Analysis of Spatiotemporal Evolution of Habitat Quality and Its Driving Mechanisms in Shaanxi Province (Postprint)

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Abstract

Habitat quality constitutes a critical foundation for biodiversity conservation and regional ecological environment improvement, and investigating its spatiotemporal evolution and driving mechanisms within the context of ecological civilization construction holds significant importance. This study takes Shaanxi Province as the research area and employs land use data from 2000, 2010, and 2020 to analyze the spatiotemporal evolution characteristics and driving factors of habitat quality across three major regions (Southern Shaanxi, Northern Shaanxi, and Guanzhong) utilizing the InVEST model, Theil index, and Geodetector model. The results indicate: (1) During 2000–2020, the provincial mean habitat quality demonstrated a stable and slightly upward trend, with pronounced spatial distribution heterogeneity, manifesting as higher values in Southern Shaanxi and Northern Shaanxi compared to Guanzhong; (2) Substantial inter-regional and intra-regional disparities in habitat quality existed among the three major regions, with Southern Shaanxi and Guanzhong exhibiting greater variation than Northern Shaanxi; (3) Spatial scale effects led to differing driving factors between the provincial level and the three regions; vegetation and topographic factors exerted the strongest influence on provincial habitat quality, whereas land use factor emerged as the primary determinant for the three regions, with its impact progressively intensifying over time; the effects of topographic and vegetation factors varied across the three regions; (4) Beyond single-factor effects, the synergistic interactions between socioeconomic and natural environmental factors significantly influenced habitat quality changes in the three major regions.

Full Text

Abstract

Habitat quality constitutes a fundamental basis for biodiversity conservation and regional ecological environment improvement. Against the backdrop of ecological civilization construction, investigating the spatiotemporal evolution and driving mechanisms of habitat quality holds significant importance. This study examines Shaanxi Province as the research area, analyzing spatiotemporal evolution characteristics and driving factors of habitat quality across three major regions (southern Shaanxi, northern Shaanxi, and Guanzhong) from 2000 to 2020 using land use data, the InVEST model, Theil index, and geographic detector model. Results indicate: (1) The average habitat quality index for the entire province showed a stable and slightly increasing trend, with pronounced spatial distribution differences—habitat quality in southern and northern Shaanxi was higher than in Guanzhong; (2) Inter-regional and intra-regional differences in habitat quality among the three major areas were substantial, with greater disparities between southern Shaanxi and Guanzhong compared to northern Shaanxi; (3) Influenced by spatial scale, driving factors differed between the provincial level and the three regions. Vegetation and terrain factors exhibited the strongest influence on provincial habitat quality, while land use factors represented the primary influence across the three regions, with their impact gradually strengthening over time. Terrain and vegetation factors showed varying effects across the three regions; (4) Beyond single-factor effects, synergistic interactions between socioeconomic and natural environmental factors significantly influenced habitat quality changes in all three regions.

Keywords: habitat quality; InVEST model; geographic detector; driving factor; Shaanxi Province

1. Study Area and Methods

1.1 Study Area Overview

Shaanxi Province spans 105°29 -111°15 E and 31°42 -39°35 N, covering a total area of 2.056×10^{5} km^2 with 107 county-level administrative units. The province extends from north to south across three distinct physiographic regions: northern Shaanxi (the Loess Plateau), Guanzhong Plain, and southern Shaanxi (the Qinling-Daba mountainous area). Northern Shaanxi, characterized by the Loess Plateau at elevations of 850–1900 m, experiences a semi-arid monsoon climate with annual temperatures of 8–12°C and low precipitation. This region includes Yulin and Yan' an municipalities, with Yulin situated in the farming-pastoral ecotone featuring sparse vegetation and representing a key ecological restoration zone, while southern Yan' an maintains higher forest coverage and serves as an important ecological functional area.

Guanzhong Plain, dominated by plains at 460–850 m elevation, has a temperate monsoon climate with annual temperatures of 12–13°C and precipitation of 500–

800 mm. As Shaanxi' s primary economic, political, and cultural center, this region hosts major cities including Xi' an, Xianyang, and Baoji, with dense populations and concentrated urban-industrial-agricultural development. Southern Shaanxi comprises the Qinling-Daba mountainous region, dominated by mountains at 1000–3000 m elevation with a subtropical monsoon climate (14–16°C annual temperature, 800–1000 mm precipitation). This area features abundant rainfall, dense vegetation, and constitutes the province' s main forest zone and ecological barrier, providing crucial ecosystem services including water conservation and biodiversity protection. Shaanxi' s unique geographic location and natural environment create a typical ecological gradient from north to south, forming the basis for analyzing regional habitat quality patterns.

