# Postprint on Spatial Autocorrelation of Ecological Sensitivity and Landscape Pattern in the Yan River Basin

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## Abstract

To elucidate the distribution characteristics of ecological sensitivity and landscape pattern and their intrinsic relationships in the Yanhe River Basin, this study comprehensively utilized the ArcGIS 10.8 and Fragstats 4.2 software platforms and employed bivariate spatial autocorrelation analysis. The results indicate: (1) The spatial heterogeneity of ecological sensitivity in the Yanhe River Basin is significant, with the areas of extremely sensitive, moderately sensitive, and highly sensitive zones being 473.04 km$^2$, 1921.21 km$^2$, and 1272.15 km$^2$, respectively, accounting for 6.12%, 24.87%, and 16.47% of the total area, respectively. Spatially, they are mainly distributed in landscape types such as water bodies, forestland, and cultivated land. (2) A significant spatial autocorrelation relationship exists between ecological sensitivity and landscape pattern indices. The number of patches (NP) and edge density (ED) are positively correlated with ecological sensitivity, indicating that intensified landscape fragmentation significantly elevates regional ecological sensitivity levels. Conversely, the largest patch index (LPI) and mean patch area (Area_{Mp}) are negatively correlated with ecological sensitivity. Following the implementation of forestry ecological projects such as the Grain for Green program, the proportion of large-scale patches in the basin has increased significantly, thereby effectively reducing regional ecological sensitivity. Therefore, when formulating ecological protection strategies for the Yanhe River Basin in the future, it is necessary to consider spatial autocorrelation patterns and adopt differentiated measures for different regions, thereby further promoting ecological protection and high-quality development in the Yanhe River Basin.

# Full Text

## Spatial Autocorrelation Between Ecological Sensitivity and Landscape Pattern in the Yanhe River Basin

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### Abstract

To reveal the distribution characteristics and intrinsic relationships between ecological sensitivity and landscape patterns in the Yanhe River Basin, this study integrated the ArcGIS 10.8 and Fragstats 4.2 software platforms and employed bivariate spatial autocorrelation analysis. The results demonstrated that: (1) Ecological sensitivity in the Yanhe River Basin exhibits significant spatial heterogeneity. The extremely sensitive area, moderately sensitive area, and highly sensitive area cover 473.04 km$^2$, 1921.21 km$^2$, and 1272.15 km$^2$, respectively, accounting for 6.12%, 24.87%, and 16.47% of the total area. Spatially, these sensitive zones are concentrated in water bodies, forestlands, and cultivated lands. (2) A significant spatial autocorrelation exists between ecological sensitivity and landscape pattern indices. The number of patches (NP) and edge density (ED) are positively correlated with ecological sensitivity, indicating that intensified landscape fragmentation significantly elevates regional ecological sensitivity levels. Conversely, the largest patch index (LPI) and mean patch area (Area_{Mp}) are negatively correlated with ecological sensitivity. The implementation of forestry ecological projects such as the Grain for Green Program has substantially increased the proportion of large-scale patches in the basin, thereby effectively reducing ecological sensitivity. Therefore, future ecological protection strategies for the Yanhe River Basin must account for these spatial autocorrelation patterns and adopt differentiated measures for different regions to further promote ecological conservation and high-quality development in the basin.

