Postprint: Simulation of Typical Oasis City Expansion in the Yellow River Basin and Its Ecological Resilience Response

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Abstract

Establishing a robust ecological network constitutes a crucial pathway for enhancing urban ecological resilience. This study employs the PLUS model to simulate and analyze the evolution of urban ecological networks and their resilience response characteristics under impervious surface expansion, using the central urban area of Yinchuan—a typical oasis city in the Yellow River Basin—as a case study. The findings reveal: (1) Rapid expansion of impervious surfaces has occurred in Yinchuan’ s central urban area. The impervious surface area in 2020 reached 2.61 times that of 2000, and is projected to reach 3.24 times the 2000 level by 2030; the spatial configuration of impervious surfaces has transformed from an east-west longitudinal linear pattern into a rightward-tilting “T”-shaped pattern, with this horizontal “T”-shaped configuration being further reinforced by 2030. (2) Concomitant with impervious surface expansion, the ecological network pattern in Yinchuan’ s central urban area has undergone significant alteration. In 2000, a single-ring ecological network formed around the periphery of the central urban area; by 2020, the outer ring expanded westward, the inner ring shifted northward overall, and relatively complex circuits emerged in the northeast district. Simulation results indicate that by 2030, the ecological network in Yinchuan’ s central urban area will develop a “川”-shaped structure. (3) Both structural and functional resilience of the ecological network have improved. Between 2000 and 2020, the α, β, and γ indices increased by 0.09, 0.17, and 0.06, respectively, while network propagation and diversity increased by 0.08 and 0.29, respectively. By 2030, both structural and functional resilience of the ecological network will be further enhanced, though the overall level remains comparatively low.

Full Text

Preamble

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Simulation of Urban Expansion and Its Response to Ecological Resilience of Typical Oases in the Yellow River Basin

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Abstract: Establishing a robust ecological network is essential for enhancing urban ecological resilience. Using the central urban area of Yinchuan City—a typical oasis city in the Yellow River Basin—as a case study, we simulated and analyzed changes in the urban ecological network and its resilience responses under impervious surface expansion based on the PLUS model. The results indicate: (1) Rapid expansion of impervious surfaces has occurred in central Yinchuan. The impervious surface area in 2020 expanded to 2.61 times that of 2000, and by 2030, the projected area will be 3.24 times the 2000 level. Spatially, the pattern evolved from an east-west longitudinal "—" shape to a rightward-tilting "T"shape, with this horizontal "T"pattern further strengthened by 2030. (2) Accompanying this expansion, the ecological network pattern in central Yinchuan has changed significantly. In 2000, a single-ring ecological network formed around the urban fringe. By 2020, the outer ring expanded westward while the inner ring shifted northward, creating more complex circuits in the northeast sector. Simulations predict that by 2030, the ecological network will develop a "川" structure. (3) Both structural and functional resilience of the ecological network have improved. Between 2000 and 2020, the α, β, and γ indices increased by 0.09, 0.17, and 0.06, respectively, while network transmissibility and diversity rose by 0.08 and 0.29. By 2030, structural and functional resilience will further improve, though overall levels remain relatively low.

Keywords: oasis city; ecological network; resilience; PLUS model; Yellow River Basin

Cities are complex social-ecological systems facing intensifying challenges from rapid urbanization, environmental pollution, resource shortages, and biodiversity loss. As the "organism" of cities, ecosystems are often the first to perceive ecological risks. Ecological resilience represents the capacity of ecosystems to resist, recover from, and adapt to external disturbances. Enhancing urban ecological resilience is crucial for sustainable urban development. Ecological networks serve as green corridors connecting urban cores and suburbs, forming spatial structural systems that link isolated green patches and water bodies according to natural laws. These networks are closely associated with ecosystem resilience in both structure and function, making them important indicators for assessing ecological resilience. Urban spatial expansion and ecological network pattern evolution share potential correlations. Analyzing changes in impervious surface expansion and ecological network resilience can effectively avoid the pitfall of "emphasizing pattern while neglecting process." Integrating urban expansion simulation with ecological network resilience analysis holds significant value for healthy urban ecosystem management.

