Comprehensive Assessment of Land Ecological Quality in the Yellow River Basin Based on Grid GIS: Postprint

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Abstract

Using 8 km$×$8 km grid cells as evaluation units, a land ecological quality evaluation system was constructed from four perspectives: landscape characteristics of land ecosystems, habitat quality and anti-interference capacity, ecosystem service value, and socio-economic benefits. Weights were determined using the Analytic Hierarchy Process and entropy method, and spatial differentiation patterns of land ecological quality in the Yellow River Basin were investigated through spatial autocorrelation, hot and cold spot analysis, and obstacle degree diagnostic model. The results show that: (1) The land ecological quality in the Yellow River Basin exhibits a spatial pattern of higher quality in the central and southwestern regions, moderate quality in the southeastern and northeastern regions, and lower quality in the northwestern region; the overall land ecological quality is relatively low, with critical safety and dangerous areas accounting for 31.4% and 27.7%, respectively. (2) The spatial autocorrelation of land ecological quality in the Yellow River Basin is high; hot spots are mainly distributed in the Loess Plateau and Mu Us Sandy Land ecological protection areas with high governance intensity, while cold spots are distributed in the northwestern part of the basin; governance of land ecology in the upstream region should be appropriately strengthened to eliminate extreme cold spots. (3) The main obstacle factors for land ecological quality in the Yellow River Basin are economic density, land use structure diversity, distance from ecological protection areas, and distance from water bodies; management should be based on regional natural conditions and resource endowments, accelerate green innovation-driven development, transform abundant natural resources, biological resources, and historical and cultural resources into market value, rationally configure artificial ecosystem structures during ecological restoration and renovation, and establish additional nature reserves when necessary.

Full Text

Comprehensive Evaluation of Land Ecological Quality in the Yellow River Basin Based on Grid-GIS

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Abstract: Using 8 km × 8 km grids as evaluation units, this study constructs a land ecological quality evaluation system from four perspectives: landscape characteristics of land ecosystems, habitat anti-interference capacity, ecosystem service value, and socio-economic benefits. The analytic hierarchy process and entropy method were employed to determine indicator weights. Through spatial autocorrelation, hot/cold spot analysis, and obstacle degree diagnosis modeling, the spatial differentiation patterns of land ecological quality in the Yellow River Basin were investigated. Results indicate: (1) Land ecological quality in the Yellow River Basin exhibits a spatial pattern of relatively high quality in the central and southwestern regions, moderate quality in the southeast and northeast, and low quality in the northwest. The overall land ecological quality is relatively low, with critical safety and dangerous areas accounting for 31.4% and 27.7% of the total area, respectively. (2) The spatial autocorrelation of land ecological quality in the basin is strong. Hot spots are mainly distributed in the Loess Plateau and Maowusu Sandy Land ecological protection zones with intensive governance, while cold spots are concentrated in the northwestern part of the basin. Management of land ecology in upstream areas should be strengthened to eliminate extreme cold spots. (3) The main obstacle factors for land ecological quality are economic density, land use structure diversity, distance to ecological protection areas, and distance to water bodies. Policies should be based on regional natural conditions and resource endowments, accelerate green innovation-driven development, transform abundant natural, biological, and historical-cultural resources into market value, rationally allocate artificial ecosystem structures during ecological restoration and transformation, and establish additional nature reserves when necessary.

Keywords: Fragstats; Grid-GIS; land ecological quality; Yellow River Basin

1 Introduction

Land constitutes the material foundation for human survival and development, representing a complex system formed by the interaction of near-surface climate, landforms, geology, hydrology, soil, flora and fauna, and the results of past and present human activities. The suitability of these internal elements for human survival and sustainable development constitutes land ecological quality. With population growth and socio-economic development, land ecosystem degradation has intensified, exacerbating human-land conflicts. Scientific evaluation of land ecological quality has become an urgent challenge for sustainable land resource utilization in the 21st century.