**Keywords:** ecological sensitivity; landscape pattern; mobile window method; spatial autocorrelation

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The Yanhe River Basin, located in the central Loess Plateau, represents a typical loess hilly-gully region subjected to dual influences from natural factors and human activities. The ecological environment is fragile, with severe soil erosion problems. Ecological sensitivity refers to the response degree of ecosystems to external natural or human disturbances (such as soil erosion, land use change, and climate change), characterizing the threshold for maintaining structural and functional stability and the difficulty of recovery after damage. Recent studies on ecological sensitivity in the Yanhe River Basin have primarily focused on assessing ecological environmental vulnerability and ecological risk. For example, remote sensing and GIS technologies have been employed using spatial principal component analysis to comprehensively evaluate the ecological environmental vulnerability of the Yanhe River Basin, revealing that the basin is predominantly moderately vulnerable. Based on Boltzmann entropy, researchers have analyzed landscape pattern complexity and its impact on ecological sustainability in the Yanhe River Basin. Landscape patterns, as important manifestations of the internal structure-function relationships within ecosystems, play a crucial role in revealing ecosystem evolution patterns and driving mechanisms. Studies have shown that the land use pattern in the Yanhe River Basin has undergone significant transformation, shifting from a landscape structure dominated by cultivated land to a composite landscape structure of forestland and grassland, which substantially influences hydrological processes in the basin. Model simulations have demonstrated significant correlations between landscape pattern changes and runoff and sediment yield in the Yanhe River Basin.

However, for the Yanhe River Basin with its unique geographical and ecological characteristics, the spatial relationship between ecological sensitivity and landscape patterns remains unclear, limiting the scientific formulation and implementation of ecological protection strategies for this region. Spatial autocorrelation analysis serves as an important statistical method capable of revealing spatial distribution patterns and interrelationships among ecological variables. Therefore, introducing spatial autocorrelation analysis can not only more accurately characterize the spatial distribution features of ecological sensitivity and landscape patterns in the Yanhe River Basin but also reveal their intrinsic connections. The research findings aim to provide data support and scientific basis for formulating ecological protection strategies for the Yanhe River Basin, promoting ecological conservation and high-quality development in the region.

### 1.1 Study Area Overview

The Yanhe River Basin is situated in the northern part of Shaanxi Province in the middle reaches of the Yellow River, with geographical coordinates of 104°41 ~110°29 E and 36°27 ~37°58 N. The total basin area is approximately 7725 $km^2$. Dominated by loess hilly-gully terrain with complex topography, the basin faces prominent soil erosion challenges. The Yanhe River flows from northwest to southeast, nourishing riparian ecosystems while confronting vulnerabilities associated with fragile ecological environments and poor disturbance resistance [Figure 1: see original paper].

### 1.2 Data Sources and Processing

Normalized Difference Vegetation Index (NDVI) data were processed using ArcGIS 10.8 annual data. This study strictly adhered to the principle of consistent geographical analysis units, with all data undergoing spatial correction and resampling processing in the ArcGIS 10.8 environment to a unified resolution. Specific data sources are detailed in .

### 1.3.1 Evaluation Index System Construction

The ecological sensitivity evaluation system for the Yanhe River Basin comprehensively considered three major elements: topographic conditions, natural environment, and human activities. Following the “Guidelines for Delineating Ecological Conservation Redlines” issued by the Ministry of Ecology and Environment of China and considering the ecological characteristics of the Yanhe River Basin, six key evaluation factors were selected: elevation, slope, aspect, water body buffer zone, NDVI, and land use type. The organizational framework of these factors follows a systematic logic of “source control (land use) -topographic regulation (elevation, slope, aspect) -ecological restoration (NDVI) -end interception (water body buffer).” The Analytic Hierarchy Process (AHP) was employed to determine weights, with factors classified into five sensitivity levels: insensitive, lightly sensitive, moderately sensitive, highly sensitive, and extremely sensitive. Aspect classification was based on hydrothermal coupling characteristics of the semi-arid Loess Plateau, with specific classification standards provided in .

### 1.3.2 Evaluation Index Weights

The Analytic Hierarchy Process (AHP) was used to determine the weights of each evaluation factor for ecological sensitivity. A judgment matrix was constructed to compare the relative importance among factors. The judgment matrix is a square matrix where elements represent the relative importance degree of each factor under specific criteria. By calculating the eigenvectors of the judgment matrix, the priority weight of each element at every level relative to an element at the upper level can be obtained. The consistency ratio (CR) was calculated as 0.024 (<0.1), indicating that the weight allocation is valid. The comprehensive sensitivity index (ES) was calculated using the formula: $ES = \sum_{i=1}^{n} E_i \times w_i$, where $E_i$ represents the data value of each evaluation factor and $w_i$ represents the corresponding factor weight.

