Spatiotemporal Evolution of Habitat Quality in the Wei River Basin: Topographic Gradient Effects and Influencing Factors (Postprint)

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Abstract

Habitat quality constitutes a crucial foundation for human well-being and regional sustainable development, holding significant importance for biodiversity conservation, enhancement of ecosystem service functions, and construction of regional ecological security patterns. Based on three-phase land use data from 2000 to 2020, this study integrally applies methods including the InVEST model, topographic position index, geographical detector, and spatial statistical analysis to conduct a comprehensive analysis of the spatial distribution characteristics of habitat quality in the Wei River Basin and its topographic gradient effects and influencing factors. The results indicate that: (1) From 2000 to 2020, the habitat quality index in the Wei River Basin demonstrated a year-on-year increasing trend, rising from 0.607 to 0.624 with a growth rate of 2.463%, spatially exhibiting a polarized distribution pattern wherein the areas of low and high habitat quality continued to increase while those of medium and good habitat quality decreased. (2) The spatial distribution of habitat quality in the Wei River Basin is substantially influenced by topographic factors, exhibiting significant topographic gradient effects, with low habitat quality being widely distributed on low topographic gradients and showing the highest distribution index, whereas high habitat quality predominantly occupies high topographic gradients. (3) Land use type represents the primary influencing factor for the spatial differentiation of habitat quality in the Wei River Basin, and the interaction effects of any two factors on the spatial differentiation of habitat quality exceed those of individual driving factors, with the interaction determination power between land use type and precipitation, temperature, altitude, and Normalized Difference Vegetation Index (NDVI) all exceeding 0.6. The research findings can provide scientific theoretical support and decision-making support for sustainable development, ecological protection, and high-quality development in the Wei River Basin.

Full Text

Preamble

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Spatiotemporal Evolution of Habitat Quality and Its Terrain Gradient Effects and Influencing Factors in the Weihe River Basin

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Abstract: Habitat quality is a crucial foundation for human well-being and regional sustainable development, holding significant practical importance for protecting biodiversity, enhancing ecosystem service functions, and constructing regional ecological security patterns. Based on three-phase land use raster data from 2000, 2010, and 2020, this study comprehensively applied the InVEST model, topographic position index, distribution index, geographic detector, and spatial statistical analysis methods to analyze the spatiotemporal evolution characteristics and spatial distribution patterns of habitat quality in the Weihe River Basin, along with its terrain gradient effects and influencing factors. The results indicate that: (1) From 2000 to 2020, the habitat quality index in the Weihe River Basin showed a yearly increasing trend, rising from 0.607 to 0.624 with a growth rate of 2.463%. Spatially, it exhibited a polarized distribution pattern, with areas of low and high habitat quality continuing to increase while areas of medium and good habitat quality decreased. (2) The spatial distribution of habitat quality in the Weihe River Basin was significantly influenced by topographic factors, showing a pronounced terrain gradient effect. Low habitat quality was extensively distributed in low terrain gradient zones with the highest distribution index, whereas high habitat quality dominated in high terrain gradient zones. (3) Land use type was the primary influencing factor for the spatial differentiation of habitat quality in the Weihe River Basin. The interaction of any two factors on spatial differentiation was greater than the independent effect of a single driving factor. Specifically, the interactive determinants of land use type combined with rainfall, temperature, altitude, and normalized vegetation index all exceeded 0.6. These research results can provide scientific theoretical and decision-making support for sustainable development, ecological protection, and high-quality development in the Weihe River Basin.

Keywords: habitat quality; InVEST model; terrain gradient effect; influencing factors; geographic detector; Weihe River Basin

1 Study Area Overview

The Weihe River Basin (104°01 ~110°21 E, 33°50 ~37°18 N) originates from Niaoshu Mountain in Weiyuan County, Gansu Province. Located in northwestern China, it is the largest tributary of the Yellow River Basin, spanning three provinces (regions): Shaanxi, Gansu, and Ningxia, with a total basin area of approximately 13.4$\times10^{4}$ km^2. The terrain of the Weihe River Basin slopes from high in the west to low in the east, and it belongs to a continental monsoon climate zone with an average annual temperature of 7.8–13.5°C and average annual precipitation of 550–850 mm. Precipitation distribution is uneven, decreasing from southeast to northwest under topographic influence. The northern and western parts of the Weihe River Basin are located in China's concentrated contiguous poverty-stricken areas, with fragile ecological environments and slow socioeconomic development. However, with the continuous advancement of poverty alleviation and ecological projects, regional socioeconomic development and ecological environments have steadily improved, though ecosystem stability still needs enhancement. The central part is a plain area with flat terrain, concentrated population, and rapid economic development, where human activities are frequent and the human-land relationship is prominent. The southern part is the Qinling mountainous area with high vegetation coverage and good ecological environmental quality.