Research on land ecological quality originated from Aldo Leopold’ s concept of “land health” in the 1940s. Early studies focused primarily on soil physicochemical properties and pollution conditions. Following the United Nations Food and Agriculture Organization’ s series of guidelines on land quality assessment in the 1970s, land ecological quality evaluation gradually gained attention. With the introduction of theories from landscape ecology and regional economics, the indicator system for land ecological quality has continuously improved, encompassing natural, economic, and social dimensions. Current research primarily focuses on exploring the connotation of land ecological quality, evaluation methods, land ecological suitability, land ecological vulnerability, land ecological security, land ecosystem health, and land ecological quality itself.

However, several issues persist: (1) No consensus has been reached on the connotation of land ecological quality and selection of evaluation indicators; (2) Overreliance on statistical data constrains research within administrative boundaries; (3) Standards and criteria for land ecological quality classification are lacking, requiring further investigation of ecological quality thresholds to enhance practical significance of classification.

Using administrative regions as evaluation units fails to adequately consider spatial heterogeneity, artificially severing natural geographical connections and obscuring internal variations within units. Grid-based evaluation units can overcome these limitations. The anti-interference capacity, resilience, and stability of land ecosystems are closely related to landscape heterogeneity and ecosystem service functions. Few studies have simultaneously integrated landscape characteristics, ecosystem service functions, ecological background, and economic attributes into land ecological quality evaluation systems, presenting an opportunity to explore their combined effects.

The Yellow River Basin serves as a crucial ecological barrier in northwestern China, characterized by water scarcity, prominent water environmental issues, and extremely fragile ecological conditions. The regions traversed by the river hold strategically important positions in national development. In September 2019, President Xi Jinping proposed the major national strategy of ecological protection and high-quality development in the Yellow River Basin. However, research on land ecological quality in this basin remains scarce. Addressing these gaps, this study employs grids as evaluation units to investigate spatial differentiation of land ecological quality in 2018 from four perspectives—landscape characteristics, habitat anti-interference capacity, ecosystem service functions, and socio-economic benefits—and proposes corresponding management measures to support sustainable land use and development in the Yellow River Basin.

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2 Study Area and Methods

2.1 Study Area Overview

The Yellow River Basin (96°-119°E, 32°-42°N) flows eastward through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong provinces, covering a total area of 7.46×10^5 km^2. The western region comprises the river source area with developed glacial landforms, extensive grassland degradation, and declining water conservation functions. The central region features loess landforms with fragmented terrain, severe soil erosion, and extremely fragile ecological environments. The eastern region consists mainly of alluvial plains with serious sediment deposition, frequent river channel shifts, and elevated riverbeds above ground level (Figure 1). The basin exhibits a continental climate, with arid conditions in the northwest, semi-arid in the central region, and semi-humid in the southeast. The basin' s water resources account for only 2% of the national total, yet support 15% of the country' s arable land and 12% of its population.

Figure 1. Topographic map of the Yellow River Basin [Figure 1: see original paper]

Note: This map is based on the standard map downloaded from the National Administration of Surveying, Mapping and Geoinformation Standard Map Service website (Approval No. GS(2019)1698), with no modifications to the base map. The same applies below.

2.2 Data Sources

This study utilized the following datasets: - Land use data, elevation data, and 2018 NDVI data from the Resource and Environment Science and Data Center (http://www.resdc.cn/) - Ecological protection zone data and water system distribution data from the National Earth System Science Data Center - Road network data from OpenStreetMap (https://www.openstreetmap.org/) - 2018 population, economic, and grain production data for cities in the Yellow River Basin from municipal statistical yearbooks - Spatialized population density data from WorldPop (https://www.worldpop.org/)

2.3 Indicator System Construction

Land represents a complex natural-socioeconomic composite with systematic and complex characteristics. Therefore, evaluation of land ecological quality must adopt a multi-dimensional, scientific selection of indicators based on land ecosystems as the object of study. Drawing upon the “Economy-Society-Nature” composite ecosystem model, this study establishes an indicator system from four perspectives: landscape characteristics of land ecosystems, habitat anti-interference capacity, ecosystem service functions, and socio-economic benefits of land use.

