

Coupling Ecosystem Services and Landscape Connectivity for Ecological Security Pattern Assessment in Tarim Basin Rim Oasis Regions: Postprint

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Abstract

Ecological security plays a crucial role in protecting biodiversity and maintaining ecosystem services. Currently, research on ecological security pattern construction mostly focuses on treating nature reserves as ecological sources, while neglecting patches with potential ecological services and the impact of patch connectivity. To this end, this study proposes an improved method for ecological security pattern construction, taking the oasis area of the Tarim Basin rim as an example. By coupling four ecosystem services—carbon storage, water conservation, soil retention, and windbreak and sand fixation—with landscape connectivity, ecological sources are optimized, a comprehensive resistance surface is constructed, and circuit theory is utilized to determine the ecological security pattern of the study area. The results show that: (1) The oasis area of the Tarim Basin rim is in a low ecological security zone, characterized by severe water shortage and desertification in the region. (2) A total of 22 ecological sources were identified in the oasis area of the Tarim Basin rim, covering an area of 69622.24 km², along with 33 ecological corridors with a total length of 4722.39 km. The sources exhibit a pattern of scattered distribution in the south and dense clustering in the north, with poor connectivity between the southern and northern sources. (3) An optimized layout scheme of “two barriers, one ring, and multiple zones” for the ecological security pattern is formed, which clarifies ecological function zoning and improves the regional ecological environment. The research results can provide references for territorial spatial planning.

Full Text

Ecological Security Pattern of the Oasis Area around the Tarim Basin Based on Coupled Ecosystem Services and Landscape Connectivity

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Abstract

Ecological security plays an essential role in protecting biodiversity and maintaining ecosystem services. However, current research on constructing ecological security patterns has predominantly focused on treating nature reserves as ecological sources while neglecting patches with potential ecological services and the influence of patch connectivity. To address this limitation, this study proposes an improved method for constructing ecological security patterns, using the oasis area around the Tarim Basin as a case study. The approach optimizes ecological sources by coupling four ecosystem services—carbon storage, water conservation, soil retention, and windbreak and sand fixation—with landscape connectivity. A comprehensive resistance surface is constructed, and the ecological security pattern of the study area is determined using circuit theory. The results reveal that: (1) The oasis area around the Tarim Basin is in a low ecological security zone, characterized by severe water shortage and desertification; (2) A total of 22 ecological sources covering an area of 69,622.24 km² and 33 ecological corridors with a total length of 4,722.39 km were identified, with sources scattered in the south and densely distributed in the north, and poor connectivity between southern and northern sources; (3) An optimal layout plan for the ecological security pattern of “two screens, one ring, and multiple areas” was developed, clarifying ecological function zones and improving the regional ecological environment. These findings can provide valuable references for territorial spatial planning.

Keywords: ecological security pattern; ecosystem service; landscape connectivity; circuit theory; Tarim Basin Rim oasis area

1 Introduction

Rapid economic development has intensified human disturbance to natural ecosystems, gradually highlighting the contradiction between human needs and ecological environmental conditions [1]. This has led to numerous ecological and environmental problems, including soil erosion, water resource scarcity, vegetation degradation, and air pollution [2]. The “EU Biodiversity Strategy for 2030” proposes protecting at least 30% of land, coastal areas, and inland waters by 2030 [3]. As conservation targets expand, so does the required protection scope. Therefore, under resource constraints, determining regional

ecological security patterns, rationally developing, protecting, and restoring territorial space, ensuring the integrity of ecosystem services, improving ecological security, and achieving sustainable territorial development have become urgent issues [4].

Ecological security patterns (ESP) are crucial for maintaining the structural and functional integrity of ecosystems [5]. Based on landscape ecology theory, ESP analyzes spatial positions and interconnections among different landscapes to simulate landscape change trends, thereby providing theoretical support and specific implementation plans for regional ecological security [6]. Construction of ESP has formed a basic paradigm: “ecological source identification—resistance surface construction—corridor extraction” [7]. Ecological sources are areas that provide high-level ecosystem services and play decisive roles in maintaining regional ecological security [8]. Previous studies often directly used protected areas, parks, water bodies, and other important ecological regions as ecological sources [9], focusing optimization and restoration efforts on these areas. However, this approach is primarily based on current conditions, tends to be subjective, and lacks in-depth consideration of the critical role of ecological sources in ecological processes and functions, often overlooking areas with potential ecological services [10].

