

## Land Ecological Quality and Change Trend Prediction in the Yellow River Basin, 2000-2020: Postprint

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### Abstract

Ecological protection of the Yellow River Basin holds important strategic significance for China's high-quality development. An evaluation index system for land ecological quality was constructed from four aspects: ecological background, ecological structure, ecological benefits, and ecological stress. Based on the ideal point method, the land ecological quality of the Yellow River Basin was evaluated for the years 2000, 2005, 2010, 2015, and 2020. Combined with Slope trend prediction and F significance test models, the changing trend of land ecological quality in the Yellow River Basin for 2025 was predicted, and cold-hot spot analysis was conducted on the prediction results to explore the agglomeration areas of development trends for the basin's land ecological quality in 2025. The results show: (1) From 2000 to 2020, the land ecological quality of the Yellow River Basin exhibited a distribution characteristic where the southeastern and southwestern parts were overall higher than the northeastern and northwestern parts. (2) The overall land ecological quality of the Yellow River Basin from 2000 to 2020 was relatively low, but it showed a gradual improvement trend from the southeast to the northwest. (3) In the middle and upper reaches of the Yellow River Basin where the ecological background quality was poor in 2000, there was substantial room for quality improvement, with obvious improvement phenomena. (4) Areas where land ecological quality in the Yellow River Basin is projected to show an upward trend in 2025 are mainly concentrated in the eastern and central parts of the Gansu section and the southern part of the Ningxia section of the basin, located within the Loess Plateau ecological function protection zone; areas where land ecological quality may decline are partially concentrated in the Yellow River Source ecological function protection zone in the southwestern part of the Qinghai section of the basin, and partially concentrated in the northwestern part of the Inner Mongolia section of the basin. The northwestern part of the Yellow River Basin should continuously

promote ecological governance to lay an ecological foundation for regional high-quality development, while the southeastern part of the basin should continue to advance economic development while strengthening ecological protection and monitoring, to achieve benign development where economy and ecology promote each other.

## Full Text

### Land Ecological Quality and Its Change Trend Prediction in the Yellow River Basin from 2000 to 2020

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**Abstract:** Ecological protection of the Yellow River Basin holds significant strategic importance for China's high-quality development. This study constructs a land ecological quality evaluation index system from four dimensions: ecological basis, ecological structure, ecological benefits, and ecological stress. Based on the ideal point method, we evaluate the land ecological quality of the Yellow River Basin from 2000 to 2020, combine the Slope trend prediction model and F significance test model to forecast the change trend of land ecological quality in the basin for 2025, and conduct cold-hot spot analysis on the prediction results to explore the clustering areas of development trends in basin land ecological quality. The results indicate: (1) The land ecological quality in the southeastern and southwestern parts of the Yellow River Basin is higher than that in the northeastern and northwestern parts. (2) From 2000 to 2020, the overall land ecological quality of the Yellow River Basin is relatively low, but shows a gradual improvement from the southeast to the northwest. (3) The middle and upper reaches of the basin, where the background land ecological quality is poor, have substantial room for improvement, with noticeable improvement phenomena. (4) Areas where land ecological quality may increase in 2025 are mainly concentrated in the eastern and central parts of the Gansu section and the southern part of the Ningxia section of the basin, located within the Loess Plateau ecological function protection zone. Areas where land ecological quality may decline are partially clustered in the southwestern part of the Qinghai section of the basin within the Yellow River source ecological function protection zone, and partially clustered in the northwestern part of the Inner Mongolia section of the basin. The northwestern part of the Yellow River Basin should continue to advance ecological governance to lay an ecological foundation for regional high-quality development, while the southeastern part should continue to promote economic development while strengthening ecological protection and monitoring to achieve benign development with mutual promotion of economy and ecology.

