Spatiotemporal Variation and Scale Dependence of Landscape Diversity in the Yellow River Oases of Ningxia: Postprint

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Abstract

The Landscape Diversity Index (LDI) is not only an important indicator in landscape ecology research, but also a crucial component in biodiversity conservation. Based on land use raster data (30 m resolution), the spatiotemporal variation and scale-dependent characteristics of LDI in the Ningxia Yellow River Oasis were investigated using the Neighborhood and Fo cal tools in the ArcMap environment. The results indicate that: (1) Repeated statistical analysis across five periods for basic unit (square) side lengths ranging from 90 to 6000 m demonstrates that the landscape in the Ningxia Yellow River Oasis exhibits distinct scale-dependent characteristics in space, with a turning point at 3000 m. (2) Over the past 50 years, LDI changes in the study area have exhibited periodicity, with the year 2000 serving as a turning point. Specifically, from 1975 to 2000, LDI showed a decreasing trend, and LDI zoning analysis revealed that the primary characteristics were the largest class area (CA) in degradation zones and the smallest CA in improvement zones, at 6840 km2 and 1332 km2, respectively. From 2000 to 2020, LDI exhibited an increasing trend, characterized by the largest CA in stable zones and the smallest CA in degradation zones, at 7848 km2 and 792 km2, respectively; since the initial LDI in this period (year 2000) was the lowest, the degree of later improvement in LDI did not reach the level of the earlier period. (3) LDI hierarchical area conversion was primarily characterized by the transfer from early-stage improvement zones to later-stage stable zones (796 km2, accounting for 60.5% of the improvement zones) and the transfer from degradation zones to stable zones (3519 km2, accounting for 51.5% of degradation zones) and improvement zones (3036 km2, accounting for 44.4% of degradation zones). (4) The pattern of landscape diversity change is characterized by a negative correlation between CA and the Relative Splitting Index (RSI), and this relational mechanism demonstrates universality across different periods and change types. Overall, identifying the turning points of analytical

indicators on spatiotemporal scales in regional landscape change research is not only a necessary condition for ensuring that research results are referential and shareable, but also forms the basis for the visualization and analysis of regional landscape diversity.

Full Text

Abstract

The landscape diversity index (LDI) is not only a crucial metric in landscape ecology research but also an important component of biodiversity conservation. Based on land use/cover raster data (30-m resolution), this study investigated the spatiotemporal variation and scale-dependent characteristics of landscape diversity in the oasis along the Yellow River in Ningxia using Neighborhood and Focal tools in ArcMap from 1975 to 2020. The results indicate: (1) The LDI exhibited significant spatial scale dependence across five analytical periods, with a turning point identified at 3000 m. (2) The temporal trend of LDI showed cyclical changes, with 2000 serving as the turning point. During 1975–2000, LDI demonstrated a decreasing trend, with zoning analysis revealing that the degraded area had the largest class area (CA) at 6840 km^2, while the improved area had the smallest CA at 1332 km^2. Conversely, during 2000–2020, LDI showed an increasing trend, characterized by the maximum CA in the stable area (7848 km^2) and the minimum CA in the degraded area (792 km^2). Because the initial LDI in 2000 was the lowest across the entire study period, the degree of improvement in the later period did not reach the level of the early period. (3) The conversion of LDI-graded areas was primarily characterized by transfers from the early improved area to the later stable area (796 km^2, accounting for 60.5% of the improved area) and from the degraded area to the stable area (3519 km^2, 51.5% of the degraded area) and improved area (3036 km^2, 44.4% of the degraded area). (4) Changes in landscape diversity patterns featured a negative correlation between CA and the relative splitting index (RSI), a relationship mechanism that proved universal across different periods and change types. Overall, identifying turning points in the spatiotemporal scales of analytical indicators is essential for ensuring that research results are both referential and shareable, and it also forms the basis for visualizing and analyzing regional landscape diversity.

Keywords: landscape diversity index; landscape pattern; scale effect; oasis along the Yellow River in Ningxia

1 Study Area Overview

The oasis along the Yellow River in Ningxia (37°20 -39°20 N, 105°00 -107°00 E) is located in the northern part of the Ningxia Hui Autonomous Region, extending from Shizuishan in the north to the Loess Plateau in the south, reaching the Ordos Plateau in the east, and bordering the Helan Mountains in the west, covering an area of 10,831.3 km^2. The core area of the Ningxia Yellow River oasis consists of artificial irrigation regions—the Weining irrigation district and the Yinchuan irrigation district—connected by the Yellow River, with oasis areas accounting for 56.3% of the total area. The study area is characterized by dense lakes and wetlands, with extensive artificial irrigation canals including the East Main Canal, West Main Canal, Hanyan Canal, and Tanglai Canal. The dominant soils are anthropogenic irrigation-silt soils and meadow soils, while natural vegetation primarily consists of *Elaeagnus angustifolia* forests and scattered wetland shrubs along the Yellow River. Key plant species include *Elaeagnus angustifolia*, *Lycium chinense*, *Tamarix chinensis*, and *Phragmites australis*. This region represents the core area of the national Yellow River Economic Zone and a key zone in China' s ecological function regionalization.

