Optimization of Production-Living-Ecological Space in Loess Hilly-Gully Region County Towns under Dual Guidance of Constraints and Growth: A Case Study of the Central Urban Area of Mizhi County (Postprint)

Authors: Jia Ruonan, Wu Zuobin

Date: 2025-02-27T00:00:00+00:00

Abstract

Against the backdrop of strong ecological baseline constraints and growing urban development demands in the Loess Hilly and Gully Region, exploring the optimization of production-living-ecological space provides a reference for promoting rational resource allocation in this region. Based on the bidirectional guidance of ecological constraints and urban growth in the Loess Hilly and Gully Region, an integrated research method combining ecological baseline identification and urban growth simulation is proposed. Taking the central urban area of Mizhi County as an example, the MCR model is employed to evaluate the ecological baseline conditions of the central urban area, the FLUS-Markov model is utilized to simulate the distribution of production-living-ecological space in 2035, based on which high-conflict zones, moderate-conflict zones, and low-conflict zones between ecological baseline conditions and the 2035 production-living-ecological space distribution are identified, and optimization strategies for each conflict zone are proposed. The results indicate: (1) The ecological baseline conditions of the central urban area of Mizhi County are classified into three levels: ecological protection zone, ecological control zone, and general ecological zone, with the ecological protection zone having the largest area and the general ecological zone the smallest. (2) Under the natural development scenario in 2035, the ecological space area in the central urban area of Mizhi County decreases by 803.33 hm^2, while both production and living space areas show growth trends, with increases of 612.03 hm^2 and 191.30 hm^2, respectively. (3) In the central urban area of Mizhi County, 40.80% of the land area faces conflict risks in the future, with high-conflict zones covering 1606.54 hm^2 (approximately 23.29% of the urban area), moderate-conflict zones covering 968.19 hm^2 (approximately 14.04%), and low-conflict zones covering 239.32 hm^2 (approximately 3.47%);

based on the characteristics of each conflict zone, optimization strategies for production-living-ecological space are proposed, emphasizing ecological priority, moderate integration, and compatible development.

Full Text

Optimization of Ecological-Production-Living Spaces for County Towns in Loess Plateau Hilly and Gully Region through Dual Guidance of Constraints and Growth: A Case Study of Central Urban Area of Mizhi County

JIA Ruonan[1], **WU Zuobin**[1],[2]

[1]Xi'an University of Architecture and Technology, Xi'an 710055, Shaanxi, China
[2]Xi' an Jianda Institute of Urban Planning and Design Co., Ltd, Xi' an 710055, Shaanxi, China

Abstract: Against the backdrop of stringent ecological constraints and escalating urban development demands in the Loess Plateau hilly and gully region, optimizing ecological-production-living (EPL) spaces provides critical reference for rational resource allocation. This study proposes an integrated research approach combining ecological base identification with urban growth simulation, guided by dual considerations of ecological constraints and urban expansion. Taking the central urban area of Mizhi County as a case study, the Minimum Cumulative Resistance (MCR) model was employed to evaluate ecological base conditions, while Markov and FLUS models simulated the spatial distribution of EPL spaces for 2035. Based on these results, conflict zones of varying intensity between ecological base conditions and EPL spatial distribution were identified, and targeted optimization strategies were developed. The findings reveal: (1) The ecological base conditions in Mizhi County' s central urban area can be classified into three zones—ecological protection area, ecological control area, and general ecological area—with ecological protection area being the largest and general ecological area the smallest. (2) Under natural development scenarios, ecological space is projected to decrease by 803.33 hm^2 by 2035, while production and living spaces will increase by 612.03 hm^2 and 191.30 hm^2, respectively. (3) Approximately 40.80% of the urban area faces future conflict risks, comprising intense conflict zones (1606.54 hm^2, 23.29% of urban area), moderate conflict zones (968.19 hm^2, 14.04%), and weak conflict zones (239.32 hm^2, 3.47%). Tailored optimization strategies emphasizing ecological priority, moderate integration, and compatible development are proposed for each conflict zone.