**Keywords:** land ecological quality; ideal point method; Slope trend prediction; Yellow River Basin

## Introduction

Land ecological quality, which changes with the contradictions in human-land relationships, refers to the suitability of different combinations of land elements for human survival and sustainable socio-economic development within a certain time and space. The extensive economic development model that prioritized development over protection in the past has intensified human-land conflicts, leading to a series of ecological and environmental problems such as water resource shortages, biodiversity loss, land desertification, and water-soil pollution, which threaten sustainable socio-economic development. Land ecological quality evaluation is fundamental for identifying the current status and problems of regional land ecological quality and implementing targeted measures, holding significant importance for improving the ecological environment and supporting sustainable socio-economic development.

Since the mid-20th century, following the proposal of the “soil genesis theory” and “mineral nutrition theory,” research in land ecology-related fields has gradually expanded. Kellogg proposed the concept of land quality, which led to the extension of land ecological quality, and related content has been widely studied. Current research on land ecological quality primarily focuses on ecosystem health evaluation, ecological security and risk assessment, land ecological quality evaluation, land ecological suitability evaluation, and land ecological vulnerability and sensitivity assessment. Among these, land ecological quality evaluation is conducted based on evaluation index systems, mainly including three types: improved indicator systems based on the FAO’s “Framework for Sustainable Land Use Evaluation,” indicator systems established based on the “Pressure-State-Response (PSR)” model, and indicator systems constructed based on the “Economy-Society-Environment” model. Research methods include landscape models, ideal point models, comprehensive index models, ecological footprint models, and matter-element models. For instance, Chen Zhen used the ideal point model to evaluate land ecological quality in Guang’an City from 2006 to 2016, demonstrating that the ideal point model can simplify analysis while retaining high-quality indicator information. Ao Yong et al. used the cold-hot spot model to explore spatial differentiation characteristics of land ecological quality in the Yellow River Basin, showing that the cold-hot spot model can investigate clustering features from a statistical perspective. Currently, land ecological quality research mostly constructs indicator systems and selects different quantification methods to evaluate, analyze spatiotemporal changes, and identify driving factors for specific study areas and periods.

In September 2019, ecological protection and high-quality development of the Yellow River Basin was elevated to a major national strategy. As one of China’s important ecological barriers, the Yellow River Basin holds great significance for national sustainable socio-economic development and ecological security pattern

construction. Current research on the Yellow River Basin mainly focuses on status evaluation, with less attention paid to future development trends of basin land ecological quality. Therefore, this study evaluates land ecological quality and its spatiotemporal differentiation from 2000 to 2020, and predicts future change trends to identify ecologically vulnerable areas, providing references for future ecological protection and governance efforts in the basin and supporting ecological protection and high-quality development of the Yellow River Basin.

## 1 Study Area Overview

The Yellow River flows through nine provinces and regions: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong. The main stream spans 5,464 km with a basin area of  $7.46 \times 10^5$  km<sup>2</sup>. The Yellow River Basin is an important economic zone in China. The Huang-Huai-Hai Plain, Fenwei Plain, and Hetao Irrigation District within the basin serve as major agricultural production areas, with grain and meat output accounting for approximately one-third of the national total. The basin is rich in land, water energy, coal, oil, natural gas, and mineral resources, earning it the reputation as China's "energy basin." The Yellow River Basin is also a crucial ecological barrier, forming an ecological corridor connecting the Qinghai-Tibet Plateau, Loess Plateau, and North China Plain. It encompasses several national parks and ecological function protection zones such as the Sanjiangyuan and Qilian Mountain areas, undertaking various ecological functions including water and soil conservation, windbreak and sand fixation, species resource conservation, and water source conservation.

## 2 Data and Methods

### 2.1 Data Sources and Processing

The primary data sources for this study include precipitation, temperature, Normalized Difference Vegetation Index (NDVI), Net Primary Productivity (NPP), land use, Gross Domestic Product (GDP) spatial grids, population, and nighttime light data, mainly obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (<https://www.resdc.cn/>). Some precipitation and temperature data were sourced from the U.S. National Climate Data Center (<https://www.ncdc.noaa.gov/>), some population data from WorldPop (<https://www.worldpop.org/>), and some nighttime light data from the Earth Observation Group (<https://eogdata.mines.edu/>). Elevation data were obtained from the Geospatial Data Cloud (<http://www.gscloud.cn/>).