Regarding urban expansion simulation, scholars commonly employ cellular automata (CA) models such as SLEUTH, Markov chains, and CLUES. Markov chains are used for temporal sequence dynamic simulation but have limitations in spatial pattern simulation. CA models excel at spatial pattern change simulation but fall short in temporal dynamic simulation and defining complex interactions. The PLUS (Patch-generating Land Use Simulation) model, which integrates a rule-mining framework based on land expansion analysis strategy (LEAS) and multi-type random seed mechanisms, can simulate interactions and spatial dynamics of multiple land-use change types. It has gained widespread application due to its superior simulation accuracy.

Oasis cities are core areas for human production and life in arid regions, with fragile ecosystems that are easily damaged, directly affecting regional sustainable development. The Yellow River Basin is a critical ecological barrier and important region for population and economic activity in China. The 2021 "Outline for Ecological Protection and High-Quality Development of the Yellow River Basin" elevated this to a national strategy. Yinchuan City, a typical oasis city in the upper Yellow River region, has experienced severe landscape fragmentation and impaired ecological functions due to rapid urbanization and human disturbance. This study examines the response characteristics of ecological networks to impervious surface expansion in central Yinchuan, providing decision-making references for healthy development of oasis city ecosystems.

1.1 Study Area Overview

Yinchuan, the capital of Ningxia Hui Autonomous Region, is located in the Yinchuan Plain oasis irrigation area, bordered by Helan Mountain to the west and the Yellow River to the east. It administers three districts (Xingqing, Jinfeng, Xixia), two counties (Yongning, Helan), and one city (Lingwu). Yinchuan has a temperate arid climate with abundant sunshine, strong winds, and frequent sandstorms. The city features numerous lakes and wetlands, covering 5.31$×10^{3}$ hm^{2}, with lake wetlands accounting for 9700 hm^{2}, earning it the title of one of the first "International Wetland Cities" globally. Based on the "Yinchuan Territorial Spatial Master Plan (2021-2035)," this study defines the central urban area using the Yinchuan Ring Expressway as the outer boundary, incorporating built-up areas in Helan County and Yongning County [Figure 1: see original paper].

1.2.1 Impervious Surface Expansion Simulation Model

The PLUS model was selected for this study. The model calculates the development probability of land use type k at grid i using the formula:

$$P_{i,k}^{t} = P_{g,i,k} \times P_{o,i,k} \times P_{c,i,k} \times (1 + \Omega_{i,k}^{t}) \times D_{k}^{t}$$

where $P_{i,k}^{t}$ represents the comprehensive probability of grid i transitioning to land use type k at time t; $P_{g,i,k}$ is the suitability probability; $P_{o,i,k}$ denotes the neighborhood effect; $P_{c,i,k}$ is the constraint factor; $\Omega_{i,k}^{t}$ represents the adaptive inertia coefficient; and D_{k}^{t} is the demand for land use type k at future time t.

Large water bodies were set as constraints. Based on literature [31], eleven driving factors were selected: digital elevation model (DEM), slope, precipitation, temperature, soil, GDP, population density, distance to government, distance to railway, distance to roads, and distance to water bodies. A land use transfer cost matrix was established based on Yinchuan’ s 2020 land use conditions, where 1 indicates convertible land types and 0 indicates non-convertible. The neighborhood weight values for six land use types (cropland, forest, grassland, water, unused land, and impervious surface) were set as 0.2, 0.9, 0.6, 1.0, 0.1, and 1.0, respectively. Simulation accuracy was repeatedly tested [32], achieving a Kappa coefficient above 0.85, meeting accuracy requirements.