Keywords: Loess Plateau hilly and gully region; ecological-production-living spaces; ecological constraints; urban growth; conflict identification

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The 18th National Congress of the Communist Party of China proposed "promoting intensive and efficient production space, livable and moderate living space, and beautiful ecological space," emphasizing the optimization of territorial spatial patterns and prioritizing ecological civilization. The 20th National Congress further advocated "adhering to integrated protection and systematic governance of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts,"highlighting the importance of protecting and managing resource elements in ecological civilization construction. In this context, the Central Committee and State Council' s "Opinions on Establishing a Territorial Spatial Planning System and Supervising Its Implementation" identified scientific layout of production, living, and ecological spaces as a key measure for advancing ecological civilization.

How to promote organic coordination among ecological, production, and living spaces has become a critical issue in modern urban development. However, with continuous urbanization, problems such as ecological environmental degradation, low production efficiency, and reduced livability of living spaces persist, and EPL space contradictions require further resolution. Research on EPL space optimization strategies is therefore essential for constructing coordinated development patterns and promoting rational resource allocation.

Current academic research on EPL spaces primarily focuses on function identification, spatial evolution, and optimization. Function identification mainly involves land type classification, quantitative measurement indicators, and utilization of emerging data such as POI. Spatial evolution research analyzes spatial change characteristics and driving factors over time, employing methods such as land use dynamic degree, spatial autocorrelation analysis, and transition matrices. Existing optimization studies primarily address spatial problems and propose adjustment schemes from perspectives of suitability and spatial simulation. In terms of research scale and objects, most studies focus on large scales such as watersheds, urban agglomerations, provinces, and cities, with fewer examining the Loess Plateau hilly and gully region. Methodologically, research typically employs either spatial simulation methods like CA-Markov to predict future EPL space development directions, or suitability evaluation to identify conflicts between current conditions and optimal land use. However, integrated approaches combining ecological constraints and urban growth guidance remain relatively rare for the Loess Plateau hilly and gully region.

The Loess Plateau hilly and gully region represents a typical ecologically fragile area in China, characterized by crisscrossing gullies, fragmented terrain, and loose soil, with severe soil erosion. Gully density reaches 12 $\mathrm{km} \cdot \mathrm{km}^{-2}$, with depths of 100-300 m and average erosion intensity of 10,000-25,000 $\mathrm{t} \cdot \mathrm{km}^{-2} \cdot \mathrm{yr}^{-1}$, creating extremely fragile local ecosystems. Development is strongly constrained by topography and ecological conditions, resulting in scarce urban construction land. According to the Seventh National Population Census, the urbanization rate in this region is 53.32%, relatively low compared to other areas, yet towns face persistent development demands and continuous construction growth, intensifying EPL space conflicts. County-level planning serves as a critical link in the territorial spatial planning system, connecting higher-level plans with implementation, making EPL space research at this scale highly practical and operable. The central urban area of a county town, as the most densely populated region, exhibits particularly prominent human-land conflicts. Therefore, developing EPL space optimization strategies under dual guidance of ecological constraints and urban growth is crucial for guiding territorial spatial optimization practices and achieving high-quality development.

2 Data and Methods

2.1 Data Sources

This study utilized land use data for 2020, DEM data, soil erosion data, road networks, and water systems obtained from the Mizhi County Natural Resources and Planning Bureau. Remote sensing imagery was sourced from the Geospatial Data Cloud Platform of the Chinese Academy of Sciences Computer Network Information Center (https://www.gscloud.cn/).

2.2 Research Framework

Considering the ecologically fragile characteristics and urgent urban development needs of the Loess Plateau hilly and gully region, this study proposes an integrated research method combining ecological base identification with urban growth simulation. This approach uses ecological constraints as the foundation while accounting for urban development demands, balancing ecological protection and urban growth through dual guidance. Based on this, potential conflicts between future urban development and ecological base conditions are identified, and targeted EPL space optimization strategies are proposed [Figure 2: see original paper].