The elevation data have a resolution of 30 m, meteorological data are station-based, and other data have a resolution of 1 km. All data were uniformly projected and converted, then extracted using the Yellow River Basin boundary mask. Terrain roughness was calculated from elevation data using the raster calculator and resampled to 1 km resolution through spatial resampling. Meteorological station data underwent spatial interpolation analysis and were output

as 1 km resolution raster data. Based on Xie Gaodi's "Equivalent Factor Table of Ecosystem Service Value per Unit Area of Terrestrial Ecosystems in China," land use data were reclassified and assigned values according to the ecosystem service value of each land type to obtain ecosystem service value data. Population density and GDP grid data were also processed. This study ultimately uses a 1 km $\times$ 1 km grid cell as the evaluation unit, completing land ecological quality evaluation through weighted summation of various spatial data using the raster calculator.

## 2.2 Methods

**2.2.1 Ideal Point Method** The ideal point method treats each alternative in multi-attribute decision-making as a point in multi-dimensional space and determines the ranking of alternatives based on their distances to the "positive ideal point" and "negative ideal point." The implementation process for land ecological quality evaluation based on the ideal point method is as follows:

- 1) Data forwardization and standardization processing. The formulas are as follows:

$$B = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

$$B^- = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

where  $B$  represents the processing method for maximum-type indicators;  $B^-$  represents the processing method for minimum-type indicators;  $X$  is the indicator value;  $X_{\min}$  is the minimum indicator value; and  $X_{\max}$  is the maximum indicator value.

- 2) Calculation of Euclidean distances between each indicator and the positive and negative ideal values. The formulas are as follows:

$$d_{ij}^+ = \sqrt{(Z_{ij} - Z_j^+)^2}$$

$$d_{ij}^- = \sqrt{(Z_{ij} - Z_j^-)^2}$$

where  $d_{ij}^+$  is the Euclidean distance between the  $j$ th evaluation indicator value ( $Z_{ij}$ ) of the  $i$ th evaluation unit and the positive ideal value of the  $j$ th evaluation indicator;  $d_{ij}^-$  is the Euclidean distance between the  $j$ th evaluation indicator value ( $Z_{ij}$ ) of the  $i$ th evaluation unit and the negative ideal value of the  $j$ th evaluation indicator;  $Z_j^+$  and  $Z_j^-$  are the positive and negative ideal values of the  $j$ th evaluation indicator, respectively. For indicators processed through

forwardization and standardization, the positive ideal value is the maximum value (1) and the negative ideal value is the minimum value (0).

- 3) Calculation of ideal value vectors and comprehensive ideal values. The formulas are as follows:

$$S_{ij} = \frac{d_{ij}^-}{d_{ij}^+ + d_{ij}^-}$$

$$\alpha_{ij} = \frac{S_{ij}}{\sum_{i=1}^n S_{ij}}$$

$$W = \sum_{j=1}^m \beta_j \alpha_{ij}$$

where  $S_{ij}$  is the final score of the  $i$ th grid cell for evaluation indicator  $j$ ;  $\alpha_{ij}$  is the ideal value vector of evaluation indicator  $j$  for the  $i$ th grid cell;  $\beta_j$  is the weight value of evaluation indicator  $j$ ; and  $W$  is the comprehensive ideal value of land ecological quality. A larger  $W$  indicates better land ecological quality and greater suitability of land element combinations for sustainable socio-economic development.

**2.2.2 Slope Trend Prediction and F Significance Test** The Slope trend analysis method predicts change trends through linear regression analysis of time-varying variables. Slope model analysis requires that the simple linear regression equation fitting between the analyzed variable and time be significant. This study uses Slope trend analysis to predict land ecological quality change trends in the study area from 2000 to 2025, with F significance testing to indicate confidence levels. The implementation process is as follows:

- 1) Slope trend analysis. Using ArcGIS software, the study area's annual average land ecological quality values from 2000 to 2020 are fitted with time using a simple linear regression equation. If the fitted equation is significant, Slope analysis is conducted. Using simple linear regression analysis and the least squares method, the change trend is calculated pixel by pixel. The formula is as follows:

$$\text{Slope} = \frac{n \times \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n \times \sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2}$$

where  $x_i$  is the year value for year  $i$ ;  $y_i$  is the land ecological quality for year  $i$ ; and  $n$  is the number of years. When Slope  $> 0$ , it indicates an upward trend; when Slope  $< 0$ , it indicates a downward trend.