Landscape Pattern Characteristics: Landscape pattern reflects the coordination of land ecosystem structure and influences ecological processes. The spatial distribution of landscape elements—whether dispersed or aggregated—represents landscape pattern, resulting from interactions among natural, biological, and social factors. Patch shape, size, quantity, and spatial configuration affect species distribution and transport while influencing ecological processes such as runoff and erosion, as well as edge effects. This study selects Shannon' s diversity index (SHDI), largest patch index (LPI), landscape shape index (LSI), and contagion index (CONTAG) to condense landscape pattern information. SHDI characterizes landscape type richness; higher diversity indicates greater landscape heterogeneity and biological habitat diversity, corresponding to better environmental quality. LPI reflects landscape dominance. LSI measures landscape shape regularity and fragmentation, indicating human disturbance intensity. CONTAG reflects connectivity of dominant landscapes, directly affecting species reproduction, diffusion, migration, and conservation.

Habitat Anti-Interference Capacity: This capacity forms the foundation of land ecological security, reflecting ecosystem functional stability. Based on relevant literature, this study selects elevation, slope, NDVI, distance to water bodies, distance to ecological protection zones, distance to roads, and land use structure diversity as indicators.

Ecosystem Service Functions: Ecosystem services represent goods and services provided by ecosystem conditions and processes, linking natural and social processes. This study selects four primary service types: provisioning, regulating, supporting, and cultural services.

Socio-Economic Benefits: Economic benefits drive sustainable land ecological development. Good economic conditions facilitate investment in ecosystem construction and enhance development potential. This study selects per capita income, economic density (reflecting land use efficiency and optimization), per capita grain production (reflecting self-sufficiency), and population density (reflecting human-land carrying capacity relationships). Specific indicators are listed in Table 1.

Table 1. Comprehensive evaluation index system of land ecological quality in the Yellow River Basin

2.4 Grid Division and Indicator Calculation

The average patch area in the Yellow River Basin is 14.22 km^2. Considering the study area' s geographical characteristics, 8 km × 8 km grids were selected as evaluation units. Using ArcGIS 10.7, fishnet grids were created for the basin. Landscape characteristic indices were calculated using Fragstats 4.2 based on land use raster data, computing corresponding landscape indices for each grid.

Indicators for habitat anti-interference capacity were derived from ArcGIS 10.7 slope analysis and buffer analysis. For non-quantifiable indicators, classification and assignment were based on relevant standards and research. Distance to water bodies is a positive indicator—closer proximity indicates richer water resources favorable for ecosystem functioning. Elevation and slope are negative indicators—higher values increase land use difficulty. Distance to primary roads is a negative indicator—closer proximity increases ecological sensitivity and reduces ecosystem stability. Ecological protection zones serve as core areas for ecosystem and species conservation, effectively mitigating environmental damage from rapid development.

For socio-economic indicators, per capita income, economic density, and per capita grain production were calculated as municipal averages from statistical yearbooks and then zonal statistics were performed. Population density utilized spatialized raster data products.

Regarding ecosystem service functions, due to strong spatial heterogeneity, applying national-scale equivalent factors would produce significant errors. Therefore, ecosystem service equivalents for the Yellow River Basin were corrected following reference [28], yielding regional correction coefficients. Combining land cover characteristics, the study area was classified into seven ecosystem types: cropland, forest, grassland, water bodies, construction land, wetland, and desert. Based on the equivalent factor table [29] and corrected values, ecosystem service value coefficients were calculated for each land use type (Table 2), enabling computation of ecosystem service values for the basin. Construction land value was calculated according to reference [30].

