution of ecological security patterns is critical. In this study, the principle of “ecological source identification-resistance surface construction-ecological corridor extraction” was used. Based on these factors and the evaluation of the importance of ecosystem services and ecological sensitivity, the land use data of Urumqi in 2000, 2010, and 2020 were used to identify the ecological source. Next, the ecological corridors were extracted using the minimum cumulative resistance model. Furthermore, ecological pinch points were determined using the circuit theory. Finally, the resistance threshold method was used to develop the ecological security space and define the high alert restoration area. The results revealed the following: (1) In recent 20 years, the area of ecological source areas has increased considerably, and its area of 445.63 km² was more than 3.19% of the study area. The newly increased ecological source areas were distributed in Urumqi County and Dabancheng District in the southwest and east of the study area. (2) In the three periods, 27, 30, and 40 ecological corridors with a total length of 870.42 km, 1115.83 km, and 1277.12 km, respectively, were identified. (3) The spatial distribution of the five levels of ecological security in the study area was uneven. The northeast, southwest, and periphery regions of the study area had a concentration of high ecological security spaces, whereas the middle region had a moderate concentration. The two spatial distributions revealed a continuous expansion trend. The medium ecological security space showed

zonal distribution from northwest to southeast in the study area, whereas low ecological security space was concentrated in the north and sparse in the south. The spatial distribution of the three space types exhibited a decreasing trend. (4) Seven ecological pinch points were observed in the study area. The areas of high alert repaired were 188.17 km². The maximum accumulated current was reduced from 4.75 A to 3.82 A after restoration. The results can effectively coordinate the contradictory relationship between economic development and ecological protection in the study area. The results of the study can provide a scientific foundation and support the territory development plan for optimizing ecological civilization construction.

Keywords: multi-temporal remote sensing data; minimum cumulative resistance model; circuit theory; ecological security pattern; Urumqi City

Introduction

The 19th National Congress report proposed the important concept of “strengthening ecosystem protection and optimizing ecological security barriers,” making ecological security assurance a pressing social need and research hotspot. Ecological security, derived from environmental security theory, was first introduced by the International Institute for Applied Systems Analysis (IIASA) to safeguard the fundamental right to human health and well-being. In ecologically fragile areas, irrational resource utilization has caused severe landscape fragmentation. Ecological networks that connect fragmented habitats through corridors and nodes are crucial for maintaining regional ecological security. Therefore, constructing scientific and rational ecological protection patterns plays a fundamental role in ensuring regional ecological security and represents a key focus in territorial spatial planning.

Recent research on ecological security patterns has extensively explored concepts, construction methods, ecological source and corridor identification, and ecological restoration. Building ecological security patterns for territorial spatial restoration has emerged as a cutting-edge research focus. For instance, scholars have constructed land use ecological security patterns using the Minimum Cumulative Resistance (MCR) model, identified ecological pinch points based on circuit theory for restoration, and recognized key restoration zones through ecological security pattern analysis. Additionally, research has examined ecological security patterns in typical environmental regions from perspectives such as landscape ecology, ecological carrying capacity, ecological footprint, and safety index evaluation systems. However, current studies inadequately address the structural, functional, and edge effects of corridors and networks based on ecological processes. Further detailed research is needed, particularly regarding the identification of key restoration areas after corridor construction. Moreover, most studies focus on economically developed urban agglomerations and metropolitan belts, with relatively few addressing ecological security patterns in arid oasis cities.

Urumqi, the political, economic, and cultural center of Xinjiang, is a typical arid oasis city. Due to topographical and geological constraints and uneven spatial distribution of water and soil resources, the principle of “determining land use based on water availability” cannot be followed to achieve cultivated land requisition-compensation balance during rapid industrialization and urbanization. Local land degradation and pollution are serious, and conflicts between agricultural development, ecological protection, and urbanization are increasingly acute. Analyzing the spatiotemporal evolution of ecological security patterns has become an urgent issue. This study follows the framework of “ecological source identification-resistance surface construction-ecological corridor extraction.” By evaluating ecosystem service importance and ecological sensitivity, we identify critical ecological security zones in Urumqi. Using the MCR model to extract ecological corridors and circuit theory to identify ecological pinch points, we construct an ecological security pattern that meets the needs of Urumqi’s ecosystem health and sustainable socioeconomic development. This provides scientific support for coordinating economic development and ecological protection and optimizing territorial spatial planning under ecological civilization construction.