- 2) F significance test. F significance analysis is conducted on land ecological quality change trends to indicate confidence levels. The formula is as follows:

$$F = \frac{U}{Q/(n-2)}$$

where  $y_i^*$  is the fitted regression value of land ecological quality;  $\bar{y}$  is the average land ecological quality;  $U$  is the regression sum of squares;  $Q$  is the residual sum of squares; and  $F$  is the significance test result. The critical value is obtained from the F distribution table and used to reclassify  $F$ , completing the significance test of land ecological quality change trends.

**2.2.3 Cold-Hot Spot Analysis** Cold-hot spot analysis explores the local spatial clustering properties of geographic attributes by establishing local indicators of spatial association to determine whether high-value or low-value clustering exists. To obtain statistically significant spatial clustering areas of land ecological quality change trends, cold-hot spot analysis of the elements is required. The prerequisite for cold-hot spot analysis is that the target elements have spatial clustering characteristics. Therefore, before conducting cold-hot spot analysis, global spatial autocorrelation analysis is needed to determine whether the target elements have clustering characteristics globally. This study uses ArcGIS Moran' s I method for global spatial autocorrelation analysis of land ecological quality change trend prediction results. A positive Moran' s I indicates a clustering trend, while a negative value indicates a dispersion trend. Referring to relevant research, if the data show a clustering trend, Getis-Ord  $G_i^*$  in ArcGIS can be used for cold-hot spot analysis, where cold spots represent low-value clustering areas and hot spots represent high-value clustering areas.

### 2.3 Land Ecological Quality Evaluation

Based on theories of land ecology and landscape ecology, and referring to existing research results [6,13-14], this study selects evaluation indicators from four dimensions: ecological basis, structure, benefits, and stress, and determines indicator properties. Ecological basis reflects the land baseline conditions of climate, terrain, and vegetation in the Yellow River Basin; ecological structure reflects human activity impacts on land ecology; ecological benefits reflect the beneficial impacts of land systems on human society; and ecological stress reveals ecological pressures generated during land use. This study uses the Delphi method and Analytic Hierarchy Process to assign indicator weights (Table 1). Land ecological quality evaluation for the Yellow River Basin from 2000 to 2020 is completed using the raster calculator to execute Formula (3). To ensure comparability of land ecological quality over time, the natural breaks method is used to divide the comprehensive ideal value ( $W$ ) of land ecological quality in the Yellow River Basin from 2000 to 2020 into five levels: high ( $W \geq 0.59$ ), relatively high ( $0.50 \leq W < 0.59$ ), medium ( $0.43 \leq W < 0.50$ ), relatively low

( $0.37 \leq W < 0.43$ ), and low ( $W < 0.37$ ). This classification forms the basis for analyzing land ecological quality change data from 2000 to 2025.

### 3 Results and Analysis

#### 3.1 Spatial Distribution Characteristics of Land Ecological Quality

Land ecological quality in the Yellow River Basin exhibits the spatial distribution characteristic of being higher in the southeastern and southwestern parts than in the northeastern and northwestern parts, as well as a spatial change trend of gradual improvement from the southeast to the northwest (Figure 1). Areas with better land ecological quality are mainly distributed in the Shandong, Henan, and Shanxi sections, the southwestern part of the Gansu section, the eastern, central, and southern parts of the Shaanxi section, and the eastern, central, and southern parts of the Qinghai section. Areas with poorer land ecological quality are mainly concentrated in the western part of the Qinghai section, the Gansu section, the Ningxia section, and the Inner Mongolia section. The southeastern part of the Yellow River Basin is mostly in a semi-humid climate zone with good natural endowments and high levels of coordinated ecological and economic development, while the northwestern part is in arid and semi-arid regions with harsh climate conditions, poor natural endowments, and lower levels of ecological and economic development, resulting in consistently better land ecological quality in the southeast than in the northwest.