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2 Data and Methods

2.1 Data Sources

The data used in this study mainly included land use data and habitat quality influencing factor data. The three-phase land use data (2000, 2010, and 2020) were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.redc.cn) with a spatial resolution of 30 m. Land use types were classified into six categories: cultivated land, forest land, grassland, water area, construction land, and unused land. Habitat quality influencing factors mainly included altitude, slope, normalized vegetation index (NDVI), rainfall, temperature, land use type, population density, and gross domestic product (GDP). Digital elevation model (DEM) data were obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn/) with a resolution of 30 m, from which altitude and slope were derived. Rainfall and temperature data were obtained from the National Earth System Science Data Center (http://www.geodata.cn). Population density data were obtained from Worldpop (http://www.worldpop.org/), and NDVI data were obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.redc.cn). Land use degree was calculated following reference [25]. The administrative boundary of the study area was obtained from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.redc.cn).

2.2 InVEST-Based Habitat Quality Assessment Model

This study used the habitat quality module (Habitat Quality) in the InVEST model to assess habitat quality in the Weihe River Basin. This module can reflect the degree of impact of human activities on the environment [14]. The basic principle is to treat different land use types as corresponding ecosystem types or human activity disturbance factors, and to simulate and evaluate habitat quality based on the habitat suitability of each ecosystem type for flora and fauna and the threat intensity of human disturbance factors [15]. The calculation formulas are:

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y \beta_x S_{jr} i_{rxy}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{r\max}} \right) \quad \text{(linear decay)}$$

$$i_{rxy} = \exp\left(-\frac{2.99 d_{xy}}{d_{r\max}} \right) \quad \text{(exponential decay)}$$

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

Where: D_{xj} is the habitat degradation degree, with a value range of [0,1], where larger values indicate higher habitat degradation; r is the threat factor; y is the number of grids corresponding to threat factor r; w_r is the weight of threat factor r; r_y is the stress value of threat factor r; β_x is the level of habitat protection; S_{jr} is the sensitivity of habitat j to stress factor r; i_{rxy} is the impact of threat factor r in grid y on grid x; Q_{xj} is the habitat quality; H_{xj} is the habitat suitability; k is the half-saturation constant, usually taken as half of the maximum habitat degradation value; and z is the scaling parameter, typically set to 2.5.

Based on the actual situation of the Weihe River Basin and relevant research results, land use types with high human interference intensity—urban land, rural settlements, other construction land, cultivated land, and unused land—were set as threat factors to habitat quality. Their weights, maximum influence distances, and degradation types were determined based on the InVEST model user manual and related research results to extract threat factor layers. Furthermore, the habitat suitability of different land types and their relative sensitivity to threat factors were established .

2.3 Terrain Gradient Analysis Method

Terrain factors are key elements affecting the spatial distribution and development of geographic features [16]. The topographic position index is a composite terrain factor that analyzes the altitude and slope attribute information of any point in space, expressing the spatial differentiation characteristics of terrain conditions. Using the topographic position index can comprehensively analyze the influence of terrain factors on the spatial distribution pattern of habitat quality [16,22]. The calculation formula is:

$$T = \log\left[\left(\frac{E}{\bar{E}} + 1\right) \times \left(\frac{S}{\bar{S}} + 1\right)\right]$$

Where: T is the topographic position index; E and $\bar{E}$ are the altitude and mean altitude of any grid cell in space (m), respectively; S and $\bar{S}$ are the slope and mean slope of any grid cell in space (°), respectively.