1 Study Area Overview

Urumqi (42°54'16"–44°58'16" N, 86°46'10"–88°59'48" E) is located in the center of the Eurasian continent, at the northern foot of the central Tianshan Mountains and the southern margin of the Junggar Basin. The region is surrounded by mountains on three sides (east, west, and south), with terrain gradually descending from south to north, comprising mountains, intermontane basins or hills, and plains. The city governs seven districts and one county (Tianshan District, Shayibak District, Xinshi District, Shuimogou District, Toutunhe District, Midong District, Dabancheng District, and Urumqi County), with a total area of 1.42×10^4 km². The region has a mid-temperate continental arid climate with large diurnal temperature variations, an annual average temperature of 7.4 °C, and annual precipitation of 27.9 mm. All rivers are inland rivers, primarily fed by snow and ice melt, with short and scattered channels. Major rivers include the Urumqi River, Toutun River, Baiyang River, and Daheyan River [Figure 1: see original paper].

2 Materials and Methods

2.1 Data Sources and Preprocessing

The study utilized Landsat-5 TM and Landsat-8 OLI remote sensing images from 2000, 2010, and 2020, all with cloud cover less than 10%. Digital Elevation Model (DEM) data were used for filling and excavation processing. All data were sourced from the Geospatial Data Cloud (<http://www.gscloud.cn/>). Using ENVI 5.3 and ArcGIS 10.5, preprocessing included image mosaicking, atmospheric correction, radiometric correction, and geometric correction. Based

on the “Current Land Use Classification” standard and Urumqi’s land use planning status, a random forest classifier was used to extract six land use types: cultivated land, water bodies, forest land, grassland, construction land, and unused land. The Kappa coefficients for the three classification results were 90.63%, 90.53%, and 90.24%, respectively, meeting analysis requirements.

2.2 Methodology

2.2.1 Ecological Source Identification Ecological sources typically refer to areas with high habitat quality that are crucial for regional ecological security and sustainable development. Following the “Technical Guidelines for Ecological Protection Redline Delineation” issued by the Ministry of Environmental Protection, we selected ecosystem service importance and ecological sensitivity as evaluation criteria. The Analytic Hierarchy Process determined ecological land evaluation factors and weights. The highest composite indices from these evaluations were extracted as core ecological land, and landscape patch connectivity was used to analyze well-connected areas within sources. Using Conefor Sensinode 2.6 software in ArcGIS 10.5, we calculated the probability of connectivity index and patch importance index to complete source identification.

The calculation formulas are:

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

where PC is the probability of connectivity index for a patch in the landscape; P_{ij}^* is the maximum product of probabilities of all paths between patches i and j ; a_i and a_j are the areas of patches i and j (km^2); and A_L is the total landscape area (km^2).

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

where dPC is patch importance; PC is the probability of connectivity index; and PC_{remove} is the connectivity index after removing the patch.

Habitat patches larger than 10 km^2 were selected, with a connectivity threshold of 2500 m, probability of connectivity index > 0.5 , and patch importance index > 0.2 . The extracted ecological sources were 10, 14, and 18 patches for 2000, 2010, and 2020, respectively.

2.2.2 MCR Model The MCR model, first proposed by Knaapen, simulates spatial patterns of ecological processes. Species migration and diffusion in landscapes incur costs. Since ecological processes tend to occur along paths of least resistance, minimum cost distance represents the straight-line distance modified

by resistance coefficients as material flows through the landscape, enabling ecological corridor identification by determining minimum cumulative resistance paths between sources. The formula is:

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

where MCR is the minimum cumulative resistance value; f_{min} represents the positive correlation between minimum cumulative resistance from a point to the base surface and ecological processes; D_{ij} is the spatial distance from source i to j ; and R_i is the resistance coefficient of grid i to ecological source expansion.

