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Postprint: Ecological Land Use Planning in Beijing Based on the Minimum Cumulative Resistance Model

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Abstract

Ecological land use planning emphasizes the protection of regional ecosystem structure and function, thereby enhancing the ecological environmental support capacity for socio-economic development. From the perspectives of ensuring fundamental ecological security of the capital, improving atmospheric environmental quality, and building a livable city, this study identifies the spatial distribution characteristics of important ecological land in Beijing through a comprehensive evaluation of ecological importance. Based on this, the Minimum Cumulative Resistance (MCR) model is adopted, using important ecological land as "sources" and employing land cover type, distance from roads, and distance from residential areas as resistance factors to generate resistance surfaces, thereby simulating the spatial expansion process of important ecological land. Subsequently, ecological land use planning scenarios are developed, and the conservation effectiveness of different scenario-based planning schemes is evaluated from three dimensions: landscape connectivity, ecological function guarantee degree, and conflict with existing construction land. Ultimately, suitable scales and optimized layout schemes for ecological land in Beijing are proposed. The results demonstrate that the total area of important ecological land in Beijing is 9879 km^2, representing 60.20% of the total municipal area; the suitable scale for ecological land is 12417 km^2, representing 75.67% of the total municipal area. Specifically, the suitable scale for ecological land in plain areas is 2944 km^2, accounting for 46.45% of the total plain area and primarily distributed in peripheral transitional zones of built-up areas; the suitable scale for ecological land in mountainous areas is 9473 km^2, accounting for 94.05% of the total mountainous area.

Full Text

Preamble

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Ecological Land Use Planning for Beijing City Based on the Minimum Cumulative Resistance Model

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Abstract

Ecological land use planning emphasizes the protection of regional ecosystem structure and function while reinforcing the eco-environmental support capacity for socio-economic development. From the perspective of ensuring basic ecological security, improving atmospheric environmental quality, and building a livable city in the capital region, this study first identified the spatial distribution of important ecological land in Beijing through a comprehensive evaluation of ecological importance. Using the minimum cumulative resistance (MCR) model, we then simulated the spatial expansion process of important ecological land, with land cover type, distance to roads, and distance to settlements serving as resistance factors. Three planning scenarios were established, and their protection effectiveness was evaluated from three aspects: landscape connectivity, ecological function security, and conflicts with existing construction land. The results indicate that the total area of important ecological land in Beijing is 9,879 km^2, accounting for 60.20% of the municipal territory. The suitable scale of ecological land is 12,417 km^2, representing 75.67% of the total area. In the plain area, the suitable scale is 2,944 km^2 (46.45% of plain area), while in mountainous areas it is 9,473 km^2 (94.05% of mountainous area). Ecological land is primarily distributed in the peripheral transition zones around built-up areas.

Keywords: ecological land; minimum cumulative resistance model (MCR); land use planning; Beijing City

Introduction

Ecological land serves critical functions including water conservation, climate regulation, wildlife protection, and recreation provision, acting as a barometer of regional environmental quality [1-2]. With rapid socio-economic development and urban expansion, escalating land demands for construction and production have encroached extensively upon ecological land, degrading already fragile ecosystems and causing many ecologically valuable lands such as forests and wetlands to lose their functions, thereby triggering numerous environmental problems [3]. As living standards rise and demands for quality of life increase, rational ecological land planning has become essential for safeguarding urban ecological security and improving residential environmental quality [4-5]. China has increasingly emphasized ecological land protection in natural resource management, particularly in spatial regulation planning [6-8].

Existing ecological land planning methods fall into two categories. The first involves ecological land zoning based on ecological function importance or sensitivity assessment [9-10], which emphasizes land attributes and ecological functions but neglects spatial connectivity. The second recognizes that landscape pattern optimization can enhance ecological land effectiveness, building upon ecological function importance evaluation using landscape ecology principles. For instance, Zhang et al. [11] combined Forman' s landscape ecology conceptual model [12] with ecological function importance assessment, extracting ecological lands corresponding to 40%, 50%, and 60% of municipal area and qualitatively analyzing connectivity under three scenarios. Guan [13] applied similar methods to Beijing, identifying scenarios using 30%, 40%, and 50% of municipal area as ecological land, concluding that 50% could connect all ecological seed patches for maximum protection. Yu et al. [14] emphasized ecological land network structure using the MCR model to analyze ecological lands based on stormwater management and biodiversity conservation needs. The MCR approach focuses not only on patch ecological functions but also on inter-patch ecological connections, emphasizing landscape connectivity optimization to promote efficient ecological function delivery [15-16].

