Spatiotemporal Response of Habitat Quality to Urban Land Expansion in Hohhot City: Postprint

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Abstract

Taking Hohhot City as the study area, this study employs gradient analysis combined with the InVEST model to evaluate urban land expansion and habitat quality evolution over the past 27 years, and utilizes bivariate spatial autocorrelation to analyze the spatiotemporal response of habitat quality to urban land expansion. The results indicate: (1) During the study period, urban expansion manifested as low-density sprawl in the core area and multi-point diffusion in the peripheral areas, with continuously decreasing compactness, unstable urban structure, and an unreasonable expansion pattern. (2) The average habitat value decreased from 0.49 to 0.44, with the quality grade declining to a relatively poor level. Low-grade habitats primarily diffused in a ring pattern toward the south and southeast, which is basically consistent with the expansion direction of construction land. (3) The spatial distribution of construction land expansion intensity and habitat quality change exhibited a negative correlation. Construction land expansion in the core-peripheral zone consistently represented the most intense area of change, where habitat quality degradation was also the most severe. (4) Patch density continued to increase, and particularly the increase in construction land patches rendered the urban landscape pattern increasingly fragmented.

Full Text

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Abstract

Taking Hohhot City as the study area, this paper employs gradient analysis combined with the InVEST model to evaluate urban land expansion and habitat quality evolution over the past 20 years. Based on this evaluation, bivariate spatial autocorrelation is used to analyze the spatiotemporal response of habitat quality to urban land expansion. The results show that: (1) During the study period, urban expansion was characterized by low-density expansion in core areas and multi-point diffusion in peripheral areas, with continuously decreasing compactness, unstable urban structure, and unreasonable expansion patterns. (2) The average habitat quality value decreased from 0.49 to 0.44, with quality levels dropping to a poor state. Low-grade habitats primarily diffused in circular layers toward the south and southeast, consistent with the direction of construction land expansion. (3) There is a negative spatial correlation between construction land expansion intensity and habitat quality change distribution. Construction land expansion in core-peripheral areas remained the most intensely changing zone, where habitat quality degradation was also most severe. (4) Patch density continuously increased, particularly due to the increase of construction land patches, which made the urban landscape pattern increasingly fragmented.

Keywords: new urbanization; habitat quality; urban land expansion; InVEST model; Hohhot City

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Introduction

Urban land expansion is the most intuitive manifestation of urbanization [?]. Under the backdrop of urbanization, the negative effects of urban land expansion on the ecological environment continuously intensify, and the natural environmental substrate is destroyed [?]. Land resources are the material foundation for human survival and the basic guarantee for socio-economic development. High-intensity economic development activities continuously approach regional safety baselines, triggering a series of ecological problems such as land pollution [?], water resource shortages [?], landscape fragmentation [?], and habitat quality degradation [?], which continuously strengthen regional sensitivity and pose severe challenges to ecological security [?]. Among these problems, habitat quality degradation has the most significant impact on urban living environments and represents the crux of human-land relationship contradictions [?]. How to mitigate the negative effects of urban land expansion on habitat quality has become a focus of attention in geography, ecology, and other disciplines [?].

For habitat quality assessment, the InVEST model has unique advantages, and this research method has been validated in numerous empirical studies [?]. However, most studies analyze the overall habitat of various regions from an ecological perspective, and research on long-term sequence habitat quality evolution and its spatial differentiation still needs to be supplemented. The research paradigm for habitat quality comprehensive evaluation is: Habitat Quality = 0.25 × vegetation coverage index + 0.15 × water network density index + land degradation index + environmental quality index [?]. For small-scale urban habitat evaluation research, the InVEST model' s habitat quality assessment module is still rarely seen in literature.

Hohhot City is located on the northern frontier of China. As the capital of Inner Mongolia Autonomous Region and the central city of the "Hohhot-Baotou-Ordos" golden triangle, and situated in an ecologically fragile agro-pastoral transitional zone, this region has complex human-land relationships and sensitive ecological environments [?]. Taking Hohhot City as the study area has certain representativeness and typicality for exploring habitat quality evolution in ecologically fragile regions. Although some scholars have conducted relevant survey research on bird habitats in the study area, comprehensive habitat quality evaluation studies for Hohhot City are still rare in the literature.