2.2.3 Important Corridor Identification To explore corridor importance and construct a hierarchical ecological corridor network, we used the gravity model to distinguish ordinary and important corridors. The formula is:

$$G_{ab} = \frac{N_a \times N_b}{D_{ab}^2} \times \frac{1}{\max(L_{ab})} \times \ln(S_a) \times \ln(S_b)$$

where G_{ab} is the interaction force between ecological sources a and b ; N_a and N_b are patch weight values; D_{ab} is the standardized potential corridor resistance between patches a and b ; P_a and P_b are patch resistance values; S_a and S_b are patch areas (km^2); L_{ab} is the cumulative resistance value of the corridor between patches a and b ; and $\max(L_{ab})$ is the maximum cumulative resistance of all corridors in the study area.

2.2.4 Ecological Pinch Point Identification Ecological pinch points, as active areas connecting sources, are crucial nodes for preventing ecological degradation and ensuring corridor flow. Proposed by McRae based on circuit theory, the approach uses resistance values to reflect ecological resistance faced during species migration and diffusion, with current and voltage quantifying connectivity between sources. Current represents migration quantity and probability of species or genotypes, while voltage represents internal differences between sources. High-quality habitat patches are treated as nodes replacing ecological sources—higher habitat quality facilitates species migration, resulting in greater current values between nodes. Current density, defined as the current passing through a single pixel, identifies pinch point areas in corridors. As regions with high current density in ecological corridors, pinch points indicate high probability of species movement between habitats with few alternative paths. Their removal or alteration would significantly impact connectivity. This study used Linkage Mapper and Pinchpoint Mapper tools to identify ecological pinch points.

3 Results and Analysis

3.1 Spatiotemporal Distribution Characteristics of Ecological Sources

The spatial distribution of ecological sources in Urumqi remained relatively stable from 2000 to 2020, concentrated in Tuoli Township, Saerdaban Township, and Miaoergou Township in Urumqi County, as well as Akesu Township in Dabancheng District and southern Midong District [Figure 2: see original paper]. These areas, restricted by terrain with high elevation, high vegetation coverage, extensive forest and grassland, and minimal human development, represent extremely important ecosystem service zones and highly ecologically sensitive areas requiring priority protection.

From 2000 to 2020, ecological source area showed an increasing trend, totaling 445.63 km², 2640.35 km², and 3085.98 km², respectively, with proportions increasing from 18.94% to 20.67% to 22.13%. The continuous increase in source area primarily benefited from strengthened green land management in the “Urumqi Urban Master Plan (2011–2020)” and effective implementation of ecological restoration policies encouraging social forces to afforest barren hills and providing subsidies for afforestation of suitable wasteland.

3.2 Construction of Minimum Cumulative Resistance Surface

Resistance surface construction is fundamental for studying resistance overcome during species migration and diffusion. Referencing Zhang et al. and considering study area conditions, we selected slope, land use type, vegetation coverage, and elevation as resistance factors, assigned relative resistance coefficients, and used expert scoring to determine factor weights. The “comprehensive weighted index sum” model was used to construct the minimum cumulative resistance surface.

Results showed that as sources expanded outward, MCR values gradually increased, with low-resistance areas expanding significantly, primarily distributed in mountainous and hilly regions in the southwest and southeast with high vegetation coverage and large terrain relief. Medium-high resistance areas showed a shrinking trend, mainly distributed in plains in the north, center, and south where construction land and cultivated land are concentrated with intense human activity [Figure 3: see original paper].

3.3 Spatiotemporal Distribution Characteristics of Ecological Corridors

Due to redundancy caused by shared patches in corridor networks, corridors with minimum resistance values were retained. Based on 18 patches, three periods extracted 27, 30, and 40 ecological corridors with total lengths of 870.42 km, 1115.83 km, and 1277.12 km, respectively. The gravity model calculated interaction forces between core patches, identifying 11, 13, and 17 important corridors. The increase in corridor quantity demonstrates reduced probability of

ecological flow interception and segmentation, significantly improving surrounding environments.