1.2.2 Ecological Network Analysis Model

Ecological networks consist of ecological sources, corridors, and nodes, representing a crucial approach for coupling landscape structure, ecological processes, and functions. Morphological Spatial Pattern Analysis (MSPA) is a structural connectivity method for identifying sources and constructing resistance surfaces. The Linkage Mapper tool, which considers species movement characteristics through random walk theory, was used for ecological corridor screening. The construction of a resistance surface system is critical for corridor extraction [33]. Land use type, distance to roads, distance to water bodies, normalized difference vegetation index (NDVI), and distance to residential areas were selected as resistance factors. Consistency checking yielded CR<0.1, indicating the matrix met consistency requirements .

1.2.3 Ecological Resilience Evaluation Index

Ecological network resilience manifests through structural and functional dimensions. Structural resilience focuses on logical connections between nodes, evaluated using network circuitry (α index), link density (β index), and connectivity (γ index). Functional resilience concerns network transmissibility and diversity, reflecting the capacity to maintain original functions under disturbance [34]. The formulas are:

$$\alpha = \frac{L - V + 1}{2V - 5}$$

$$\beta = \frac{L}{V}$$

$$\gamma = \frac{L}{3(V - 2)}$$

where α ranges from [0,1]; β is the link-node ratio; γ is connectivity; L is the number of ecological corridors; and V is the number of ecological nodes.

Network transmissibility (E) and diversity (M) express functional resilience. Transmissibility reflects migration capacity, while diversity indicates the number of independent paths between nodes. If a network maintains stability after removing certain nodes, it demonstrates good resilience. The formulas are:

$$E = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij}}{n(n-1)}$$

$$M = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} n_{ij}}{n(n-1)}$$

where d is the shortest path between nodes i and j; n is the number of independent paths; and n is the total number of nodes.

1.3 Data Sources and Processing

Land use data were obtained from the 30m resolution land cover dataset (http://doi.org/10.5281/zenodo.4417809). DEM data came from the Geospatial Data Cloud (http://www.gscloud.cn/). Slope data were derived from DEM. Annual average temperature, precipitation, soil data, and socioeconomic data (population density and GDP) were sourced from the National Ecological Science Data Center (https://www.nesdc.org.cn) and the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/). Distance to government, railway, roads, and water system data were obtained from OpenStreetMap. Administrative boundary vector data came from the National Basic Geographic Information Center (https://www.ngcc.cn/). All data were resampled to 30m resolution with unified spatial reference WGS_{{{1984}}*{{UTM}}*}{{{Zone}}_{{48N}}}.

1.4 Research Framework

The study simulates impervious surface expansion in central Yinchuan from 2000-2030 using the PLUS model, analyzes expansion trends, constructs ecological networks, and evaluates ecological resilience. The technical route is shown in [Figure 2: see original paper].

2.1 Spatiotemporal Evolution Characteristics of Impervious Surfaces in Central Yinchuan

Impervious surfaces expanded significantly from 2000-2020 [Figure 3: see original paper]. The area increased from 7292.30 hm^{2} in 2000 to 1.90$×10^{4}$ hm^{2} in 2020 (2.61 times larger). From 2020-2030, growth will continue but at a slower rate, reaching 2.36$×10^{4}$ hm^{2} (3.24 times the 2000 level). Spatial patterns shifted markedly [Figure 4: see original paper]. In 2000, impervious surfaces were concentrated in a narrow east-west belt with a central gap. By 2020, expansion occurred north-south along the east-west axis, with a new north-south expansion zone in the eastern area, transforming the “一” shape into a rightward-tilting “T” shape. By 2030, this horizontal “T” pattern will strengthen further, characterized by both infill development within the city and edge expansion.

Standard deviation ellipse analysis shows the 2000 ellipse center nearly coincides with the geometric center. By 2020, the center shifts eastward, then returns toward the geometric center by 2030. The 2000-2010 period shows the largest center migration distance (1.89 km), while 2020-2030 shows the smallest (0.31 km), reflecting spatiotemporal imbalances in expansion direction and speed . This relates to different expansion modes: infill-dominated periods show slower center movement, while expansion-dominated periods show faster movement.