From 2000 to 2020, the combined area proportion of high and relatively high land ecological quality levels in the Yellow River Basin did not exceed 30%, while the combined proportion of low and relatively low levels exceeded 40%, indicating that the overall land ecological quality of the basin is not high. However, the area proportions of high, relatively high, and medium levels increased by 4.83%, 5.64%, and 6.44% respectively, while the proportions of relatively low and low levels decreased by 9.12% and 7.79% respectively (Figure 2). The land ecological quality of the Yellow River Basin gradually improved. The upper reaches are located in arid and semi-arid regions, and the middle reaches feature loess landforms. Unreasonable human activities such as overgrazing by herders and drainage of wetlands have caused ecological problems including grassland degradation, land desertification, and water-soil loss, resulting in poor baseline land ecological quality. However, after years of industrial structure upgrading, environmental pollution control, and agricultural-water resource management, the coupling and coordinated development level between economic development and ecological environment in the basin has improved, and land ecological quality has gradually ameliorated.

[Figure 1: see original paper]

[Figure 2: see original paper]

### 3.2 Temporal Change Characteristics of Land Ecological Quality

To explore transfer change patterns, this study uses ArcGIS to generate land ecological quality transfer matrices for three periods from 2000 to 2020 (Table 2). The transfer area proportion refers to the ratio of transferred area to the total area of that land ecological quality level, explaining the improvement and deterioration conditions of each level.

Within the three periods, the transfer proportions of medium and high land ecological quality levels are small and inactive. In the three periods, the combined proportion of relatively low and low levels that experienced improvement is approximately 54.03% and 49.21% respectively, indicating large improvement proportions. The improvement in land ecological quality is mainly attributed to low and relatively low levels. Specifically, 33.02% of medium levels transferred to low and relatively low levels, indicating land ecological quality degradation that requires monitoring and management of ecological environment, socio-economic development, and their coordination in these areas. Meanwhile, 8.54% of medium levels did not transfer, showing relatively stable land ecological quality but difficulty in level improvement (only 6.44% of medium levels transferred to high and relatively high levels). Additionally, 48.15% of low levels and 32.68% of relatively low levels transferred to higher levels, indicating that low and relatively low level areas have substantial room for improvement, and ecological governance yields relatively rapid results.

### 3.3 Prediction and Analysis of Land Ecological Quality Change Trends

#### 3.3.1 Slope-Based Land Ecological Quality Change Trend Prediction

Using “time” as the independent variable and “land ecological quality” as the dependent variable, linear regression analysis was conducted using ArcGIS software. The results show the fitting equation is significant ( $R^2 = 0.714$ ), indicating that “time” can explain 71.4% of the variation in “land ecological quality” with high fitting degree. The significance value  $sig = 0.045$  indicates that at the  $\alpha = 0.05$  level, “time” has a significant effect on “land ecological quality.” There is a strong linear relationship between time and land ecological quality, allowing the use of the Slope model for trend prediction.

The Slope model predicts land ecological quality change trends in the study area. Using the raster calculator to execute Formula (4), the 2025 land ecological quality trend prediction map is generated (Figure 3). The results show that approximately 71.4% of the Yellow River Basin’s land ecological quality will show an upward trend (with 45.6% significantly increasing and 25.8% non-significantly increasing), while about 28.6% will show a downward trend (with 18.3% non-significantly decreasing and 10.3% significantly decreasing).

[Figure 3: see original paper]

#### 3.3.2 F-Test Significance Testing of Slope Prediction Results

F significance testing is conducted on Slope trend prediction results to indicate con-

confidence levels. Using the raster calculator to execute Formula (5), the F-test is completed. In this study, the sample size is the number of research years ( $n = 21$ ), so the degrees of freedom for F are (1, 19). When the tolerance rate  $\alpha = 0.05$ , the critical value from the F distribution table is 10.13, which is used as the breakpoint to reclassify F significance test results (Figure 4). When the F significance test result  $F > 10.13$ , it indicates the trend change is significant at the 0.05 level with high fitting degree; when  $F < 10.13$ , it indicates the trend change is not significant at the 0.05 level.