Overall, 2000 corridors were narrowly distributed in central areas, with connections concentrated between Urumqi County and Dabancheng District. In 2010, corridors were sparser in central areas but denser in the southwest, with connections among Urumqi County, Dabancheng District, and Tianshan District, particularly widespread in Dabancheng District due to new sources comprising natural pastures and forests. In 2020, corridor distribution was more uniform, with connections concentrated among Urumqi County, Dabancheng District, Tianshan District, Shayibak District, and Shuimogou District. Compared with 2010, Urumqi County showed significant new source area increases extending northward [Figure 4: see original paper].

3.4 Ecological Security Pattern

Using the resistance threshold method, we analyzed the relationship between minimum cumulative resistance values and grid cell area from three periods' resistance surfaces, using inflection points as critical points for discrete classification into five ecological security levels: high, relatively high, medium, relatively low, and low. Considering ecological corridors of certain width equally important as sources, we incorporated important corridors (200 m buffer) and ordinary corridors (100 m buffer) into high ecological security space, completing the ecological security pattern [Figure 5: see original paper].

Results show uneven distribution among five security levels. High and relatively high ecological security spaces concentrated in the northeast, southwest, and periphery, showing continuous expansion from 46.10% to 48.20% to 54.90%. Medium ecological security space showed northwest-southeast zonal distribution, concentrating around relatively high security space in central areas. Relatively low security space concentrated in northwest and southeast, while low security space mainly concentrated in the north with sparse southern distribution—all three showed decreasing trends [Figure 6: see original paper]. The overall improvement in ecological security level demonstrates effective ecological protection policy implementation.

3.5 Ecological Pinch Points and High-Alert Restoration Areas

Based on corridor current density distribution [Figure 7: see original paper] and natural breaks classification with resistance surface overlay, we extracted seven ecological pinch points, primarily distributed in central Urumqi (Dabancheng District: 2, Shuimogou District: 2, Urumqi County: 3). Overlay analysis of corridors, pinch points, and land use patches identified key ecological spaces with high degradation probability. Using Barrier Mapper, we compared cumulative current values before and after restoration to identify high-alert restoration areas of 188.17 km², spatially dispersed but concentrated in northern Urumqi County and eastern/western Dabancheng District.

Post-restoration cumulative current values in restored areas ranged from 0.55–1.47 A, with maximum cumulative current reduced from 4.75 A to 3.82 A, demonstrating improved connectivity and positive effects on ecological security pattern optimization.

3.6 Ecological Security Protection Strategies

Based on Urumqi's ecological security pattern analysis, we propose the following strategies:

- 1) **Strengthen existing ecological source protection:** Maintain natural development status by designating sources as prohibited development zones in planning. For this typical arid oasis city, key sources should include river headwaters and water conservation areas (Glacier No. 1, Wulabo Reservoir, Toutun River, Zhaobi Mountain Reservoir) and alpine forest-grassland conservation areas. Illegal occupation and development must be prosecuted, and urban planning should synchronize remediation of damaged sources.
- 2) **Optimize ecological corridors:** Enhance four river corridors (Toutun River, Urumqi River, Shuimo River, Baiyang River) emphasizing connectivity between upstream and downstream environments. Develop small green spaces, large parks, and vegetated slopes along rivers to maintain high greening rates. For transportation corridors near or crossing construction land (such as Hetan Road and Wuchang Avenue), implement technical restoration using native vegetation adapted to regional ecological characteristics to improve environmental integration.
- 3) **Optimize land use planning:** Macroscopically, divide into four zones—mountain forest ecological protection zone, piedmont hilly forest-grassland ecologically sensitive zone, oasis agricultural ecological construction zone, and desert ecological restoration zone. Conduct land consolidation in severely degraded and desertified areas, such as establishing grazing and mining prohibition zones in low mountains and piedmont areas of the southern and eastern Tianshan Mountains with severe soil erosion. Strengthen comprehensive environmental protection of the Urumqi River and Glacier No. 1 area, and implement wetland protection and restoration projects for East Daohaizi and Chaiwopu Lake. Microscopically, formulate Urumqi territorial spatial planning based on the “three red lines,” classifying urban areas into key development, moderate development, ecological protection, and prohibited development zones to establish a foundation for future urban development. Create a circular ecological green barrier around the central urban area.