This paper employs gradient analysis combined with the InVEST model to evaluate urban land expansion and habitat quality evolution in the study area over the past 20 years. Based on this evaluation, bivariate spatial autocorrelation is used to analyze the spatiotemporal response of habitat quality to urban land expansion, aiming to provide a reasonable basis for coordinated development between cities and ecological environments, and to offer references for other cities with similar development backgrounds.

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1. Study Area and Data Sources

1.1 Study Area Overview

Hohhot City is located in central-western Inner Mongolia Autonomous Region, with its urban area situated on the Tumochuan Plain at the southern edge of the Mongolian Plateau, backed by the Yinshan Mountains to the north and facing the Yellow River to the south. The climate is a typical mid-temperate continental monsoon climate, with an average annual temperature of 6.4°C and precipitation concentrated mainly in summer. The dominant wind direction is northwest, with an average annual wind speed of 1.8 $m \cdot s^{-1}$. Due to its location in an arid region of northwest China, water resources are extremely limited, with few surface runoff. In 2017, the per capita water resource availability in the urban area was only 316 m^3. This study takes Hohhot's urban district as the study area, with a total area of 2,083.68 km^2. By 2017, the total construction land area reached 457.95 km^2, accounting for approximately 22% of the study area. Rapid changes in land use not only damage local ecological environments but also create stress effects on ecosystems, thereby affecting regional sustainable development.

1.2 Data Sources

Landsat imagery served as the basic data for land use information extraction (Table 1). All image data were obtained from the Geospatial Data Cloud (http://www.gscloud.cn/). A human-computer interactive visual interpretation method was used to classify land use types according to the national standard "Current Land Use Classification" (GB/T21010-2017), dividing them into five types: cultivated land, forest land, grassland, construction land, water bodies, and unused land. Through field sampling survey verification, the Kappa coefficient reached over 85%, meeting research requirements. Transportation network information such as highways, railways, and roads was derived from the national basic geographic database (1:250,000 scale). Other data were primarily processed using software such as Fragstats and GeoDa.

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2. Research Methods

2.1 Gradient Analysis Method

Gradient analysis is a method that decomposes research objects according to vertical or horizontal spatial characteristics to achieve internal analysis of the objects. This method is more common in habitat and landscape pattern research. Common gradient analysis methods include terrain gradients and concentric ring gradients [?]. Given that construction land in the study area is mainly distributed in the alluvial plain zone in front of mountains, the concentric ring gradient is more suitable [?]. Urban construction land is generally extracted through impervious surfaces, calculating the area and related morphological indices of construction land in various urban periods to characterize the basic features of urban land expansion. To quantify the impact of urban expansion on habitat quality, combined with the actual situation of the study area, a 3 km buffer zone was used. The built-up area boundary line was taken as the initial boundary for ring analysis, and buffer zones were constructed simultaneously inward and outward, establishing a total of 30 buffer zones. The built-up area boundary line was located in buffer zone No. 16.

2.2 Urban Land Expansion Characterization

Combined with gradient analysis, the urban expansion core index and urban expansion intensity index were used to characterize the spatial evolution features of urban land expansion. The urban expansion core index (BCI) characterizes the compactness of urban external morphology, calculated as:

$$BCI = Nc + Nf$$

where BCI is the urban expansion core index with a value range of [0,1]. Larger values indicate more compact urban morphology; Nc and Nf represent the number of buffer zones in the urban core area (from city center to construction land density >50% area) and urban peripheral area (from urban core boundary to construction land density >20% circular area), respectively [?].

The urban expansion intensity index (UII) characterizes the intensity of construction land expansion in each period, calculated as:

$$UII = \frac{\Delta U_{ij}}{\Delta t_{ij} \times A_i}$$

where UII is the urban expansion intensity index; ΔU_{ij} is the change in construction land area from time i to j; Δt_{ij} is the time step from i to j; and A_i is the construction land area at time i.