To better analyze the terrain gradient effects of habitat quality in the Weihe River Basin, this study introduced the terrain distribution index of habitat quality to explore the spatial distribution characteristics of habitat quality with changes in terrain factors [23]. The calculation formula is:

$$P = \frac{S_{ie}}{S_i} \bigg/ \frac{S_e}{S}$$

Where: P is the distribution index; S_{ie} is the area of habitat quality grade i in terrain gradient level e (km^2); S_i is the total area of habitat quality grade i (km^2); S_e is the total area of terrain gradient level e (km^2); and S is the total area of the study area (km^2).

2.4 Geographic Detector Model

The geographic detector, created by Wang Jinfeng et al. [24], is a statistical method for analyzing spatial heterogeneity of geographic phenomena and revealing their driving factors. Compared with other models, this model considers spatial heterogeneity between factors and has been widely applied in disease prevention and ecological environmental management [25]. The calculation formula is:

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

Where: q is the detection value of habitat quality influencing factors, with a value range of [0,1]; h is the classification number of the independent variable; L is the total number of evaluation units; N_h and N are the number of samples in each partition and the entire region, respectively; σ_h^2 and σ^2 are the variance of each partition and the total variance of habitat quality in the region, respectively.

To further explore the causes of spatial differentiation patterns of habitat quality in the Weihe River Basin, different driving factors needed to be discretized and graded before being imported into the geographic detector for calculation. The discretization and grading of driving factors are detailed in .

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3 Results and Analysis

3.1 Spatiotemporal Changes in Habitat Quality

3.1.1 Temporal Change Analysis of Habitat Quality As shown in , the habitat quality index in the Weihe River Basin increased from 0.607 in 2000 to 0.624 in 2020, showing a yearly increasing trend with an average annual growth rate of 0.128%. Among these, high and medium habitat quality areas were most extensive, together accounting for more than 85% of the total area, while low and good habitat quality areas accounted for less than 15%, indicating that the overall habitat quality level in the Weihe River Basin was relatively high. From 2000 to 2020, the areas of low and high habitat quality continued to increase, expanding by 1508.89 km^2 (1.13%) and 3288.67 km^2 (2.45%), respectively. In contrast, medium and good habitat quality areas showed a decreasing trend, reducing by 4420.17 km^2 (3.29%) and 377.39 km^2 (0.29%), respectively. During the study period, the overall habitat quality in the Weihe River Basin remained at a medium-high level and showed a yearly increasing trend, indicating that watershed ecological environment management has achieved good results.

3.1.2 Spatial Change Analysis of Habitat Quality in the Weihe River Basin As shown in [Figure 2: see original paper], the spatial distribution patterns of different habitat quality grades in the Weihe River Basin from 2000 to 2020 exhibited obvious heterogeneity. Low habitat quality was mainly concentrated in the Guanzhong Plain urban agglomeration, river valley built-up areas, and around urban districts—regions with intensive human activities—with sporadic distribution in other areas. These areas were dominated by construction land. Medium habitat quality was mainly distributed in agricultural production areas in the northern, western, and southeastern parts of the Weihe River Basin, where habitat quality degradation was relatively severe and land use was dominated by cultivated land. High habitat quality was the most widely distributed, concentrated in the northern foothills of the Qinling Mountains, Liupan Mountain, and Ziwu Mountain areas, where land use was dominated by forest and grassland with stable natural ecological environments and minimal human disturbance.

[Figure 3: see original paper] shows that stable habitat quality areas were widely distributed, accounting for nearly 88.12% of the total area, mainly concentrated in the northern foothills of the Qinling Mountains, Ziwu Mountain, and the Guanzhong Plain. Improvement areas covered 3915.71 km^2 (6.24% of the basin), primarily distributed in Pingliang and Qingyang cities in the central Weihe River Basin, Yan'an City in the north, and Dingxi City in the western Gansu section—areas that highly coincide with regions of the Grain-for-Green Project. Degradation areas covered 2929.99 km^2 (6.11%), mainly distributed in built-up areas and their surroundings in plains and river valleys. During the study period, the area of stable habitat quality regions decreased but remained extensively distributed, with significant spatial pattern changes. Improvement areas increased substantially, with their proportion rising from 2.93% to 6.24%. Meanwhile, degradation areas increased rapidly, with their proportion rising from 2.18% to 6.11%, mainly concentrated in cities and surrounding areas in plains and river valleys with intense human activities, where habitat quality degradation was severe and habitat fragmentation intensified, urgently requiring effective measures to improve habitat quality.