Ecosystem services (ES) provide humans with regulation, provisioning, cultural, and supporting services [11]. Methods for identifying ecological sources based on ecosystem services have been widely applied [12]. This approach quantitatively evaluates a series of ecological processes to identify key carrying spaces for ecosystem services as ecological sources [13]. However, such methods neglect the impact of patch connectivity. Ecological resistance surfaces represent the spatial distribution of regional ecological resistance [14], indicating the degree to which landscape heterogeneity hinders species movement and material/energy flow within ecosystems [15]. Early studies typically assigned resistance values based on land use types [16], while recent research has used human activity intensity data (e.g., nighttime light data and comprehensive ecological land value) to modify resistance values [17]. Additionally, species migration characteristics affect resistance value distribution, necessitating consideration of animal movement behaviors in resistance surface construction.

Ecological corridors serve as channels for species migration and play vital roles in biodiversity conservation and ecological processes [18]. Most studies have used the minimum cumulative resistance model to extract corridors [19], but these methods ignore the randomness of species migration. Other research has employed circuit theory to simulate random behavior characteristics of species to determine ecological corridors [20]. Regional ecological security pattern research is maturing, providing ideas and methods for territorial spatial planning, yet the ESP optimization system still faces challenges.

The Tarim Basin Rim oasis area is a typical ecologically fragile region in Xinjiang, facing dual pressures from rapid economic development and natural ecological protection. It is necessary to identify the ecological security pattern

status of this region. This study proposes an improved ecological security pattern construction method, evaluating four ecosystem services (carbon storage, water conservation, soil retention, and windbreak and sand fixation) according to the climatic characteristics of the study area, and coupling landscape connectivity to optimize ecological source selection. Considering both natural environmental and human activity impacts, this research integrates land use type, elevation, slope, vegetation coverage, and nighttime light intensity to construct a comprehensive resistance surface. Using circuit theory to determine the spatial range of ecological corridors and key areas, this study comprehensively considers the radiation effects of ecological sources and resistance surfaces as well as species migration randomness. The aim is to reveal the ecological security pattern status of the Tarim Basin Rim oasis area and provide scientific basis and reference for improving the regional ecological environment and achieving sustainable urban development.

2 Study Area and Methods

2.1 Study Area Overview

The Tarim Basin Rim oasis area is located in southern Xinjiang, in the interior of the Eurasian continent, between the Tianshan and Kunlun Mountains. It comprises 10 prefecture-level administrative units: Bayingolin Mongol Autonomous Prefecture (Bayingol), Kizilsu Kirghiz Autonomous Prefecture (Kizilsu), Kashgar Prefecture, Aksu Prefecture, Hotan Prefecture, Aral City, Tumshuk City, Tiemenguan City, and Kunyu City. The area covers 1.03×10^6 km², accounting for 62% of Xinjiang's total area. The region has an arid climate with sparse vegetation, dominated by salt-tolerant and drought-resistant shrubs and herbaceous plants. Land types are primarily Gobi and desert, with average annual precipitation of only 50–100 mm and high evapotranspiration. The average annual temperature is 8.63 °C. The permanent population of the Tarim Basin economic circle is 11.95 million, accounting for 46.2% of Xinjiang's total population, with a regional GDP of 4.82×10^{11} yuan, representing 30.1% of Xinjiang's total. Accelerated urbanization has severely impacted natural ecological processes. To achieve healthy sustainable development and build a beautiful Xinjiang, it is necessary to assess the ecological status of the Tarim Basin Rim oasis area and implement strict ecological protection and restoration measures to guide future territorial spatial planning.