Table 2. Ecological service value coefficients of all kinds of land in the Yellow River Basin

2.5 Indicator Standardization and Weighting

2.5.1 Indicator Standardization To ensure comparability and facilitate weighted summation, indicators were normalized using range standardization:

For positive indicators:

$$R_{ij} = \frac{X_{ij} - \min|X_{ij}|}{\max|X_{ij}| - \min|X_{ij}|}$$

For negative indicators:

$$R_{ij} = \frac{\max|X_{ij}| - X_{ij}}{\max|X_{ij}| - \min|X_{ij}|}$$

where R_{ij} is the standardized score; X_{ij} is the value of the j-th indicator in criterion layer i; and $\min|X_{ij}|$ and $\max|X_{ij}|$ represent the minimum and maximum values of indicator j in criterion layer i.

2.5.2 Indicator Weights The entropy method accurately judges the dispersion degree of entropy values to determine weights objectively, but excessive dependence on mathematical methods may cause instability when information entropy (E_j) approaches 1. The analytic hierarchy process compensates for this subjectivity. This study combines both methods to calculate combined weights, with formulas detailed in reference [31].

2.6 Land Ecological Quality Comprehensive Index

The comprehensive evaluation model is:

$$P = \sum_{j=1}^{n} W_j \times T_j$$

where P is the comprehensive evaluation value; n is the number of evaluation factors; W_j is the combined weight; and T_j is the standardized score of factor j.

2.7 Spatial Autocorrelation and Hot/Cold Spot Analysis

Spatial autocorrelation quantitatively describes the similarity and spatial association patterns of attribute values among neighboring regions, revealing spatial interactions. It includes global and local spatial autocorrelation. This study employs global Moran’ s I to investigate overall spatial correlation of land ecological quality. Moran’ s I ranges from -1 to 1, with absolute values representing correlation strength—positive values indicate positive correlation and vice versa [32].

Hot/cold spot analysis explores local spatial clustering characteristics to identify high-value or low-value aggregations. Formulas are detailed in reference [33].

2.8 Obstacle Degree Diagnosis

The obstacle degree model quantitatively identifies limiting factors for land ecological quality, providing scientific basis for precise management. The model comprises factor contribution degree, indicator deviation degree, and obstacle degree [34]:

$$M_j = W_j \times (1 - T_j)$$

where M_j is the obstacle degree of indicator j to land ecological quality; W_j is the combined weight; and T_j is the standardized score.

3 Results and Analysis

3.1 Spatial Characteristics of Evaluation Results

3.1.1 Spatial Characteristics of Criterion Layers Using the natural breaks method [35], the comprehensive quality of landscape characteristics, habitat anti-interference capacity, ecosystem service value, and socio-economic benefits were classified. As shown in Figure 2, high and relatively high landscape characteristic quality aligns with the distribution of primary water systems. Low and moderate levels mainly occur in the central Loess Plateau, where high fragmentation, irregular patch shapes, small patch sizes, and poor connectivity of similar landscape types create complex, heterogeneous, discontinuous mosaics.

High habitat anti-interference capacity zones are distributed in the Maowusu Sandy Land Ecological Function Reserve, Loess Plateau Ecological Function Reserve in the central region, and the Yellow River Source and Zoigê-Maqu Ecological Function Reserve in the southwest. Low-value areas concentrate in southeastern Qinghai, central and southwestern Gansu, and Ningxia, characterized by high elevation and slope, predominantly grassland vegetation, low land use structure diversity, and poor natural conditions.

Low ecosystem service value areas are found in parts of Ordos and Bayannur, where extensive sandy land, bare rock, and grassland result in poor ecosystem service functions and high ecological sensitivity. The comprehensive socio-economic benefit index shows a stepwise distribution pattern of high in the east and low in the west, with high and relatively high benefit zones mainly in Shanxi, northern Shaanxi, and Ordos—regions rich in coal, petroleum, and non-ferrous mineral resources with high economic density and leading per capita grain production.