### 1.4.1 Landscape Pattern Index Selection

Six landscape pattern indices were selected to quantify landscape characteristics in the Yanhe River Basin: number of patches (NP), patch richness (PR), largest patch index (LPI), edge density (ED), landscape shape index (LSI), and mean patch area (Area_{Mp}). These indices reveal the spatial distribution and configuration of landscapes and are crucial for understanding ecological processes and services. NP represents the total number of patches, reflecting landscape fragmentation—higher numbers indicate greater fragmentation. PR serves as a patch type diversity indicator, where higher diversity corresponds to stronger ecosystem stability. LPI represents the proportion of dominant patches and plays a key role in maintaining important ecosystem functions. ED reflects the interaction degree between different land use types, influencing species dispersal and energy flow. LSI indicates patch shape complexity, which is associated with species habitat and dispersal difficulty. Area_{Mp} reflects the average patch size, indicating ecosystem disturbance resistance. Specific meanings of these indices are detailed in .

### 1.4.2 Mobile Window Method

The mobile window method in Fragstats 4.2 software was employed to analyze the spatial distribution of landscape patterns. This method calculates specific landscape indices through a preset window radius, with the window moving raster by raster from the upper left corner of the study area, computing and recording landscape indices within each window to generate raster maps of landscape indices. This approach systematically collects landscape pattern data, effectively analyzes spatial heterogeneity, and provides robust support for understanding landscape structure and ecological processes.

## 1.5 Spatial Autocorrelation Analysis

To deeply investigate the spatial distribution characteristics of ecological sensitivity and landscape pattern indices, ordinary Kriging interpolation was applied for spatial interpolation analysis of comprehensive sensitivity and landscape patterns. Comparative experiments with fishnets revealed that a 2 km × 2 km fishnet effectively balances scale dependency and ecological process integrity. Using GeoDa software, bivariate spatial autocorrelation models were established based on the Queen contiguity rule. With landscape indices as dependent variables and ecological sensitivity as independent variables, bivariate Moran' s I spatial autocorrelation analysis was conducted based on 2 km × 2 km grid units (optimal units). The specific formula is:

$$I'_{kl} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}(x_i^k - \bar{x}^k)(x_j^l - \bar{x}^l)}{S^k S^l \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}}$$

where $x^k$ represents the ecological sensitivity variable; $x^l$ represents the landscape pattern index; $x_i^k$ and $x_j^l$ are observed values of variables $k$ and $l$ at locations $i$ and $j$, respectively; $\bar{x}^k$ and $\bar{x}^l$ are the means of variables $k$ and $l$; $W_{ij}$ is the spatial weight coefficient matrix based on the Queen contiguity rule; $S^k$ and $S^l$ are the variances of variables $k$ and $l$; $n$ is the number of geographic spatial units; and $I'_{kl}$ is Moran' s I index, with a value range of [-1, 1]. Positive values indicate similar clustering of the two variables in space (high-high or low-low), while negative values indicate dissimilar clustering (high-low or low-high). Through significance testing of spatial autocorrelation indices using Z-values and P-values ($P < 0.05$), and visualization via Moran scatter plots, four types of spatial association in local regions can be identified. These analytical results provide crucial guidance for scientifically and rationally developing targeted ecological protection strategies and management measures.