3.2 Terrain Gradient Effects of Habitat Quality in the Weihe River Basin

From the perspective of elevation gradient distribution index [Figure 4: see original paper], low and medium habitat quality showed a decreasing trend with increasing elevation gradient, both reaching maximum distribution indices in the first gradient (0–500 m) at 1.32 and 1.18, respectively. Good habitat quality showed a fluctuating decreasing trend with elevation, with greater distribution advantages in the 500–1000 m gradient. High habitat quality's distribution advantage was mainly concentrated above 1500 m, with distribution indices of 1.45, 1.56, and 1.68 in the 1500–2000 m, 2000–2500 m, and >2500 m gradients, respectively.

From the slope gradient distribution index, different habitat quality grades showed significant differences in distribution. Low habitat quality had an absolute distribution advantage in the 0–5° gradient, with a maximum distribution index of 1.85 that increased yearly. Medium and good habitat quality showed a gradual decreasing trend in distribution index with increasing slope gradient, with greater distribution advantages in the 5–15° gradient (distribution indices >1.0). High habitat quality had a significant distribution advantage in gradients >25°, with its distribution index increasing rapidly with slope gradient.

From the topographic position index distribution, different habitat quality grades showed significant spatial distribution differences. Low habitat quality was concentrated in the 1st topographic gradient, with maximum distribution indices of 1.89, 1.92, and 1.96, decreasing rapidly with increasing gradient. Medium habitat quality was mainly distributed in the 1st–3rd gradients, with a maximum distribution index of 1.25, also decreasing rapidly with increasing gradient. Good habitat quality was concentrated in the 1st–2nd gradients, though with relatively low distribution indices (maximum 1.12). High habitat quality had weak distribution advantages in the 1st–3rd gradients, but its distribution index increased rapidly with topographic gradient, reaching 1.68 in the >7th gradient. During the study period, the distribution advantage of low habitat quality in low topographic gradients strengthened, while the distribution advantages of medium and good habitat quality in low topographic gradients gradually weakened.

3.3 Influencing Factors of Spatial Differentiation of Habitat Quality in the Weihe River Basin

shows that land use type had the strongest influence on habitat quality (q=0.815), significantly higher than other factors, making it the primary factor for spatial differentiation of habitat quality. This was followed by rainfall (q=0.412) and temperature (q=0.387), while NDVI (q=0.285), altitude (q=0.234), and land use degree (q=0.189) had relatively weaker but still significant effects. Population density (q=0.089) and GDP (q=0.067) had the weakest influence, indicating that natural factors had a stronger impact on habitat quality than socioeconomic factors.

From the interaction perspective, the interaction between any two factors on spatial differentiation of habitat quality was greater than the single factor effect. The interactive determinants of land use type NDVI (q=0.872), land use type rainfall (q=0.868), land use type temperature (q=0.851), and land use type altitude (q=0.843) were the strongest. The interactions of land use type slope (q=0.821), land use type land use degree (q=0.819), and land use type population density (q=0.818) were the next most significant, while population density GDP (q=0.152) had the weakest effect. [Figure 5: see original paper] shows that the interactive determinants of any two factors were higher than single-factor determinants, indicating that the spatial differentiation pattern of habitat quality is comprehensively influenced by multiple factors. Natural factors significantly enhanced the influence of socioeconomic factors on habitat quality.

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4 Discussion

This study evaluated habitat quality and its spatiotemporal evolution in the Weihe River Basin using the InVEST model, and revealed its terrain gradient effects and influencing factors through the topographic position index and geographic detector model. The results can provide decision-making support for regional ecological protection and ecosystem management, effectively mitigating local habitat quality degradation risks. The findings show that from 2000 to 2020, habitat quality in the Weihe River Basin showed a polarized trend—local degradation but overall improvement—consistent with research by Li et al. [3] and Huang et al. [11]. On one hand, regional socioeconomic development, particularly the rapid expansion of the Guanzhong Plain urban agglomeration centered on Xi'an City, created a "siphon effect" on surrounding areas, leading to continuous urban land expansion and encroachment on farmland, thereby degrading surrounding habitats. On the other hand, the implementation of ecological projects such as Grain-for-Green converted large areas of cultivated land into forest land with higher habitat suitability, increasing high-grade habitat areas and continuously improving overall habitat quality. Both improvement and degradation coexisted in the study area, but the improvement magnitude exceeded the degradation magnitude, resulting in an overall upward trend in habitat quality. This aligns with findings in the Shule River Basin [31], Yellow River Delta [33], and Michigan Basin [34], demonstrating that land use type is a crucial cause of habitat quality changes.