1.2 Data Sources and Processing

Habitat quality is influenced by multiple factors, including climate, terrain, and vegetation as primary natural environmental factors, and population-economy and land use as key socioeconomic factors. Based on regional characteristics and data availability, this study selected natural environment and socioeconomic conditions as first-level indicators, comprising 12 second-level indicators and 3 third-level indicators as habitat quality impact factors. All indicators were rasterized and resampled to 1 km grids, yielding 20,560 evaluation units for the geographic detector analysis. Data series from 2000, 2010, and 2020 were obtained from various sources: land use data from the Chinese Academy of Sciences Resource and Environmental Science Data Center; meteorological data from 47 national weather stations; NDVI, LAI, and NPP data from MODIS products; DEM data from Geospatial Data Cloud; population statistics from the China County Statistical Yearbook; and road network data from OpenStreetMap. Detailed processing methods included Kriging interpolation for climate data, maximum value compositing for vegetation indices, and Euclidean distance calculations for accessibility metrics.

1.3 Research Methods

1.3.1 InVEST Model The InVEST Habitat Quality module was employed to evaluate habitat quality based on land use data and biodiversity threat factors. Drawing from regional characteristics and existing literature, six stressors heavily impacted by human activities were selected: industrial/mining land, transportation land, rural residential land, urban land, dryland, and paddy field. Sensitivity relationships between land use types and stressors were established (Table 2), incorporating stressor distance, weight, and decay patterns (Table 3) to calculate habitat quality indices ranging from 0 to 1, where higher values indicate better habitat conditions. The natural breaks method classified habitat quality into five levels: low [0, 0.16), relatively low [0.16, 0.43), moderate [0.43, 0.60), relatively high [0.60, 0.77), and high [0.77, 1].

1.3.2 Geographic Detector Geographic detector is a statistical method for detecting spatial heterogeneity and revealing driving factors. This study employed factor detection and interaction detection to analyze factor explanatory power on habitat quality. Factor detection quantifies the influence of independent variable X on dependent variable Y using the q-statistic:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where q represents the explanatory power of X on Y (range [0,1]), h denotes strata (categories/regions), N_h and N are unit numbers for stratum h and the entire region, and σ_h^2 and σ^2 represent variances. Interaction detection identifies combined effects of different factors, classifying interactions as nonlinear weakening, single-factor nonlinear weakening, dual-factor enhancement, independent, or nonlinear enhancement based on comparative q-values.

2. Results

2.1 Spatiotemporal Characteristics of Habitat Quality

From 2000 to 2020, the provincial average habitat quality index increased slightly from 0.54 to 0.56, remaining at a moderate level. Spatially, habitat quality exhibited a distinct pattern of high values in the north and south with low values in the central region. Southern Shaanxi showed the highest quality (0.68–0.70), followed by northern Shaanxi (0.52–0.54), with Guanzhong showing the lowest (0.44–0.46). The proportion of different habitat quality grades remained relatively stable province-wide, with relatively low, relatively high, and moderate quality comprising approximately 85% of total area. However, relatively low quality decreased while relatively high quality increased, indicating gradual improvement.

Regionally, southern Shaanxi was dominated by relatively high habitat quality (45–48%), concentrated in the densely forested Qinling Mountains. Northern Shaanxi showed predominantly relatively low quality (47–57%), particularly in eastern and southern Yulin, though relatively high quality increased significantly after 2010 (reaching 20.08% by 2020). Guanzhong exhibited the highest proportion of relatively low quality (54–57%), concentrated in urban centers of Xi'an, Baoji, and Xianyang, but also contained substantial high-quality habitat patches.

Theil index analysis revealed increasing spatial disparities, with the provincial index rising 18.64% and inter-regional differences increasing 32.16%. Inter-regional variation dominated provincial disparities, while intra-regional differences remained minimal. Guanzhong showed the highest internal heterogeneity, followed by southern Shaanxi, with northern Shaanxi displaying the most spatially uniform patterns.

2.2 Analysis of Driving Factors

2.2.1 Single-Factor Effects Factor detection revealed scale-dependent variations in explanatory power. At the provincial scale, vegetation factors (NDVI, LAI, NPP) and terrain factors (elevation, slope, terrain position) showed the strongest influence ($q > 0.30$), while land use intensity ranked third. Climate and socioeconomic factors exhibited weaker effects ($q < 0.10$). At the regional scale, land use intensity emerged as the dominant factor across all three regions, with q-values increasing over time. Southern Shaanxi showed additional sensitivity to vegetation factors, while Guanzhong was influenced by both vegetation and terrain. Northern Shaanxi' s habitat quality responded strongly to vegetation factors and precipitation, reflecting climatic sensitivity in this arid region.