However, most existing studies base their analysis on spatial distribution data of nature reserves, scenic spots, and other protected areas [17-20], lacking comprehensive consideration of ecological quality, major urban environmental problems, and livability requirements, resulting in somewhat partial estimates of ecological land scale. This study adopts the official definition of ecological land [6], treating grassland, forest, and wetland with important ecological functions as ecological land. Considering Beijing' s natural conditions, urban development level, and citizens' quality-of-life demands, we evaluate ecological importance to identify spatial distribution characteristics of important ecological land. Using the MCR model to simulate spatial expansion, we establish scenarios and evaluate protection effectiveness to propose suitable scale and optimized layout for Beijing' s ecological land, providing technical support for capital environmental protection and urban planning.

1. Study Area Overview

Beijing is located on the northwestern edge of the North China Plain (39°26 -41°03 N, 115°25 -117°30 E). Western mountains belong to the Taihang Range, northern mountains to the Yan Range, connecting with the Inner Mongolia Plateau in the north. Mountainous areas, generally 1,000–1,500 m in elevation, cover 16,410 km^2. Beijing has a warm temperate semi-humid continental monsoon climate with annual average temperature of 10-12°C and precipitation of 20-60 mm, unevenly distributed across seasons with 80% concentrated in summer. Prevailing winds are southerly/southeasterly in summer and northerly/northwesterly in winter. The frost-free period lasts 180-200 days.

Under the interaction of natural environment and human activities, Beijing' s ecosystems exhibit a concentric ring structure centered on urban areas. Satellite imagery interpretation shows construction land covers 8,888.09 km^2 (54.14% of total area), while forest, farmland, and urban ecosystems dominate. Plain areas primarily host farmland ecosystems with artificial vegetation, covering 3,165.99 km^2 (19.29% of total area). Wetland and other ecosystems account for 2,563.89 km^2 (15.62%). Remote mountainous areas predominantly feature forest ecosystems.

2. Methods

2.1 Minimum Cumulative Resistance Model

The minimum cumulative resistance model, proposed by Knaapen et al. in 1992 [21], calculates the cost species expend moving from source to destination. The model has been widely applied to natural and human processes [22-28], demonstrating good adaptability for analyzing horizontal spatial expansion. The formula is:

$$MCR = f\left(\min \sum_{i=1}^{m} \sum_{j=1}^{n} D_{ij} \times R_i\right)$$

where MCR is the minimum cumulative resistance value, Dij is the spatial distance from source i to j, and Ri represents the resistance coefficient of grid i to ecological land expansion. The model can be implemented using ArcGIS cost-distance modules.

2.2 Model Assumptions

Applying MCR to ecological land planning rests on three assumptions: (1) ecological land expansion can be viewed as a horizontal process from "source" land; (2) due to spatial heterogeneity in land cover, different land units exert varying resistance; and (3) based on cumulative resistance values, the minimum area and optimal layout of ecological land can be determined.

2.3 Expansion Source Determination

This study treats Beijing' s important ecological land as expansion sources, identified through ecological importance evaluation. Aiming to ensure capital ecological security, improve atmospheric environment, and build a livable city, we conducted importance evaluation from two dimensions: ecological quality and ecological function.

Ecological Quality Assessment: Using 250 m resolution MODIS NDVI data (2000-2013), we calculated multi-year average vegetation coverage after preprocessing (mosaicking, filtering). Biomass was derived from fitting relationships between typical sample plot biomass and spectral reflectance for forests, grasslands, and croplands. Importance levels were classified for vegetation coverage and biomass to identify high ecological quality areas.

Ecological Function Assessment: We evaluated water conservation, soil conservation, and biodiversity maintenance. Water conservation capacity was estimated using Cheng et al.' s formula [29] considering surface cover, soil development index, and runoff coefficient. Soil conservation used the Universal Soil Loss Equation (USLE) [30] with monthly precipitation, vegetation coverage, and land use data to identify soil erosion sensitivity. Biodiversity maintenance employed the InVEST model [31], which uses land use/cover information combined with threat factors to evaluate habitat quality, degradation, and diversity at the landscape scale. Threat factor influence ranges were determined by spatial distance to patches, with maximum impact distance, weights, and correlation indices set according to Beijing' s urban development level. Sensitivity of different land types to threats was classified from high to low following ecological and landscape ecology principles.

Atmospheric Environment Improvement Assessment: Different forest types vary in dust retention and pollutant absorption capacity due to community structure differences. Using Beijing' s forest inventory data, we identified important ecological land for atmospheric improvement based on forest type, vegetation coverage, and other indicators.

Residential Environment Improvement Assessment: According to Beijing' s geomorphic and ecosystem distribution characteristics, we analyzed green space systems and key green areas in mountainous, plain, and urban zones, considering important ecological corridors, forest parks, nature reserves, water source protection areas, and scenic spots.

Integration: After completing individual assessments, spatially overlapping areas were merged and raster data converted to vector format using ArcGIS 10.1 to finalize the spatial distribution of important ecological land.