Terrain is an important factor affecting population distribution patterns and maintaining community diversity [35]. The Weihe River Basin has extremely complex terrain, and its land use patterns are constrained by topography, forming unique population and industrial layouts. Under the coupling effects of related factors, habitat quality in the Weihe River Basin shows obvious hierarchical distribution characteristics across terrain factors [36], with extremely significant terrain gradient effects. High habitat quality is mainly distributed in mountainous areas rich in ecological resources such as forest and grassland, gradually dominating with increasing terrain gradient. Low habitat quality is mainly distributed in plain areas with extensive cultivated land and construction land, reaching maximum distribution index in low terrain gradient zones. This is consistent with findings by Jia et al. [16] and Liu et al. [22], mainly because low terrain gradient areas have flat terrain, suitable hydrothermal conditions, and concentrated distribution of cultivated land and construction land, becoming centers of population and economic development. Intensifying human activities have increased encroachment on ecological land, resulting in lower habitat quality in these areas. High terrain gradient areas have high vegetation coverage, and due to limitations of terrain factors and natural conditions, human disturbance is minimal and ecosystems are relatively stable, leading to high habitat quality levels.

The spatial differentiation pattern of habitat quality is comprehensively influenced by multiple factors. Among them, the interaction between land use type and other factors was most significant, primarily because habitat quality assessment is based on land use types, and the spatial characteristics of habitat quality are mainly influenced by the spatial pattern of land use types. Socioeconomic factors had relatively weak independent influence on habitat quality, but their determinants increased significantly when interacting with natural factors. The interaction intensity of population density factors reached 0.818, indicating that natural factors enhanced the impact of socioeconomic factors on habitat quality.

This study analyzed the spatiotemporal evolution patterns, terrain gradient effects, and key influencing factors of habitat quality in the Weihe River Basin using the InVEST model combined with topographic position index and geographic detector model. The results align with the ecological environment of the Weihe River Basin and provide an important reference for ecological environmental protection and regional sustainable development. However, the Weihe River Basin spans a large area, and its habitat quality influencing factors show significant spatial heterogeneity. Future research should strengthen the identification and detection of key influencing factors of habitat quality at different spatial scales to seek more targeted ecosystem management approaches. Additionally, although the habitat quality module of the InVEST model is relatively mature, its parameters still reference the operation manual and related research, retaining some subjectivity. Future studies should strengthen field monitoring of biodiversity in the study area to further revise and improve the assessment model, providing more accurate references for regional ecological construction and related policy formulation.

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5 Conclusions

Based on land use data, this study evaluated the spatiotemporal evolution of habitat quality in the Weihe River Basin using the InVEST model and analyzed its terrain gradient effects and influencing factors. The main conclusions are:

1) From 2000 to 2020, habitat quality in the Weihe River Basin showed a yearly upward trend with an average annual growth rate of 0.128%. Spatial polarization was evident, with areas of low and high habitat quality increasing yearly while areas of medium and good habitat quality decreased. Spatially, habitat quality improvement areas were mainly distributed in the loess hilly and gully regions in the northern and western parts of the basin, while degradation areas were concentrated in the contiguously urbanized Guanzhong Plain.

2) Habitat quality distribution in the Weihe River Basin from 2000 to 2020 showed significant terrain gradient effects, generally increasing with terrain gradient. Low habitat quality was extensively distributed in low terrain gradient zones with severe degradation, while high terrain gradient zones were dominated by high habitat quality with stable growth trends.

3) Land use type was the primary influencing factor for spatial differentiation of habitat quality in the Weihe River Basin, followed by rainfall and temperature, while population density had the weakest effect. Natural factors had a greater influence on habitat quality than socioeconomic factors. The interaction of any two factors was stronger than single-factor effects, indicating that the spatial differentiation pattern of habitat quality is comprehensively influenced by multiple factors.

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