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

2.2 Data Sources

This study primarily utilized land use data, nighttime light data, basic geographic data (soil, elevation), meteorological data (precipitation, temperature, evapotranspiration, wind speed), and normalized difference vegetation index (NDVI) data. All spatial datasets were resampled to a resolution of 1000 m × 1000 m. Detailed data sources are listed in Table 1.

Research data of the study

2.3 Methods

2.3.1 Identification of Ecological Sources Ecological sources are critical for maintaining ecological integrity and providing high-quality services in ecological processes [21]. This study used morphological spatial pattern analysis (MSPA) to calculate landscape connectivity, normalized and weighted the four ecosystem services, employed hotspot analysis to calculate the comprehensive ecosystem services index, and finally overlaid the landscape connectivity and ecosystem service importance evaluation results to extract ecological sources.

(1) Landscape Connectivity Analysis

Morphological spatial pattern analysis (MSPA) can classify raster data into seven mutually exclusive categories: core, islet, perforation, edge, bridge, loop, and branch [22]. Among these, core areas are large natural patches with high connectivity. Using forest land, grassland, wetland, and water bodies as foreground with default parameters (Edge Width=1), this study calculated the connectivity integral index (IIC) and connectivity probability (PC) for core areas in Conefor 2.6 software:

$$IIC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \times a_j \times nl_{ij}}{A_L^2}$$

$$PC = \frac{\sum_{i=1}^n \sum_{j=1}^n a_i \times a_j \times p_{ij}}{A_L^2}, \quad 0 < PC < 1$$

where: n is the total number of ecological patches; a_i and a_j are the areas of patches i and j ; nl_{ij} is the number of connections in the shortest path between patches i and j ; A_L is the total landscape area; and p_{ij} is the maximum product probability of all paths between patches i and j .

(2) Ecosystem Services Assessment

Based on the ecological environment status and climate characteristics of southern Xinjiang, this study selected carbon storage, water conservation, soil retention, and windbreak and sand fixation for evaluation.

Carbon storage was assessed using the carbon storage and sequestration module in the InVEST 3.13 model [23]:

$$C_i = C_{i_{above}} + C_{i_{below}} + C_{i_{soil}} + C_{i_{dead}}$$

where: C_i is the total carbon density of land use type i ; $C_{i_{above}}$ is the aboveground vegetation carbon density; $C_{i_{below}}$ is the belowground root

carbon density; C_{i_soil} is the soil carbon density; and C_{i_dead} is the dead organic matter carbon density.

Water conservation was assessed using the annual water yield module in InVEST 3.13 [24]:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x$$

where: Y_x is the annual water yield of grid cell x ; AET_x is the annual evapotranspiration; and P_x is the annual precipitation.

Soil retention was assessed using the Revised Universal Soil Loss Equation (RUSLE) [25]:

$$A = R \times K \times LS \times (1 - C \times P)$$

where: A is the annual average soil retention; R is the rainfall erosivity factor; K is the soil erodibility factor; LS is the topographic factor; C is the vegetation cover factor; and P is the soil and water conservation factor.

Windbreak and sand fixation was assessed using the Revised Wind Erosion Equation (RWEQ) [26]:

$$S = S_L - S_P$$

where: S is the annual windbreak and sand fixation capacity per unit area; S_L and S_P are the actual and potential wind erosion amounts per unit area, respectively.

Comprehensive Ecosystem Services Index (CESI): To uniformly quantify the capacity of ecosystems to provide multiple services, the four ecosystem service results were normalized to eliminate dimensional effects and weighted according to the natural climate characteristics of the study area:

$$CESI = \sum_i w_i \times IES_i$$

where: $CESI$ is the comprehensive ecosystem services index; IES_i is the normalized value of ecosystem service i ; and w_i is the weight of ecosystem service i .

(3) Hotspot Analysis

Traditional natural breaks methods for extracting ecological sources from ecosystem services and biodiversity factors yield highly fragmented, small, and isolated patches. Therefore, this study employed Getis-Ord hotspot analysis to process

ecosystem services [27], which can eliminate the influence of highly fragmented small areas. Areas with high connectivity, high ecological value, and high species richness were identified by overlaying landscape connectivity and hotspot analysis results. Finally, patches smaller than 500 km² were removed, yielding 22 core ecological source patches (Figure 2) covering 69,622.24 km² (6.71% of the study area).