2 Data and Methods

2.1 Data Sources

The analysis years selected for this study were 1975, 1990, 2000, 2010, and 2020. Land use/cover data were obtained from two sources: (1) the 30-m resolution national land use dataset for the 1980s-2015 interpreted from Landsat MSS/TM/ETM+/OLI satellite remote sensing data by the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, and (2) Landsat MSS remote sensing data downloaded by the research team in 1975 from https://earthexplorer.usgs.gov, interpreted with guidance from Ningxia Academy of Agriculture and Forestry Sciences experts and field validation surveys. The original land use types were integrated into eight categories: farmland, forestland, shrubland, grassland, wetland, water body, artificial surface, and bare land, with an overall interpretation accuracy (Kappa coefficient) exceeding 85%.

2.2 Methodology

2.2.1 Study Area Boundary Delineation The boundary was determined using the elevation at the highest water diversion points in the Weining irrigation district (Shapotou Headworks) and Yinchuan irrigation district (Qingtongxia Headworks) as limiting conditions. The "Reclassify" command in ArcGIS was applied for preliminary classification of digital elevation data, generating multiple patches. Subsequently, farmland, wetland, and water body classes from multi-year land use data were used as buffer sources, and positive/negative buffer analysis was performed using the "Buffer" command in ArcGIS to finalize the Ningxia oasis boundary.

2.2.2 Landscape Metrics Four landscape metrics were selected for analysis: class area (CA), largest patch index (LPI), relative splitting index (RSI), and landscape diversity index (LDI). The formulas are as follows:

- **Class Area (CA):** $CA_j = \sum_{i=1}^{n} a_{ij}$, where a_{ij} is the area of patch i in land use class j, and n is the number of patches in class j.

- **Largest Patch Index (LPI):** $LPI_j = \frac{\max(a_{ij})}{A} \times 100\%$, where $\max(a_{ij})$ is the area of the largest patch in class j, and A is the total area of the study area or analysis unit.
- **Relative Splitting Index (RSI):** $RSI_j = 100 \times \left(\frac{CA_j}{CA_j + \sum_{i \neq j} CA_i}\right)$, where CA_j is the area of class j. RSI emphasizes comparability among different patch types, ranging from 0-100%, with higher values indicating greater fragmentation.
- **Landscape Diversity Index (LDI):** Borrowing from the Shannon-Weiner diversity index, $LDI = -\sum_{j=1}^{m} P_j \times \ln(P_j)$, where P_j is the proportion of class j in the analysis unit, and m is the number of land use types.

2.2.3 LDI Classification and Scale Analysis Given the eight land use types, spatial scale determination began at 90 m × 90 m to ensure the minimum analysis scale contained all types. To reduce computational load, the scale increased by integer multiples: 90 m × 90 m, 300 m × 300 m, 600 m × 600 m, 900 m × 900 m, 1200 m × 1200 m, 1500 m × 1500 m, 3000 m × 3000 m, 4500 m × 4500 m, and 6000 m × 6000 m. The analysis employed the Block Statistics command in ArcMap to calculate the relative area (P_j) of each land use type within each scale unit, with final calculations performed using the LDI formula. LDI classification followed the mean-standard deviation method, dividing the index into five levels: very low, low, medium, high, and very high. Temporal change analysis involved subtracting LDI levels between different years: positive values indicated improvement, negative values indicated degradation, and zero indicated stability. Statistical analyses were conducted in R, with significance tested using F-tests ($P < 0.05$ for significance, $P < 0.01$ for high significance).

3 Results and Analysis

3.1 Temporal Change and Scale Dependence of Landscape Diversity

From 1975 to 2020, LDI exhibited a decreasing trend from 1975 to 2000, followed by an increasing trend from 2000 to 2020, forming an inverted parabola that was not statistically significant ($P = 0.590$). The scale dependence analysis revealed consistent patterns across all five years, with a significant quadratic relationship ($P < 0.001$) and a turning point at 3000 m. When the analysis scale was smaller than 3000 m, LDI increased steeply; beyond this threshold, the increase leveled off. Therefore, 3000 m × 3000 m was identified as the optimal scale for landscape diversity analysis in this region.