Figure 2. Comprehensive evaluations of criterion layer indices of land ecological quality in the Yellow River Basin [Figure 2: see original paper]

3.1.2 Spatial Characteristics of Comprehensive Land Ecological Quality Grades Using the natural breaks method, the comprehensive land ecological quality was classified. The spatial distribution is shown in Figure 3. Land ecological quality generally exhibits high quality in central and southwestern regions, moderate quality in northeastern and southeastern regions, and low quality in northwestern regions. Safe and relatively safe zones are mainly distributed in the Yellow River Source and Zoigê-Maqu Ecological Function Reserve in the southwest, eastern Gansu, southern Ordos, northern Shaanxi, and parts of Shanxi. Critical safety zones are primarily in the northeastern and southeastern basin. Dangerous zones concentrate in Qinghai, Gansu, and Ningxia in the northwestern basin.

Figure 3. Comprehensive grade of land ecological quality in the Yellow River Basin [Figure 3: see original paper]

3.2 Spatial Correlation and Obstacle Analysis

3.2.1 Spatial Autocorrelation Analysis Using Geoda' s spatial analysis function, Moran's I was calculated under Queen's contiguity spatial weights. The Moran's I values were 0.781 and 0.782, both passing significance tests, indicating strong positive spatial autocorrelation. The spatial distribution shows clustering —high-quality areas tend to neighbor high-quality areas, while low-quality areas cluster with low-quality areas (Figure 4).

Figure 4. Moran' s I scatter plot of land ecological quality [Figure 4: see original paper]

3.2.2 Hot/Cold Spot Analysis Global spatial autocorrelation reveals overall patterns but cannot identify local associations. Hot/cold spot analysis addresses this limitation (Figure 5). Hot spots (high-value clusters) occupy 22.06% of grids (1,001,761.1 km^2), mainly distributed in southern Ordos, northern and southern Shaanxi, western Shanxi, eastern Gansu, and northern Sichuan. These areas, located in the Maowusu Sandy Land and Loess Plateau ecological protection zones, exhibit high habitat anti-interference capacity and achieve good economic benefits from abundant mineral resources.

Cold spots (low-value clusters) account for 24.79% of grids (1,126,029.0 km^2), primarily in southeastern Qinghai, most of Gansu, and northern Ningxia. These high-altitude, high-slope areas with poor natural conditions and low economic development exhibit low-value clustering. The distribution reflects both natural resource endowments and policy orientation.

Figure 5. Distribution of cold and hot spots of land ecological quality in the Yellow River Basin [Figure 5: see original paper]

3.2.3 Obstacle Degree Diagnosis and Recommendations Obstacle degree calculations for individual indicators and criterion layers are shown in Table 4. The highest obstacle degrees occur in habitat anti-interference capacity and socio-economic benefits, with average values of 41.935% and 43.537%, respectively, reflecting poor natural conditions and low economic development across the basin. Among individual indicators, economic density, land use structure diversity, distance to ecological protection areas, distance to water bodies, and per capita income show high obstacle degrees, representing the dominant limiting factors.

Table 4. Obstacle level of barrier factors for land ecological quality in the Yellow River Basin

Safe Grade (12.4%, 100,176.11 km^2): Distributed in southern Ordos, parts of Yulin-Yan' an, western Shanxi, and southern Shaanxi. Main obstacles are economic density, land use structure diversity, and distance to water bodies. Despite ecological improvements from conservation efforts, traditional high-consumption industries have declined while tertiary industry remains underdeveloped. Recommendations include industrial upgrading, continued soil and water conservation, and rational artificial ecosystem configuration to achieve transformation from "yellow to green, and green to stable."

Relatively Safe Grade (28.5%, 230,622.77 km^2): Located in the central Loess Plateau Ecological Function Reserve and southwestern Yellow River Source and Zoigê-Maqu reserves. Main obstacles are economic density, land use structure diversity, and per capita income. These areas suffer from resource scarcity and ecological-economic imbalance. Eastern Gansu and southern Ningxia should strengthen loess management while developing ecological economies. The southwestern source area should prioritize conservation and develop ecological animal husbandry.