2.3.2 Construction of Ecological Resistance Surface The ecological resistance surface reflects the impact of landscape heterogeneity on ecological processes, representing the degree to which landscape patterns hinder species movement and material/energy flow [28]. Studies typically assign different resistance values based on land use types [29], but this method cannot objectively and accurately reflect landscape interference with biological flow. Therefore, this study integrated four resistance factors—elevation, slope, vegetation coverage, and nighttime light intensity—to correct land use types and construct a comprehensive ecological resistance surface. Initial resistance values were assigned to land use types (forest, grassland, water body, cropland, unused land, and construction land) based on relevant studies [30] and the characteristics of arid regions. Correction factors were classified into five categories using the natural breaks method and assigned correction coefficients. A value of 1 indicates no impact on ecological resistance, while higher values indicate greater impact. The comprehensive ecological resistance surface was calculated as:

$$R_{\text{total}} = R_i \times (w_b \times DEM_i + w_c \times Slope_i + w_d \times FVC_i + w_e \times NTL_i)$$

where: DEM_i , $Slope_i$, FVC_i , and NTL_i are the elevation, slope, vegetation coverage, and nighttime light correction coefficients for grid cell i , respectively; R_{total} is the modified comprehensive resistance value; w_b , w_c , w_d , and w_e are the weights for elevation, slope, vegetation coverage, and nighttime light (all set to 1); and R_i is the initial ecological resistance value for grid cell i 's land use type.

2.3.3 Identification of Ecological Corridors and Pinch Points Circuit theory uses random walk theory to simulate ecological connectivity, modeling species movement through random charge movement. The landscape pattern is treated as a conductive surface, where landscape types that facilitate ecological processes have low resistance, while those that hinder processes have high resistance [31]. Based on circuit theory principles, when electrons move randomly, circuits are generated, and corridor importance is determined by current density values—higher values indicate greater probability of species passage. This was implemented using the “Linkage Mapper” plugin with a threshold range of 20 km.

3 Results and Analysis

3.1 Spatial Distribution of Landscape Connectivity

The MSPA analysis results (Figure 2) show that core area covers only 160,520 km² (15.47% of the study area), mainly distributed in southeastern and northern Bayingol, southern Hotan, southwestern Kashgar, and northern Aksu. These regions have large vegetation coverage and minimal human disturbance, providing favorable habitats for biodiversity. Bridge area covers 82,619 km² (7.96% of the study area), indicating relatively low landscape connectivity. Islets are small, isolated patches that can serve as “pinch points” in ecological processes, covering 22,372 km² (2.16% of the study area). Loop area facilitates species migration within the same patch, covering 15,270 km² (1.47% of the study area). The landscape connectivity indices were calculated by importing the analysis results into Conefor software, yielding 22 core patches as ecological sources (Figure 2). The ecological sources exhibit a pattern of scattered distribution in the south and dense clustering in the north. The largest patch covers 45,343 km² in the southwestern study area, dominated by grassland and water bodies.

[Figure 2: see original paper] MSPA analysis and spatial distribution of ecological sources

3.2 Spatial Distribution of Ecosystem Services

The four ecosystem services show significant spatial heterogeneity (Figure 3). High carbon storage values are distributed in southeastern and northern Bayingol, southern Hotan, southwestern Kashgar, and northern Aksu, where high vegetation coverage provides significant climate regulation benefits. Water conservation shows a decreasing trend from periphery to center, with abundant vegetation and water resources in the southern Tianshan and northern Kunlun Mountains providing strong water conservation capacity. Due to large terrain relief, unreasonable land use structure, and sparse vegetation cover, soil retention capacity is relatively low across the study area. Northern and southern regions with higher vegetation coverage have better soil retention, while the central desert area shows poor performance. High windbreak and sand fixation values are mainly distributed in grassland, cropland, and partial forest areas with substantial vegetation cover that effectively blocks wind and sand. The Tarim Basin is dominated by desert and Gobi surfaces with sparse vegetation, resulting in high wind-sand volumes.