2.3 Habitat Quality Characterization

The InVEST model' s habitat quality assessment includes calculations of habitat degradation degree and habitat suitability. Habitat degradation degree is the disturbance intensity of threat sources on habitats, while habitat suitability is the suitability degree of evaluation units as habitats. Forest land, grassland, and water bodies were defined as habitats, while construction land, cultivated land, and roads were defined as threat sources [?]. The habitat degradation degree is calculated as:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{r_y}{\sum_{r=1}^{R} r_y} \right) \cdot \delta_r \cdot \lambda_x \cdot S_{jr} \cdot \left(\frac{d_{xy}}{d_{rmax}} \right)$$

where r_y and δ_r are the disturbance degree and weight of threat source R at its location; λ_x and S_{jr} are the disturbance resistance capability and sensitivity degree of the habitat; Y_r is the number of grid cells of the threat source; d_{xy} and d_{rmax} are the Euclidean distance between threat source and habitat and the maximum disturbance radius, respectively.

The habitat quality of the study area is calculated as:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^z}{D_{xj}^z + k^z} \right)$$

where H_j is the habitat suitability of habitat j; K is the half-saturation constant; Z is the normalization constant, generally valued at 2.5. Parameters were set and the model was run to obtain the spatial distribution of habitat quality in the study area for each period.

2.4 Bivariate Spatial Autocorrelation

Bivariate spatial autocorrelation was used to analyze the spatial correlation between construction land expansion intensity change and habitat quality change. The specific calculation method is:

$$Moran's\,I = \frac{\sum_{a=1}^{n}\sum_{c=1}^{n}\omega_{ac}(y_a - \bar{y})(z_c - \bar{z})}{\sigma_y \sigma_z \sum_{a=1}^{n}\sum_{c=1}^{n}\omega_{ac}}$$

where y_a is the attribute value y of spatial unit a; z_c is the attribute value z of spatial unit c; σ_y^2 and σ_z^2 are the variances of attribute values y and z; ω_{ac} is the spatial weight matrix; $\bar{y}$ and $\bar{z}$ are the means of attribute values y and z. GeoDa software was used for significance testing at the $p < 0.05$ level.

2.5 Landscape Characteristics Characterization of Urban Land Expansion

To further illustrate the impact of urban land expansion landscape characteristics on habitats, patch density and Shannon diversity index were selected to reflect changes in construction land landscape characteristics in the study area [?]. The specific calculation methods are as follows:

$$PD = \frac{N_t}{A_t}$$

where PD is patch density; N_t is the total number of patches; A_t is the regional area. Larger PD values indicate higher landscape fragmentation and more serious habitat islandization.

$$SHDI = -\sum_{i=1}^{m} P_i \ln(P_i)$$

where $SHDI$ is the Shannon diversity index; P_i is the proportion of landscape type i in the total landscape area. This index reflects landscape heterogeneity, with larger values indicating more sensitive habitats.

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3. Results Analysis

3.1 Urban Land Expansion Evolution Characteristics

From the overall level of construction land expansion (Table 2), the urban outline of Hohhot City continuously expanded. The construction land area in the study area increased from 115.45 km^2 to 457.95 km^2, growing by nearly 3 times, with a UII value of 10.98%. Specifically, from 1990-2000, construction land area increased from 115.45 km^2 to 238.98 km^2, with a net increase of 123.53 km^2 and a UII value of 10.70%. From 2000-2010, the urban land scale expanded significantly, with construction land area increasing from 238.98 km^2 to 382.16 km^2, a net increase of 143.18 km^2, and a UII value of 6.00%. From 2010-2017, construction land area increased from 382.16 km^2 to 457.95 km^2, a net increase of 75.79 km^2, with a UII value of 2.83%.

In terms of BCI value changes, the compactness trend continuously decreased. From 1990-2000, the compactness decreased from 0.47 to 0.31, the largest decline, indicating that urban space mainly adopted a patchy sprawl expansion form, primarily due to vigorous construction of economic development zones around the city. From 2000-2010, compactness decreased to 0.25, as Hohhot proposed a new urban development strategy guiding expansion toward the southeast, with the "Hohhot-Baotou-Ordos" integration strategy significantly intensifying this trend. From 2010-2017, compactness decreased to 0.22, as the city vigorously developed new districts, making the urban external morphology increasingly non-compact. The urban expansion direction experienced a development process from northeast to southeast, making the expansion pattern unreasonable.