Critical Safety Grade (31.4%, 253,937.66 km^2): Distributed in the northeastern and southeastern basin.

Dangerous Grade (27.7%, 224,202.90 km^2): Concentrated in the ecologically fragile northwestern region. Main obstacles are economic density, distance to ecological protection areas, and land use structure diversity. These areas should abandon the "destroy first, restore later" growth model, innovate development drivers, and implement comprehensive measures for soil and water conservation, pollution control, and biodiversity protection.

4 Discussion

This study characterizes land ecological quality from multiple perspectives—landscape characteristics, habitat anti-interference capacity, ecosystem services, and socio-economic benefits—combining subjective-objective weighting with grid-GIS to transcend traditional evaluation methods. Guo et al. [36] evaluated land ecological conditions in the Fenhe River Basin at county level, finding high-quality areas mainly in Loufan, Gujiao, and Ningwu counties, consistent with our results. However, our grid-based approach provides more precise characterization of intra-county variations.

Wang et al. [37] found that ecological conditions in the Yellow River Basin were better in upstream areas and worse in downstream areas in 2004, with the central Loess Plateau being the worst. In contrast, our 2018 results show improved conditions in the central region, with the worst conditions shifting to the northwestern upstream area. This reflects the remarkable achievements of nearly two decades of basin management. However, challenges remain: 31.4% critical safety and 27.7% dangerous areas persist, with poor economic benefits and land use diversity. The northwestern upstream region exhibits low-value clustering.

Li et al. [38] demonstrated that cities in the Yellow River Basin have not crossed the per capita GDP turning point for ecological protection (where environmental quality improves with economic growth after the turning point). Unilateral economic growth leads to environmental degradation, while excessively low environmental quality inhibits economic growth. Given this complex interaction mechanism and the current status of low economic benefits, poor habitat anti-interference capacity, and ecological fragility, the pattern of low quality in the northwest, high quality in the center, and moderate quality in the southeast/northeast will be difficult to change in the short term. Future efforts should develop green industrial systems adapted to local conditions, rationally plan land use, strengthen ecological protection investment, and clarify internal subsystem interactions to formulate reasonable development strategies.

Land ecological quality evaluation is a complex systematic project. Due to data availability constraints, this study does not investigate spatio-temporal evolution and driving mechanisms, nor does it consider soil properties. Selected indicators may have limitations. Land ecological quality evaluation is a long-term academic challenge requiring clearer conceptual definitions, identification of representative parameters and corresponding geospatial data, and further research on land ecological security thresholds [39].

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5 Conclusion

Using 8 km × 8 km grids as evaluation units, this study constructed an indicator system from four perspectives—landscape characteristics, habitat anti-interference capacity, ecosystem service value, and socio-economic benefits. Spatial autocorrelation, hot/cold spot analysis, and obstacle diagnosis were employed to explore spatial distribution patterns of land ecological quality in the Yellow River Basin. The main conclusions are:

1. Land ecological quality exhibits a spatial pattern of relatively high quality in central and southwestern regions, moderate quality in southeastern and northeastern regions, and low quality in northwestern regions. Overall quality is relatively low, with critical safety and dangerous areas accounting for 31.4% and 27.7%, respectively.
2. Strong spatial autocorrelation exists, with hot spots in intensively managed ecological protection zones (Loess Plateau, Maowusu Sandy Land) and cold spots in the northwestern basin. Management efforts in upstream areas should be strengthened to eliminate extreme cold spots.
3. Primary obstacle factors are economic density, land use structure diversity, distance to ecological protection areas, and distance to water bodies. Policies should leverage regional natural resources and resource endowments, accelerate green innovation, transform natural and cultural resources into economic value, rationally allocate artificial ecosystem structures during ecological restoration, and establish nature reserves when necessary.

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