The framework involves three steps: First, under ecological constraint guidance, the MCR model evaluates the ecological base conditions of the urban area. This includes identifying ecological source areas based on the actual conditions of Mizhi County' s central urban area, selecting and determining various resistance factors affecting ecological sources and their corresponding resistance values. Through reclassification, these resistance values are visualized as spatial distributions of each factor, which are then weighted and summed to create a comprehensive ecological base condition zoning map.

Second, under urban growth guidance, Markov and FLUS models simulate future EPL space development. Based on historical land use and related data, current EPL spatial distribution is simulated and compared with actual data using the Kappa coefficient for accuracy verification. With validated results, the Markov model predicts future EPL space quantities, which serve as parameters for the FLUS model to simulate future spatial distribution patterns.

Third, conflict identification under dual guidance involves overlaying the simulated 2035 EPL spatial distribution with ecological base zoning. Using an overlay matrix, conflict zones and their intensity levels between EPL spaces and ecological base conditions are identified, and optimization strategies are proposed for different conflict zones.

2.3 Models

2.3.1 MCR Model The Minimum Cumulative Resistance model, originally developed by Knaapen et al. for calculating cumulative costs during species movement from source to destination, is employed to construct an ecological land expansion resistance surface and identify ecological base zoning. The formula is:

$$MCR = \min \sum_{j} D_{ij} \times R_i$$

where MCR represents the minimum cumulative resistance value; D_{ij} is the spatial distance from source j to landscape unit i; and R_i is the resistance coefficient of the landscape to species movement.

Drawing on previous research and considering Mizhi County' s topographical and land use characteristics, resistance factors were selected following principles of systematicity, dominance, operability, and data availability. Factors from natural, locational, and current status dimensions were included . Resistance factor spatial distribution maps were obtained through reclassification, weighted summation, and grading to produce the final ecological base condition zoning.

2.3.2 Markov Model The Markov model, based on probability theory, estimates future possibilities from current states and trends. It is used to predict land use change through the formula:

$$S_{t+1} = S_t \times P$$

where S_t and S_{t+1} represent land use state vectors at times t and $t+1$, respectively; and P is the land use type transition probability matrix between times t and $t+1$.

2.3.3 FLUS Model The FLUS model simulates EPL space distribution through suitability probability calculation, neighborhood factor calculation, adaptive inertia coefficient calculation, and conversion cost setting.

Suitability Probability Calculation: Urban growth results from land use attribute changes driven by both natural and social factors. Natural factors such as elevation and slope affect layout and construction feasibility, while population density and distance to roads influence growth scale and direction. Based on comprehensive consideration of potential influencing factors and Mizhi County' s characteristics, natural and social drivers were determined . Suitability probability was calculated by fitting baseline land use types with driving factors using an artificial neural network:

$$p(p_k^t = \sum_j w_{jk} \times \text{sigmoid}(\sum_i w_{ij} \times n_i^t))$$

where $p(p_k^t)$ is the suitability probability; w_{ij} represents weights between input and hidden layers; n_i^t is the input value of neuron i at iteration t; and w_{jk} represents weights between hidden and output layers.

Neighborhood Factor Calculation: The neighborhood factor represents interactions between different land use types and units within a neighborhood range:

$$\Omega_{P,k}^t = \frac{\sum_{N\times N} \text{con}(c_{k'}^{t-1} = k)}{N \times N - 1} \times w_k$$

where $\Omega_{P,k}^t$ is the neighborhood influence factor for cell m at time t; N is the window range; con$(\cdot)$ counts cells of type k in the Moore neighborhood; and w_k is the neighborhood factor parameter for land use type k, with values ranging from [0, 1] proportional to expansion capacity. Through multiple tests and adjustments referencing relevant studies, final neighborhood factor parameters were determined .

Adaptive Inertia Coefficient and Conversion Cost: The adaptive inertia coefficient reflects quantity differences between expected and actual land use types:

$$\text{Inertia}_k^t = \begin{cases} \text{Inertia}_k^{t-1} & \text{if } D_k^{t-1} < D_k^t \\ \text{Inertia}_k^{t-1} \times \frac{D_k^{t-1}}{D_k^t} & \text{if } D_k^{t-1} \geq D_k^t \end{cases}$$

where Inertia_k^t is the inertia coefficient for land use type k at iteration t; and D_k^{t-1} and D_k^t represent differences between demand and actual quantity at times $t-1$ and t.