[Figure 3: see original paper] Evaluation of ecosystem services

The normalized results of the four ecosystem services were weighted and overlaid to obtain the final comprehensive ecosystem services index distribution (Figure 4). Using the natural breaks method, five importance levels were classified (Table 2). The results show that areas with general or higher importance cover 327,853.18 km² (32.58% of the study area), while low importance areas cover 517,745.11 km² (51.47%). High and relatively high importance areas are

mainly forest and grassland distributed in southeastern and northern Bayingol, southern Hotan, southwestern Kashgar, and northern Aksu, playing crucial roles in carbon storage and water conservation, effectively regulating climate and providing rich ecological resources. General importance areas (155,263.23 km², 15.43%) are primarily cropland serving as transition zones between urban areas and forest/grassland, acting as buffers for species migration. Lower and low importance areas are mainly distributed in construction land edges and desert/Gobi regions with weak soil retention and windbreak capacity, as well as urban areas with strong human disturbance, indicating that land use and human activities severely affect local ecological conditions.

[Figure 4: see original paper] Spatial distribution of the composite index of ecosystem services

Area and proportion of ecosystem service importance level

3.3 Determination of Ecological Sources

Hotspot analysis was applied to calculate ecosystem service hotspots (Figure 5). By overlaying landscape connectivity and hotspot analysis results, areas with high connectivity, high ecological value, and high species richness were identified. After removing patches smaller than 500 km², 22 patches were selected as core ecological sources (Figure 2), covering 69,622.24 km² (6.71% of the study area). The sources show high landscape fragmentation and can be divided into southern and northern groups. Northern sources are small and concentrated, mainly in northern Bayingol and Aksu. Southern sources are large and widely distributed across Bayingol, Kizilsu, Kashgar, and Hotan.

[Figure 5: see original paper] Result of hotspot analysis

3.4 Spatial Distribution of Ecological Resistance Surface

The base resistance surface derived from land use types was corrected using the four resistance factors to obtain the comprehensive ecological resistance surface (Figure 6). High resistance values are concentrated in the central Tarim Basin Rim oasis area, primarily affected by land cover (mainly desert). Smaller concentrations appear in oasis urban areas at the study area edges, influenced by construction land, roads, and human activities. Frequent human activity, developed transportation, numerous roads, and dense distribution strongly interfere with ecological processes, damaging overall ecosystem connectivity and hindering normal ecological functioning. Human development continuously encroaches on ecological space, leading to landscape fragmentation and obstructing the flow and exchange of information and materials between habitats.

[Figure 6: see original paper] Spatial distribution of core ecological sources and ecological resistance surfaces

3.5 Extraction of Ecological Corridors

The ecological security pattern of the Tarim Basin Rim oasis area consists of 33 ecological corridors with a total length of 4,722.39 km (Figure 7). The longest corridor is 901.47 km, and the shortest is 143.1 km. Corridor distribution shows significant spatial heterogeneity: eastern region corridors are numerous and short, facilitating short-distance species migration; western corridors are longer, connecting the southern Tianshan water conservation area, Pamir biodiversity conservation area, Pamir-Kunlun water and soil loss protection area with the northern Tianshan water conservation area in Aksu and the Bayanbulak National Nature Reserve in Bayingol.

Based on the ecological corridors, cumulative current density between ecological sources was calculated, revealing narrow current density between southern and northern sources but wide density within sources. This indicates poor connectivity between southern and northern landscapes, severely hindering information and material flow, while internal connectivity is better, facilitating energy flow and material exchange. Corridor width is uncertain due to resistance value influences. Areas with concentrated high resistance values experience strong human activity that squeezes and disturbs ecological space, narrowing corridor width. Wider corridors indicate larger species activity spaces with fewer restrictions, enabling better species migration and energy flow. Ecological pinch points serve as species stepping stones and turning points, representing key areas for maintaining corridor connectivity that are severely affected by human disturbance and require prioritized protection and restoration.