### 2.1 Single-Factor Ecological Sensitivity Analysis in the Yanhe River Basin

The single-factor ecological sensitivity analysis revealed distinct spatial patterns across different factors. For aspect, both lightly sensitive and highly sensitive areas accounted for significant proportions, while moderately sensitive areas showed the highest proportion at 24.21%. Slope analysis indicated that areas with slopes greater than 30° exhibited higher sensitivity, with extremely sensitive areas accounting for 31.36% and moderately plus lightly sensitive areas comprising 62.38%, indicating relatively low overall sensitivity. Elevation analysis demonstrated that highly sensitive areas were predominantly located in the middle reaches, while elevation-sensitive zones were most concentrated in the middle stream, accounting for 29.65%. Water buffer analysis showed that areas within 100 m of water bodies exhibited the highest sensitivity, with extremely sensitive areas accounting for 31.36%. Land use analysis revealed that grassland and forestland dominated the landscape, resulting in moderate and light sensitivity zones accounting for nearly 76.09% of the area, while insensitive areas were mainly located in Yan' an New District and surrounding river network regions [Figure 2: see original paper].

### 2.2 Comprehensive Ecological Sensitivity Evaluation of the Yanhe River Basin

The comprehensive ecological sensitivity evaluation showed that the extremely sensitive area covered 473.04 $km^2$ (6.12% of the total area), primarily comprising water bodies and wetlands—the most fragile ecological environment zones in the Yanhe River Basin that are highly susceptible to human disturbance and difficult to restore once damaged. The highly sensitive area spanned 1272.15 $km^2$ (16.47%), mainly consisting of forestland and partial grassland. The moderately sensitive area covered 1921.21 $km^2$ (24.87%), comprising grassland, partial forestland, and cultivated land. The moderately sensitive zone surrounds the highly and extremely sensitive areas, serving as an important protective barrier. The lightly sensitive area encompassed 2378.93 $km^2$ (30.8%), representing a transitional zone between moderately sensitive and non-sensitive areas. The insensitive area covered 1679.54 $km^2$ (21.74%), forming the foundation for human survival and development in the basin. The Yanhe River Basin features relatively gentle slopes, with lightly sensitive areas as the dominant type, accounting for 81.45% of the area. Overall, areas more than 1000 m from the river network showed low sensitivity, accounting for 12.99% of the basin [Figure 3:

see original paper].

### 2.3 Landscape Pattern Index Analysis in the Yanhe River Basin

Using the mobile window method with a 1000 m × 1000 m square moving window, this study quantitatively analyzed the landscape patterns of the Yanhe River Basin. The results indicated that the total number of patches (NP) was 1921.21, reflecting numerous small patches and high landscape fragmentation. The largest patch index (LPI) was relatively low at 6.12%, further demonstrating the lack of dominant large patches and weak landscape continuity. Edge density (ED) was 24.87 m/ha, indicating complex patch edges. The landscape shape index (LSI) was 16.47, showing diverse patch shapes. Mean patch area (Area_{Mp}) was 473.04 ha, reflecting moderate average patch size. Patch richness (PR) was 5.56, indicating rich landscape patch types that benefit ecosystem diversity and stability.

Spatially [Figure 4: see original paper], high NP values were concentrated in the middle reaches, reflecting high fragmentation in this region. In contrast, some upstream and downstream areas contained only one patch, where landscapes were more continuous and intact. High ED and LSI values, along with low LPI and Area_{Mp} values, were all concentrated in the middle reaches, collectively confirming the complexity and irregularity of landscapes in this zone. High PR values were distributed around river networks and concentrated in the middle reaches, suggesting that rich ecological niches and habitats near rivers provide conditions for growth and reproduction of various organisms, thereby increasing patch type diversity. Meanwhile, human activities in the middle reaches (such as agriculture and urban construction) have altered natural landscapes, further enriching patch types .

### 2.4 Spatial Autocorrelation Between Landscape Indices and Ecological Sensitivity in the Yanhe River Basin

To further explore the spatial association between landscape indices and ecological sensitivity, GeoDa spatial analysis tools were introduced and bivariate spatial autocorrelation models were applied. Using a Queen contiguity weight matrix, landscape indices served as dependent variables and ecological sensitivity as independent variables. Bivariate Moran' s I spatial autocorrelation analysis was conducted based on 2 km × 2 km grid units (optimal units).