Conversion rules define transformation difficulty between spatial types, with matrix values set to 0 for prohibited conversions and 1 for allowed conversions. In this study, all three EPL space types can transform mutually under natural development scenarios .

Comprehensive Probability Calculation: The overall conversion probability is calculated as:

$$TProb_{c\to k}^t = SP_{c\to k}^t \times \Omega_{P,k}^t \times \text{Inertia}_k^t \times (1 - scc_{c\to k})$$

where $TProb^{t}_{c\to k}$ is the total conversion probability; $SP^{t}_{c\to k}$ is the suitability probability; and $scc_{c\to k}$ is the conversion cost from type c to k.

3 Results and Analysis

3.1 Ecological Base Identification Under Constraint Guidance

Ecological patches larger than 2 hm^2 were selected as ecological source areas. Based on resistance factor classification , spatial distribution maps were obtained through reclassification [Figure 3: see original paper], weighted summation, and grading to produce final ecological base condition zoning [Figure 4: see original paper]. Three zones were identified: ecological protection area (3065.13 hm^2, 44.4% of urban area), ecological control area (2852.09 hm^2, 41.3%), and general ecological area (981.01 hm^2, 14.3%). The zoning exhibits strip-shaped distribution, with ecological base conditions strengthening outward from both sides of the Wuding River. Ecological protection areas are predominantly located in mountainous regions outside the urban area, with more in the north than south. Ecological control areas are unevenly distributed, tending toward the eastern region. General ecological areas are mainly clustered along both banks of the Wuding River, with some scattered distribution in mountain areas.

3.2 EPL Space Simulation Under Urban Growth Guidance

Using 2020 EPL space distribution as baseline data, the 2035 distribution was simulated and validated against actual land use data using the Kappa coefficient. With Kappa > 0.75 indicating reliable simulation, the model and parameters were deemed suitable for this study.

Based on 2020 statistics, EPL spaces were classified: irrigated land, dry land, orchards, industrial and mining land, and transportation land as production space; river water surface, pond water surface, forest land, grassland, wetland, and unused land as ecological space; and urban and village land as living space [Figure 5: see original paper].

The 2035 simulation shows ecological space decreasing by 803.33 hm^2, while production and living spaces increase by 612.03 hm^2 and 191.30 hm^2, respectively . Transformation analysis reveals minimal conversion from living to ecological or production spaces, while ecological to production space conversion reaches 1235.51 hm^2, aligning with recent priorities on farmland protection. Spatially, ecological space will be scattered across gullies and mountains, production space will concentrate in areas with relatively abundant water and gentle slopes, and living space will distribute along the flat valleys of the Wuding River, extending outward along some gullies [Figure 6: see original paper].

3.3 Conflict Identification Under Dual Guidance

Overlaying the 2035 EPL space simulation with ecological base zoning using a conflict identification matrix reveals conflict and coordination zones [Figure 8: see original paper]. Results show 40.80% of the urban area (2813.95 hm^2) faces future conflict risks, comprising intense conflict zones (1606.54 hm^2, 23.29%), moderate conflict zones (968.19 hm^2, 14.04%), and weak conflict zones (239.32 hm^2, 3.47%). The remaining 59.20% (4084.18 hm^2) represents coordination zones without conflicts.

Intense conflict zones primarily involve ecological protection-production space conflicts (1502.76 hm^2, 21.78%), scattered across mountain areas on both sides and partially along the Wuding River. Ecological protection-living space conflicts (103.78 hm^2, 1.51%) are mainly distributed along the Wuding River banks and scattered within villages in mountain areas.

Moderate conflict zones include ecological control-production space conflicts (867.34 hm^2, 12.86%), scattered in southern urban areas, and ecological control-living space conflicts (100.85 hm^2, 1.46%), distributed in belts along the Wuding River.

Weak conflict zones involve general ecological-production space conflicts (239.32 hm^2, 3.47%), scattered along the Wuding River.