From the perspective of ring differentiation in construction land expansion intensity (Figure 2), the urban core area boundary shifted from buffer zone No. 12 to No. 18. Construction land expansion intensity peaked in buffer zones No. 13-16 and No. 19-22, with expansion intensity levels exceeding 20%. The reason is that large areas of cultivated land in Saihan District were converted to construction land. Specifically, from 1990-2000, buffer zones No. 13-16 had the highest expansion intensity, reaching 25.6%. From 2000-2010, buffer zone No. 19 had the maximum expansion intensity at 18.7%, with buffer zones No. 21-22 also showing small-scale increases. From 2010-2017, expansion levels in buffer zones No. 13-16 slowed, urban morphology stabilized, the urban core boundary shifted to buffer zone No. 18, and the urban peripheral boundary shifted to buffer zone No. 24. Overall, urban expansion showed low-density expansion in core areas and multi-point diffusion in peripheral areas.

[Figure 2: see original paper]

3.2 Spatiotemporal Characteristics of Habitat Quality Change

The specific habitat quality values for each ring were calculated, and the natural breaks method was used to classify habitat quality into five levels: low [0,0.32), relatively low [0.32,0.38), medium [0.38,0.45), relatively high [0.45,0.51), and high [0.51,1]. The proportions of each habitat quality level were statistically analyzed.

From 1990-2000, lower-grade habitats began to increase, accounting for 23.73%, with the average habitat quality value decreasing to 0.49, touching the red line between relatively low and medium habitat grades. From the habitat quality spatial evolution map (Figure 4), low-grade habitats mainly diffused in circular layers toward the south and southeast, consistent with the direction of construction land expansion. Yuquan District and Saihan District experienced the most severe habitat quality degradation. By 2010, the proportion of lower-grade habitats rapidly climbed to 34.96%, with low-grade habitat range further expanding and the average habitat quality value decreasing to 0.44. Xiaohehe Town, Jinhe Town, Huangheshao Town, and Yulin Town showed significant habitat degradation, indicating that declining urban habitat quality has significantly affected suburban and surrounding areas. Areas with good habitat quality were mainly distributed in Baoheshao Town, indicating that ecological restoration work on the southern slope of Daqing Mountain in the north has been quite effective. As an ecological barrier for Hohhot City, its ecological risk resistance capability continuously improved, and habitat suitability increased.

By 2017, the average habitat quality value slightly recovered to 0.46, but remained at a relatively low level. Habitat quality in Yulin Town and Huangheshao Town improved significantly, where Manghan Mountain is located. The ecological barrier advantages of mountains should be fully utilized to strengthen ecological construction efforts. The results show that in 1990, the proportion of relatively high-grade and above habitats was 49.46%, which decreased to 43.17% in 2017, a decline of 6.29%. In 1990, the proportion of lower-grade and below habitats was only 22.23%, which increased to 31.43% in 2017, with low-grade habitats accounting for 15.02%, indicating significant habitat quality degradation.

From the perspective of ring differentiation in habitat quality (Figure 2), lower-grade habitats were mainly located in buffer zones No. 13-18. The average habitat quality value in the central urban area was 0.51 in 1990, at a medium level. By 2000, lower-grade habitats were pushed to buffer zones No. 13-22. High-intensity economic development activities made habitat quality unsustainable, and habitat quality in all buffer zones showed a downward trend during this period. Buffer zones No. 16-18 were the most significant areas of habitat quality decline. Without control measures, the range of lower-grade and below habitats will further expand outward.

[Figure 4: see original paper]

3.3 Habitat Quality Response to Urban Land Expansion

Using a spatial weight matrix, bivariate spatial autocorrelation was employed to calculate the Moran' s I values for the relationship between habitat quality and urban land expansion intensity index changes, which were -0.113, -0.127, and -0.094 for the three periods, respectively, all passing significance tests at the $p < 0.05$ level. According to the bivariate spatial autocorrelation cluster map results (Figure 5), urban land expansion intensity change and habitat quality change showed obvious ring correspondence, with aggregation types mainly manifesting as low-low clusters, high-low clusters, and low-high clusters.

Specifically, from 1990-2000, buffer zones No. 13-16 showed low-low clustering, indicating stable urban interiors with insignificant habitat quality changes. Buffer zones No. 17-18 showed high-low clustering, indicating that expanding urban core areas intensified habitat quality degradation. Buffer zones No. 19-22 showed low-high clustering, while other buffer zones showed no significant spatial relationships, indicating that construction land expansion intensity in urban peripheral areas was low and ecological environmental quality improved.