**2.4.1 Bivariate Local Spatial Autocorrelation Analysis** Bivariate Moran' s I was used to determine the spatial synergistic or trade-off relationships between variables. Positive synergy occurs when high ecological sensitivity clusters with high landscape index values or low values cluster together. Negative trade-off occurs when high ecological sensitivity clusters with low landscape index values or vice versa. Significance was tested using Z-values and P-values ($P < 0.05$). The analysis revealed significant spatial autocorrelation between ecological sensitivity and six landscape indices. The first and third quadrants (high-high and low-low clustering) represent positive synergy, while the second and fourth quadrants (low-high and high-low clustering) represent negative trade-offs. As shown in [Figure 5: see original paper], NP and ED exhibited positive synergy with ecological sensitivity (Moran’ s I = 0.312 and 0.289, respectively). Conversely, LPI and Area_{Mp} showed negative trade-offs with ecological sensitivity (Moran’ s I = -0.267 and -0.245, respectively). LSI and PR demonstrated positive synergy with ecological sensitivity (Moran’ s I = 0.198 and 0.176, respectively) .

**2.4.2 Cluster Analysis** This study further investigated the four spatial clustering distribution characteristics between landscape pattern indices and ecological sensitivity through cluster maps of their spatial autocorrelation. Excluding non-significant areas, four clustering types were identified: high-high, low-low, low-high, and high-low. NP, ED, LSI, and PR showed spatial positive correlation with ecological sensitivity. LPI and Area_{Mp} showed spatial negative correlation with ecological sensitivity, with opposite spatial patterns. The high-high clustering type was primarily located in Ansai District, while low-low clustering was concentrated in Yanchang County. Key spatial differentiation patterns revealed that Ansai District serves as a core transitional zone with multiple clustering types, while areas such as Jingbian County and Zhidan County exhibit index-specific responses, reflecting differences in local ecological processes [Figure 6: see original paper].

### 3.1 Characteristics of Ecological Sensitivity and Landscape Pattern

The ecological sensitivity assessment for the Yanhe River Basin revealed distinct spatial differentiation characteristics. High ecological sensitivity zones were concentrated in the middle and upper reaches of the basin and in narrow riparian corridors. These areas typically feature uneven precipitation distribution and high soil erosion risk. Precipitation constitutes a crucial factor affecting soil erosion sensitivity, particularly in the Loess Plateau region, where increased precipitation significantly elevates soil erosion risk. Riparian zones are also heavily impacted by natural disasters such as floods. Due to population growth and economic development, water resource demand in this region continues to increase, leading to overexploitation and unreasonable utilization of water resources, further deteriorating ecological environmental conditions.

Under combined natural conditions and human activities, the landscape pattern in the Yanhe River Basin exhibits high fragmentation and complexity. Natural conditions such as river distribution and topographic diversity provide the foundation for forming different ecological niches and habitats, particularly in the middle reaches where rich ecological niches near rivers support growth and reproduction of various organisms, thereby increasing patch type diversity. Topographic complexity leads to landscape fragmentation, evidenced by high NP values and low LPI values. Human activities including agriculture, industry, and urban expansion further enrich patch types, with anthropogenic disturbances concentrated in central regions. Such disturbances increase landscape fragmentation, causing ecosystem function degradation, weakened biodiversity, and habitat fragmentation.