2.4 Resistance Surface Determination

To analyze cumulative resistance encountered during ecological land expansion from sources outward, we considered three resistance factors: land cover type, distance to roads, and distance to settlements. Based on ecological land characteristics, we ranked resistance levels and assigned coefficients. Land cover types were sorted as: water/wetland < high-coverage grassland < medium-coverage grassland < low-coverage grassland < farmland < unused land < rural settlements < other construction land < urban construction land, with relative resistance coefficients of 1, 20, 40, 60, 80, 100, 300, 500, and 1,000, respectively. Road and settlement distances also create resistance, with higher resistance closer to these features. Three resistance factor layers were generated and summed through raster calculation to produce the spatial resistance surface.

2.5 Scenario Development and Evaluation

Using important ecological land distribution and resistance surface data, we calculated cumulative resistance values for expansion across the municipal area using ArcGIS cost-distance module. A frequency sequence of resistance values identified inflection points at 1,000, 100,000, and 300,000, forming three planning scenarios.

We evaluated scenario effectiveness from three aspects: (1) landscape pattern analysis using Fragstats 4.2 to calculate connectivity and aggregation indices; (2) ecological function security through weighted calculations comparing scenarios to the maximum (Scenario 3); and (3) conflicts with existing construction land via spatial overlay analysis. Weights were assigned as: water conservation (30%), soil conservation (20%), biodiversity (20%), dust/pollutant absorption (10% each), and residential environment improvement (30% total, divided among nature reserves, key mountainous forests, urban green space, road shelterbelts, and water source protection areas).

3. Results

3.1 Spatial Distribution of Important Ecological Land in Beijing

To identify spatial distribution, we evaluated vegetation coverage, biomass, water conservation, soil conservation, biodiversity maintenance, atmospheric improvement, and residential environment improvement, then overlaid these assessments. Important ecological land totals 9,879 km^2, accounting for 60.20% of municipal area, primarily distributed in mountainous areas with scattered patches in urban and plain areas [Figure 1: see original paper].

3.2 Resistance Surface for Ecological Land Expansion

Different land cover types generate varying resistance during expansion. Based on ecological land characteristics, resistance levels were ranked as described above, with coefficients reflecting relative rather than absolute values, which remains meaningful for trend analysis [16]. Using these coefficients, we generated resistance factor layers and calculated their sum to produce the expansion resistance surface, showing lower resistance in mountainous forested areas and higher resistance in plain farmland and urban areas [Figure 2: see original paper].

3.3 Scenario Design

Cumulative resistance analysis revealed inflection points forming three scenarios: Scenario 1 (resistance <1,000), Scenario 2 (1,000–100,000), and Scenario 3 (100,000–300,000) [Figure 3: see original paper]. The relationship between cumulative resistance and grid number shows clear thresholds [Figure 4: see original paper]. Mountainous areas exhibit low resistance suitable for expansion, while urban built-up areas and southeastern plain farmland show high resistance. Scenario maps illustrate these patterns [Figure 5: see original paper].

3.4 Evaluation of Planning Scenarios

Landscape pattern analysis showed Scenario 3 had highest connectivity and aggregation, followed by Scenario 2, then Scenario 1 . Ecological function security evaluation, using Scenario 3 as the reference (100%), rated Scenario 2 at 89.59% and Scenario 1 at 59.88%. Conflict analysis revealed Scenario 1 had minimal conflict (533.53 km^2), Scenario 2 moderate conflict (1,107.89 km^2), and Scenario 3 substantial conflict (2,161.43 km^2).

4. Suitable Scale and Layout of Minimum Ecological Land

All three scenarios show large mountainous ecological land areas, but plain areas differ significantly. Scenario 1’ s small plain component fails to form effective buffer zones or control urban sprawl, with low connectivity limiting ecological function. Scenario 2 increases plain ecological land, creating wedge-shaped corridors and ring-shaped buffer zones around built-up areas that effectively support ecological functions. Scenario 3, while maximizing ecological land, conflicts excessively with existing urban development and food security needs.

Considering Beijing’ s land use status and socio-economic context, Scenario 2 emerges as the optimal solution. Analysis shows Beijing’ s suitable ecological land scale is 12,417 km^2 (75.67% of municipal area), comprising 2,944 km^2 in plain areas (46.45% of plain area) and 9,473 km^2 in mountainous areas (94.05% of mountainous area), primarily distributed in peripheral transition zones around construction areas.

5. Conclusion and Discussion

This study applied the MCR model to analyze suitable scale and optimized layout for Beijing’ s ecological land, determining a suitable scale of 12,417 km^2 (75.67% of municipal area). Compared with previous studies [13, 3], our estimate is larger, encompassing their results while incorporating Beijing’ s major environmental problems and urban development goals, particularly regarding atmospheric environment improvement and livable city construction, making results more practical and development-aligned.

The study demonstrates MCR model feasibility for urban ecological land planning. However, resistance factor selection involves subjective elements and potential omissions. Future research should incorporate additional factors such as terrain, distance to protected areas, and distance to main urban areas to refine resistance surfaces. Quantitative methods for determining optimal scenarios should also be developed. The method remains relatively objective, but continued research is needed for broader application in urban planning.

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