From 2000-2010, high-high clustering disappeared, high-low clustering further shifted outward, and the number of low-high cluster buffer zones decreased, indicating that habitat quality at urban fringe zones was threatened. Overall, the clustering types in 2010-2017 were similar to those in 2000-2010. Construction land expansion in core-peripheral areas remained the most intensely changing zone, where habitat quality degradation was also most severe. The direction of urban land expansion was basically consistent with the direction of habitat quality change.

[Figure 5: see original paper]

3.4 Impact of Construction Land Landscape Characteristics

According to the calculation results of construction land patch density and Shannon diversity index in the study area, from 1990-2000, overall patch density increased from 0.32 to 0.52, an increase of 61.11%, while Shannon diversity increased from 0.81 to 1.02, an increase of 25.93%. This indicates that with the expansion of urban land scale, patch density continuously increased, especially the increase of construction land patches, which intensified urban landscape fragmentation and posed serious threats to habitat security.

From the perspective of ring differentiation in patch density and Shannon diversity changes (Figure 6), from 1990-2000, patch density showed an increasing trend in buffer zones after No. 13. Shannon diversity showed a decreasing trend in buffer zones No. 13-16 and an increasing trend in buffer zones No. 17-22. Patch fragmentation intensified abruptly in core-peripheral areas (buffer zones No. 16-18), and the growth trend only slowed at urban fringe zones. This indicates that patch fragmentation and uneven distribution will intensify habitat degradation.

From 2000-2010, the buffer zones with rapidly increasing patch density shifted to No. 16-22, while Shannon diversity peaked in buffer zones No. 19-22. Patches began to coalesce and distribution became more concentrated, with patch density beginning to decline in buffer zones No. 13-16. From 2010-2017, patches within the city became more fragmented again, showing a low-speed growth trend after buffer zone No. 16. The changing trend of Shannon diversity was consistent with that of patch density. Overall, the enlargement of urban outline caused drastic changes in landscape characteristics of core-peripheral areas.

[Figure 6: see original paper]

4. Conclusions

This paper employs gradient analysis combined with the InVEST model to evaluate urban land expansion and habitat quality evolution, and uses bivariate spatial autocorrelation to analyze the spatiotemporal response of habitat quality to urban land expansion. The conclusions are as follows:

(1) The urban outline in the study area continuously expanded, with the expansion intensity index at a relatively high level. Urban land expansion mainly followed an extensive expansion pattern. Compactness continuously decreased, urban structure was unstable, and the expansion pattern was unreasonable.

(2) Habitat quality levels in the study area dropped to a poor state, with significant habitat quality degradation. Habitat quality experienced a stage of rapid decline followed by slow recovery. From the perspective of spatial evolution, low-grade habitats mainly diffused in circular layers toward the south and southeast, consistent with the direction of construction land expansion.

(3) There is a spatial negative correlation between construction land expansion intensity and habitat quality change distribution in the study area. Rapid expansion of urban construction land further intensifies the trend of habitat quality degradation. Overall, construction land expansion in core-peripheral areas remains the most intensely changing zone, where habitat quality degradation is also most severe.

(4) Patch density in the study area shows a continuous upward trend, particularly as the increase of construction land patches intensifies urban landscape fragmentation. Patch fragmentation intensifies abruptly in core-peripheral areas, and the growth trend only slows at urban fringe zones. Patch fragmentation and uneven distribution will intensify habitat degradation.

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5. Discussion

Land urbanization is an important aspect of the urbanization process. However, as urban land expands, various ecological problems begin to emerge. The study area serves as an important national ecological barrier zone, making it particularly important to promote regional sustainable development. According to the long-term planning of the study area, demand for construction land remains at a relatively high level. Adjusting regional land use structure and improving land use efficiency are imperative.

This paper employs gradient analysis combined with the InVEST model to evaluate urban land expansion and habitat quality evolution in the study area, and uses bivariate spatial autocorrelation to analyze the spatiotemporal response of habitat quality to urban land expansion. The results also verify the reality that rapid urban land expansion promotes regional habitat quality degradation. The habitat threat sources in this paper were mainly selected based on construction land, without considering other threat sources (natural disasters, environmental pollution, etc.). Further enrichment of threat source data would make model results more reasonable, thereby providing better basis for coordinated development between cities and ecological environments.

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