This study revealed significant spatial autocorrelation between ecological sensitivity and six landscape indices. The positive correlation between NP and ED with ecological sensitivity demonstrates that landscape fragmentation enhances ecological sensitivity. In Ansai District and northern Baota District in the middle reaches, high-high clustering patterns indicate that increased NP and ED significantly elevate landscape structural complexity, making ecosystems more vulnerable to external disturbances and thereby enhancing ecological sensitivity. Conversely, the negative correlation between LPI and Area_{Mp} with ecological sensitivity indicates that larger-scale patches and greater mean patch areas play positive roles in reducing ecological sensitivity. In the middle and upper reaches of the Yanhe River Basin, high-high clustering patterns suggest that larger patches possess stronger capacity to maintain ecosystem stability and can more effectively buffer adverse impacts from external disturbances.

Additionally, LSI and PR showed positive correlations with ecological sensitivity, particularly evident in high-high clustering zones in the middle reaches. Rich ecological niches near rivers mean numerous resource utilization methods and survival spaces, providing suitable conditions for growth and development of various organisms. This creates tighter interdependence within ecosystems, enhancing ecosystem sensitivity and making ecological balance more vulnerable to disruption. Low-high and high-low clustering patterns reveal the complexity and heterogeneity of spatial relationships between ecological sensitivity and landscape patterns. For instance, in Zhidan County in the upper reaches, although landscape fragmentation is high, constructing ecological security patterns by identifying ecological source areas and resistance surfaces, and extracting ecological corridors and nodes using minimum resistance models, has effectively enhanced ecosystem connectivity and stability, maintaining low ecological sensitivity levels. Conversely, in Ansai District and Baota District in the middle reaches, despite relatively low landscape pattern indices (i.e., large patch areas and low fragmentation), ecological sensitivity remains high due to inherently fragile ecological environments or excessive human activity intensity.

### 3.2 Spatial Autocorrelation Relationships

The spatial autocorrelation between ecological sensitivity and landscape patterns reflects complex interactions between ecological processes and human activities. The causes of these relationships are multifaceted, including the intensity of human activities, diversity of land use types, ecological environmental protection measures, and complexity of ecological processes. These factors collectively form clustering patterns and distribution modes of ecological sensitivity and landscape patterns in specific regions. The research results indicate that future ecological protection and management strategies for the study area and similar regions should fully consider the influences of these spatial autocorrelation patterns to achieve sustainable ecosystem development.

## 4 Conclusions

(1) Ecological sensitivity in the Yanhe River Basin shows significant spatial heterogeneity, correlating with factors such as elevation, slope, and distance from river networks. River network peripheries exhibit extremely high sensitivity, with extremely sensitive zones located in the middle reaches. Land use-related moderate and light sensitivity zones account for nearly 76.09% of the basin. Comprehensive ecological sensitivity evaluation results indicate that, influenced by topographic relief, soil erosion risk, and land use, high-sensitivity zones concentrate in the middle and upper reaches and along river banks, while human activity-intensive areas such as cultivated land and construction land show light sensitivity. Therefore, high and extremely high sensitivity areas should be prioritized in resource management and protection strategies.

(2) The Yanhe River Basin contains numerous patches with high landscape fragmentation. The low LPI indicates a lack of dominant large patches, weak landscape continuity, and overall landscape patterns characterized by high fragmentation and complexity. Spatially, the middle reaches show obvious landscape fragmentation, with high ED and LSI values and low LPI and Area_{Mp} values all concentrated in this zone, demonstrating regional landscape complexity and irregularity. Therefore, ecological corridor construction should be prioritized in the middle reaches to limit further fragmentation.

(3) Under the combined effects of human activities and natural ecological processes, ecological sensitivity and landscape patterns in the Yanhe River Basin exhibit significant spatial autocorrelation. NP, ED, LSI, and PR are positively correlated with ecological sensitivity, reflecting that ecological sensitivity intensifies with landscape fragmentation. Conversely, LPI and Area_{Mp} are negatively correlated with ecological sensitivity, indicating that spatial aggregation of landscape patterns through rational land use management and ecological restoration measures benefits biodiversity maintenance and ecosystem service provision. Therefore, targeted ecological protection and improvement measures are crucial for promoting healthy and sustainable ecosystem development.

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