2.2 Spatiotemporal Evolution Characteristics of Ecological Networks

Based on MSPA analysis [Figure 6: see original paper], ecological source patches increased significantly in both number and area, particularly large patches. Source area grew from 943.02 hm^{2} in 2000 to 1978.56 hm^{2} in 2020, reaching 2670.75 hm^{2} by 2030. Lakes and wetlands are crucial habitats for bird diversity and safety, providing high ecological service value. They constitute the main component of ecological sources, accounting for 54.06% in 2000, 41.75% in 2020, and 24.72% by 2030—still a substantial proportion.

Ecological corridors connecting sources increased from 27 in 2000 to 35 in 2020, remaining at 35 by 2030, though their positions changed markedly. The network structure evolved from a single ring around the urban fringe in 2000 to a “回” shape by 2010, then to a more complex circuit in the northeast by 2020 as the outer ring expanded westward and the inner ring shifted north. By 2030, the network will develop a “川” structure with more circuits in the northeast [Figure 8: see original paper].

Ecological disturbance points (nodes impeding species movement) increased continuously from 16 in 2000 to 23 in 2020 and 28 by 2030. Their distribution hotspots shifted correspondingly with corridor patterns [Figure 7: see original paper].

2.3 Ecological Resilience Response to Impervious Surface Expansion

Ecological network resilience comprises structural and functional dimensions. Structural resilience improved from 2000-2020: the α index increased from 0.15 to 0.24 (network circuitry improved), β index from 1.35 to 1.52 (complexity and anti-interference capacity enhanced), and γ index from 0.51 to 0.57 (overall connectivity improved) . By 2030, α, β, and γ indices will increase by 0.09, 0.17, and 0.06 respectively, indicating further structural resilience enhancement.

Functional resilience, expressed through network transmissibility and diversity, also improved. Transmissibility increased from 2.41 in 2000 to 2.49 in 2020, reflecting improved functional resilience but still moderate overall transmission efficiency. Diversity rose from 1.12 to 1.41, though the average independent paths between nodes remain below 2, indicating insufficient buffering capacity during disturbances . By 2030, transmissibility and diversity will increase by 0.08 and 0.29 respectively, but overall functional resilience remains low.

3 Discussion

Urban ecological resilience is a critical metric for sustainable urban health. This study represents a beneficial attempt to apply ecological network analysis to urban ecological resilience research. The findings reveal that impervious surface expansion significantly impacts the spatial layout of urban green space and water systems. In central Yinchuan, both the number and area of ecological sources composed of green land and lake wetlands changed markedly. Correspondingly, ecological corridor and node numbers changed substantially. The ecological network structure shows clear differences across the four time periods, with further changes expected by 2030, demonstrating significant impacts of impervious surface expansion on ecological networks—consistent with Huang et al.’ s conclusions [32].

This study simulates historical development trends to project 2030 scenarios. Findings indicate that if current trajectories continue, ecological resilience will improve but remain spatially unbalanced and generally low. Future development should emphasize balanced spatial development of ecological networks to enhance structural stability and functional effectiveness. The study primarily combines process-pattern analysis, but future research should integrate ecosystem service functions and explore multi-scenario simulations under different policies to provide more comprehensive decision-making support.

4 Conclusions

1. Rapid impervious surface expansion occurred in central Yinchuan. The 2020 area was 2.61 times the 2000 level, with 2030 projected to reach 3.24 times. Spatially, the pattern evolved from an east-west “一” shape in 2000 to a rightward-tilting “T” shape by 2020, strengthening further by 2030.
2. The ecological network pattern changed significantly. A single-ring network in 2000 evolved into a “回” shape by 2010, with westward outer ring expansion and northward inner ring shift by 2020, forming complex northeast circuits. By 2030, a “川” structure is projected.
3. Both structural and functional resilience improved. From 2000-2020, α, β, and γ indices increased by 0.09, 0.17, and 0.06, while transmissibility and diversity rose by 0.08 and 0.29. By 2030, further improvements are expected, though overall resilience remains low.

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