2.2.2 Factor Interactions Interaction detection demonstrated that most factor pairs exhibited synergistic enhancement effects. At the provincial scale, interactions between vegetation/terrain factors and other variables showed the strongest combined explanatory power ($q > 0.40$). At the regional scale, land use intensity interactions were most pronounced, particularly in Guanzhong where its interaction with vegetation factors exceeded $q = 0.50$. Climate factors and distance to county centers showed the greatest enhancement when interacting with other variables, with q-values increasing from 0.05–0.10 to 0.30–0.40. Notably, land use intensity-vegetation factor interactions strengthened over time across all regions, indicating intensifying human-environment coupling.

3. Discussion

The evaluation results demonstrate clear regional disparities in habitat quality that align closely with land use patterns. Low-quality habitats concentrate in urban built-up areas such as Xi' an city proper and Hantai District in Hanzhong, while large contiguous cultivated areas in the Guanzhong Plain exhibit relatively low quality. High-quality habitats predominantly occur in the Qinling Mountains with high forest coverage. From 2000 to 2020, the explanatory power of land use intensity increased across all three regions, indicating strengthening human impacts. However, its provincial-scale influence weakened due to counteracting effects: urban expansion degraded habitat quality while ecological restoration programs (returning farmland to forest/grassland) improved it. The net 96.18% increase in urban land was offset by restoration measures, resulting in overall habitat quality improvement.

Vegetation factors represent the second major driver group, serving as important indicators of vegetation status influenced by both climate change and human activities. While warming temperatures extended growing seasons and accelerated soil organic matter decomposition, promoting plant growth, human activities such as the Grain-for-Green program and agricultural intensification significantly enhanced vegetation recovery. However, increased evaporation under higher temperatures also exacerbated water shortages, limiting vegetation development. Urbanization encroached upon substantial farmland and forest-grassland areas, reducing vegetation coverage. Studies indicate that climate change contributed 30-40% to NDVI increases, while human activities accounted for 60-70%, highlighting their combined importance.

Terrain factors constitute the third driver group, primarily constraining human activity distribution. The Qinling Mountains above 1500 m elevation maintain high vegetation coverage with minimal human disturbance, exhibiting good habitat quality. Areas at 500-1000 m, containing major cities like Xi' an and Baoji, experience intense human activity and consequently lower habitat quality. Regions below 500 m in northern Shaanxi include the Mu Us Sandy Land with severe desertification, resulting in poor habitat quality. These findings align with previous research demonstrating terrain' s regulatory role.

Scale effects significantly influence factor explanatory power. Regional-scale q-values exceed provincial values due to homogenization across regions. Southern Shaanxi' s relatively uniform terrain and high vegetation coverage reduce terrain and vegetation sensitivity, while northern Shaanxi' s fragile vegetation responds markedly to climate variability and restoration policies. Guanzhong' s diverse topography and strong north-south climatic gradients, coupled with intense human activity in the central plain, create complex natural-socioeconomic interactions.

Policy implications vary by region. Southern Shaanxi should prioritize coordinating land use intensity with vegetation protection, particularly managing urban expansion impacts on forest ecosystems. Northern Shaanxi must balance ecological restoration with climate adaptation, focusing on water resource management. Guanzhong requires integrated strategies addressing both economic development and habitat restoration, especially in rapidly urbanizing areas. The consistent dual-factor and nonlinear enhancement effects across scales underscore the necessity of multi-factor governance approaches.

4. Conclusions

Based on land use data from 2000, 2010, and 2020, this study evaluated spatiotemporal evolution patterns of habitat quality across Shaanxi Province and its three major regions using the InVEST model and identified key driving factors through geographic detector analysis. The main conclusions are:

1) Provincial average habitat quality remained at a moderate level but showed gradual improvement from 2000 to 2020. Spatial distribution exhibited significant heterogeneity, with southern Shaanxi showing the highest quality, followed by northern Shaanxi, and Guanzhong the lowest. Spatial disparities expanded over time, primarily driven by inter-regional differences, with Guanzhong showing the greatest internal heterogeneity.

2) Vegetation factors, terrain factors, and land use intensity constitute the primary drivers of habitat quality change at the provincial scale, with

land use intensity' s influence strengthening annually. At the regional scale, land use intensity dominates across all three regions, supplemented by vegetation factors in northern Shaanxi and both vegetation and terrain factors in Guanzhong. Climate and socioeconomic factors show relatively minor direct effects.

3) Interaction analysis reveals that dual-factor and nonlinear enhancement effects predominate across scales. At the provincial level, vegetation and terrain factor interactions are strongest. Regionally, land use intensity interactions are most powerful, particularly its combination with vegetation factors in Guanzhong (explanatory power >0.50). Climate and accessibility factors show the greatest enhancement when interacting with other variables, warranting attention in regional planning.

These findings provide scientific support for region-specific ecological protection strategies and sustainable development policies in Shaanxi Province.

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