[Figure 7: see original paper] Ecological security patterns

4 Discussion

4.1 Ecosystem Services Assessment and Ecological Source Identification

This study coupled ecosystem services and landscape connectivity, combining circuit theory to determine corridor spatial ranges and key nodes, providing new insights for ESP construction. The MSPA analysis simplified landscape pattern assessment, offering a new basis for landscape ecology analysis. Additionally, this study used quantitative evaluation of core patches from landscape connectivity, avoiding the subjectivity of manually selecting ecological sources in previous research. In past studies, forest land and water bodies with important ecological services were often directly treated as ecological sources. This research, considering the natural ecological conditions and needs of the study area, identified important areas with carbon fixation, soil retention, water conservation, and windbreak/sand fixation functions as ecological sources. We argue that important ecosystem service areas are low-intensity land use buffers around ecological networks, protecting the ecological environment from high-intensity disturbances associated with urban development. These areas serve as transition zones between natural ecosystems (represented by the ecological

environment) and socio-economic systems, providing buffers for ecological protection and delivering effective ecosystem services to human society.

4.2 Recommendations for Ecological Security Pattern Protection

This study identified the ecological security pattern of the Tarim Basin Rim oasis area. Overall, connectivity between southern and northern regions is weak, and areas with general ecological importance are mainly surrounded by construction land and cropland, making them vulnerable to disturbance and destruction. Clear demarcation of “three zones and three lines” is needed to strengthen protection of these areas. ESP construction should formulate appropriate protection and restoration plans based on local conditions, forming an optimal layout of “two screens, one ring, and multiple areas.” This includes the Tianshan and Kunlun-Altun mountain ecological barriers, the Tarim Basin oasis ecological ring, and various ecological service protection areas (water conservation, biodiversity, water and soil loss, windbreak and sand fixation, desertification control). According to different ecological function protection needs, ecological function zones should be clearly defined, protection of important ecological spaces such as lakes, reservoirs, water systems, and wetlands should be enhanced, desertification prevention should be strengthened, and integrated restoration of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts should be promoted.

4.3 Limitations and Future Research

This study has several limitations. For instance, correctly setting resistance values remains challenging, as resistance surface construction affects model validity and substantially impacts ecological network construction, with no universally accepted standards currently available. Empirically determined resistance values neglect connectivity effects between different land use types, inadequately expressing resistance conditions across land use types. Therefore, reasonable landscape resistance value setting should consider multiple factors, including research objectives and dispersal behaviors of different wildlife species. Additionally, corridor width determination remains a challenge in environmental footprint research, with immature methodologies. Different thresholds are often set according to various research purposes, and the rationality of these thresholds requires further investigation.

5 Conclusions

This study coupled ecosystem services and landscape connectivity to identify the ecological security pattern of the Tarim Basin Rim oasis area, determined corridor spatial ranges and locations based on circuit theory, and proposed corresponding optimization strategies, providing new insights for ESP construction. The main conclusions are:

- (1) The four ecosystem services—carbon storage, water conservation, soil retention, and windbreak and sand fixation—in the Tarim Basin Rim oasis

area show significant spatial heterogeneity. The region suffers from severe water shortage and desertification, with relatively weak water conservation and windbreak/sand fixation capacities. Areas with importance levels of general or above cover 327,853.18 km² (32.58% of the study area), while low importance areas cover 517,745.11 km² (51.47%).

- (2) A total of 22 ecological sources covering 69,622.24 km² and 33 ecological corridors totaling 4,722.39 km were identified. Ecological sources show a pattern of scattered distribution in the south and dense clustering in the north, with poor connectivity between southern and northern sources.
- (3) Based on the actual conditions of the study area, an optimal layout plan of “two screens, one ring, and multiple areas” was proposed, including the Tianshan and Kunlun-Altun mountain ecological barriers, the Tarim Basin oasis ecological ring, and multiple ecological service protection zones. This clarifies ecological function zoning and is expected to promote sustainable economic and ecological development.

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