3.2 Temporal Characteristics of LDI Classification Patterns

Based on the optimal 3000 m × 3000 m scale, LDI patterns across the five years were analyzed. The year 2000 marked a turning point in landscape diversity change. During 1975-2000, the degraded area dominated with the largest

CA (6840 km^2), while the improved area had the smallest CA (1332 km^2). In contrast, during 2000-2020, the stable area had the maximum CA (7848 km^2), and the degraded area had the minimum CA (792 km^2). The spatial pattern evolution showed that high-value areas were predominantly low-value areas before 2000 but shifted toward equilibrium thereafter, though high-value areas remained relatively small while low-value areas remained large.

3.3 Landscape Diversity Classification Patterns and Spatial Conversion

Temporal analysis identified 2000 as the key transition year. To simplify the analysis, two periods (1975-2000 and 2000-2020) were examined. The conversion characteristics revealed that: (1) 796 km^2 of the early improved area (60.5%) transferred to the later stable area; (2) 3519 km^2 of the degraded area (51.5%) transferred to the stable area, and 3036 km^2 (44.4%) transferred to the improved area; (3) 3533 km^2 of the stable area (80.1%) remained unchanged. Other conversion types accounted for less than 12.5% of their respective source areas.

The landscape pattern composition showed distinct characteristics: the 1975 degraded area, despite its large spatial extent, contained only 0.18% of total patches, indicating dominance by a few large patches. Similarly, the 2020 stable area, with the largest CA (7848 km^2), contained only 0.12% of patches. In contrast, the smallest areas (2020 degraded area and 1975 improved area) exhibited the highest and lowest patch densities (35.48% and 0.52%, respectively), demonstrating an inverse relationship between CA and RSI that was consistent across all periods and change types.

4 Discussion

The selection of an appropriate analysis scale is critical in landscape pattern research. With the widespread use of medium-high resolution data (2.5 m × 2.5 m to 30 m × 30 m), landscape complexity has become a major confounding factor. The mean-standard deviation classification method effectively simplified LDI expression while reflecting hierarchical theory. The inverse CA-RSI relationship was universal across different periods and change types, with correlation coefficients of -0.192 in high-value areas, -0.023 in medium-value areas, and -0.045 in low-value areas, indicating stronger negative correlations at higher diversity levels.

The temporal trend of LDI in Ningxia' s Yellow River oasis was primarily driven by farmland expansion, urbanization, and ecological restoration. Farmland area peaked at 6700.7 km^2 in 2000, coinciding with the lowest LDI, confirming that agricultural expansion was a primary driver of landscape diversity change. This highlights the importance of identifying temporal turning points for segmenting analysis periods when statistical trend analysis is impractical due to limited data.

Scale effect analysis of five years of data revealed that for artificial oases in arid/semi-arid regions along rivers, with eight land use classes, the optimal analysis unit is approximately 3000 m × 3000 m. Further analysis showed that increasing the scale to 6000 m × 6000 m only increased LDI by 0.18-0.22%, while decreasing to 1500 m × 1500 m reduced LDI by 4.24-4.71%. Researchers studying similar oases can thus use 3000 m × 3000 m as a reference scale, adjusting according to oasis size.

A cautionary note: when using the Splitting Index (SI) in Fragstats software, results may occasionally contradict the theoretical definition ($1 < \mathrm{SI} \leq$ number of patches), a problem still observed in recent studies. Therefore, careful verification is recommended.

5 Conclusions

Identifying spatiotemporal turning points for analytical indicators is essential for ensuring that regional landscape change research produces referential, shareable results and enables visualization and analysis of landscape diversity. Based on this study of the Ningxia Yellow River oasis:

1) LDI exhibits significant spatial scale dependence, with a turning point at approximately 3000 m. Repeated analysis of five years confirms that 3000 m × 3000 m is the optimal scale; similar studies can use this as a reference and conduct simplified analyses around this scale according to oasis size.

2) Temporally, LDI showed a decreasing trend during 1975-2000 and an increasing trend during 2000-2020. The pattern was characterized by degraded areas having the largest CA and improved areas the smallest during the first period, while the second period showed the opposite pattern. Because the initial LDI in 2000 was the lowest in the study period, the later improvement did not reach the early period’ s level.

3) LDI-graded area conversion was dominated by transfers from early improved areas to later stable areas (60.5% of improved area) and from degraded areas to stable areas (51.5% of degraded area) and improved areas (44.4% of degraded area).

4) Landscape diversity pattern changes were universally characterized by a negative correlation between CA and RSI across different periods and change types.

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