These conflicts stem from the region's unique topography and severe soil erosion. Terraces built on mountain slopes serve both ecological (soil conservation) and production functions, creating functional conflicts. Along the Wuding River, areas that should serve as ecological safety buffers also possess good cultivation conditions in the arid climate, leading to competing land uses.

3.4 Optimization Strategies

3.4.1 Ecological Priority: Optimizing Intense Conflict Zones In zones with intense conflicts between urban development and ecological protection, ecosystem integrity and functionality must be prioritized through strict protection systems. For areas already impacted by inappropriate development, ecological restoration and land return programs should be implemented.

For ecological protection-production space conflicts along the Wuding River (190.41 hm^2), all cultivation and construction activities should be prohibited with enhanced management measures. For mountain area conflicts (1245.93 hm^2), which are prone to soil erosion and geological disasters, cultivation should be strictly banned. Scientific afforestation using suitable trees and shrubs (e.g., *Caragana*, poplar, locust) combined with soil conservation measures should be implemented.

For ecological protection-living space conflicts (91.02 hm^2 of undeveloped land), development activities should be strictly prohibited with effective monitoring systems. For already disturbed areas, ecological restoration projects should be designed to reintroduce native vegetation and restore hydrological cycles. For developed areas (12.76 hm^2), relocation should be pursued where possible; where not feasible, safety precautions must be implemented with strict control over expansion to gradually return these spaces to ecological functions.

3.4.2 Moderate Integration: Optimizing Moderate Conflict Zones In moderate conflict zones, ecological, production, and living functions should be moderately integrated without compromising basic ecosystem functions, scientifically planning and managing production and living activities to enhance scale, efficiency, and quality of life.

For ecological control-production space conflicts along the Wuding River (181.23 hm^2), high-value crops (e.g., vegetables) should be developed under strict ecological safety guarantees, providing quality agricultural products to urban residents while improving land output efficiency. For mountain area conflicts (579.21 hm^2), terracing should be implemented to reduce runoff, combined with fruit tree planting featuring strong soil-fixing capabilities, simultaneously expanding agricultural land and reducing soil erosion.

For ecological control-living space conflicts, developed areas (107.11 hm^2) should strengthen ecological safety prevention while gradually reducing living space proportions in environmentally poor and inaccessible areas, promoting intensive and economical development with ecological protection and restoration. Undeveloped areas (100.64 hm^2) may incorporate appropriate sightseeing and recreation functions without compromising ecological integrity, significantly enhancing residents' quality of life while ensuring effective ecological protection.

3.4.3 Compatible Development: Optimizing Weak Conflict Zones In weak conflict zones, land use characteristics demonstrate compatibility between ecological and production functions. Based on location conditions, geological characteristics, and infrastructure, rational selection between ecological and production uses can maximize land use benefits.

For general ecological-production space conflicts along the Wuding River (149.21 hm^2), production types with minimal ecological and residential impacts should be selected while promoting industrial agglomeration to improve land use efficiency. For mountain area conflicts (79.18 hm^2), these may serve as supplementary production land for future development.

4 Conclusions

This study yields three main conclusions: (1) Ecological base conditions in Mizhi County' s central urban area are classified into ecological protection area, ecological control area, and general ecological area, with ecological protection area being the largest (44.4% of urban area) and general ecological area the smallest (14.3%). The zoning exhibits strip-shaped distribution with conditions strengthening outward from the Wuding River. (2) The 2035 simulation shows ecological space decreasing by 803.33 hm^2, while production and living spaces increase by 612.03 hm^2 and 191.30 hm^2, respectively. Ecological to production space conversion is most significant (1235.51 hm^2). (3) Approximately 40.80% of the urban area faces future conflicts, including intense (1606.54 hm^2, 23.29%), moderate (968.19 hm^2, 14.04%), and weak (239.32 hm^2, 3.47%) conflict zones. Tailored strategies emphasizing ecological priority, moderate integration, and compatible development are proposed.

The integrated method combining ecological base identification with urban growth simulation demonstrates strong applicability to the Loess Plateau hilly and gully region, offering valuable insights for future EPL space optimization.

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