4 Discussion

This study constructs an ecological security pattern for a typical arid oasis city, expanding research beyond major urban agglomerations and proposing a small-

scale construction method. The “Urumqi Urban Master Plan (2011–2020)” emphasized strict control of ecological protection redline core areas, encouraged farmland and ecological land protection, and strengthened green land management to regulate and improve the ecological environment, resulting in continuously increasing ecological source areas—findings consistent with Halimulati et al. Regarding temporal evolution, research shows that in both quantity and quality, Urumqi’s cultivated land requisition-compensation balance and ecological factors have steadily improved, with ecological security pattern indicators reaching safe or very safe states, aligning with our results.

Territorial spatial ecological restoration is crucial for ecological civilization construction. Scientifically identifying key restoration areas and rationally arranging restoration spaces are current challenges. However, the ecosystem is an organic living system, and single-element, single-measure land consolidation and ecological restoration models cannot comprehensively solve complex problems. Approaches must shift from single-element, single-objective remediation to systematic restoration and governance of entire territorial spaces from an ecosystem integrity and comprehensive perspective. Ecological security patterns fully consider systematicness and landscape component connectivity. This study achieves the transformation of ecological corridors from “lines” to “areas” and quantifies corridor width and “patch” (ecological restoration area) size, making restoration area identification more ecologically valuable and breaking previous single-object remediation limitations. This provides new references for holistic protection, systematic restoration, and comprehensive governance of “mountains, waters, forests, farmlands, lakes, and grasslands.”

However, indicator selection for ecosystem service function and ecological sensitivity evaluation has certain subjectivity, potentially causing errors requiring continuous improvement of indicator systems and parameter correction. Additionally, quantitative measurement standards for ecosystem structure optimization and functional connectivity enhancement need further development to improve scientific rigor.

5 Conclusions

Based on ecosystem service function and ecological sensitivity evaluation, combined with the MCR model and circuit theory, we constructed ecological sources, corridors, pinch points, and the overall ecological security pattern, and identified high-alert ecological restoration areas. The main conclusions are:

- 1) From 2000 to 2020, ecological source areas continuously increased by 445.63 km², reaching 22.13% of the study area. Spatially, they showed an approximate east-west “dual-core” pattern concentrated in Dabancheng District in the east and Urumqi County in the southwest—areas that are extremely important for ecosystem services and highly ecologically sensitive, requiring priority protection.
- 2) The total number of ecological corridors was 27, 30, and 40, with total

lengths of 870.42 km, 1115.83 km, and 1277.12 km, respectively. The ecological network connectivity level continuously improved, enhancing species migration and energy flow efficiency between sources.

- 3) The five-level ecological security spaces showed uneven distribution. High and relatively high ecological security spaces concentrated in the northeast and southwest, showing continuous expansion. Medium ecological security space showed northwest-southeast zonal distribution around relatively high security space in central areas. Relatively low and low security spaces concentrated in the northwest, southeast, and north, all showing decreasing trends.
- 4) Seven ecological pinch points were identified with good corridor connectivity. Although a “point-line-area” ecological network pattern has formed among sources, further improvement and protection are needed.
- 5) High-alert restoration areas of 188.17 km² were identified. The cumulative current value range after restoration was 0.55–1.47 A, with maximum cumulative current reduced from 4.75 A to 3.82 A. Improving these high-alert restoration areas positively enhances connectivity between ecological sources and optimizes the ecological security pattern.

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