**3.3.3 Spatial Clustering of Land Ecological Quality Change Trends Based on Cold-Hot Spot Model** Overlay analysis is performed on the Slope trend prediction results and their F significance test results. Data with significant upward trends are assigned low values, data with non-significant downward trends are assigned high values, and data with non-significant upward and significant downward trends are assigned intermediate values. The newly assigned data are spatially counted using a 5 km  $\times$  5 km fishnet, and cold-hot spot analysis is conducted on the fishnet data using ArcGIS (Figure 4) to explore the spatial clustering distribution characteristics of land ecological quality change trends in the Yellow River Basin in 2025.

Global spatial autocorrelation analysis (Moran' s I) of land ecological quality change trends shows a Moran' s I index of 0.83 with significance less than 0.01, indicating the data have significant clustering trends suitable for cold-hot spot analysis. The clustering distribution shows that areas with significant upward trends in 2025 land ecological quality are mainly concentrated in the eastern and central parts of the Gansu section and the southern part of the Ningxia section, primarily located in the Loess Plateau ecological function protection zone. These areas have been under key protection and management for many years, with stable improvement trends in land ecological quality. Areas with non-significant downward trends are partially distributed in the southwestern part of the Qinghai section within the Yellow River source ecological function protection zone, and partially in the northwestern part of the Inner Mongolia section. The land ecological quality in these areas may decline contiguously in the future, providing key directions for basin ecological protection and governance efforts.

[Figure 4: see original paper]

## 4 Discussion

Land ecological quality is influenced by multiple social, economic, and environmental factors, and a unified evaluation index system has not yet been established. Although the indicators selected in this study are representative, they are not comprehensive. For example, while the study considers the stress effects of nighttime light and population density indicators on land ecosystems, it does not consider their positive promoting effects, nor does it include factors such as water-soil pollution and loss. Future research could consider further refining and enriching the indicator system. Additionally, when using the Slope model

for trend prediction, increasing the number of study years could strengthen the data foundation and improve prediction reliability. Based on evaluation and prediction results, further quantitative research on driving factors could be conducted to enhance the practical applicability of the study.

## 5 Conclusions

Based on the ideal point method evaluation of land ecological quality in the Yellow River Basin from 2000 to 2020, this study predicts and analyzes the change trends and clustering distribution of land ecological quality in the basin for 2025, reaching the following conclusions:

- 1) From 2000 to 2020, the land ecological quality in the southeastern and southwestern parts of the Yellow River Basin is higher than that in the northeastern and northwestern parts. Areas with better land ecological quality are mainly distributed in the Shandong, Henan, and Shanxi sections, the southwestern part of the Gansu section, the eastern, central, and southern parts of the Shaanxi section, and the eastern, central, and southern parts of the Qinghai section. Areas with poorer land ecological quality are mainly distributed in the western part of the Qinghai section, the Gansu section, the Ningxia section, and the Inner Mongolia section.
- 2) From 2000 to 2020, the combined area proportion of high and relatively high land ecological quality levels in the Yellow River Basin did not exceed 30%, indicating relatively low overall land ecological quality but an improving trend. Spatially, this manifests as gradual improvement from the southeast to the northwest; quantitatively, the area proportions of high, relatively high, and medium levels increased by 4.83%, 5.64%, and 6.44% respectively, while the proportions of relatively low and low levels decreased by 9.12% and 7.79% respectively.
- 3) The overall improvement in land ecological quality in the Yellow River Basin from 2000 to 2020 is mainly attributed to the middle and upper reaches where background land ecological quality is poor. These areas have substantial room for improvement, and governance effects are relatively significant. In contrast, the lower reaches with better land ecological quality show relatively stable conditions, where quality improvement requires stricter conditions and more time, making advancement more difficult.
- 4) Areas where land ecological quality is predicted to significantly increase in 2025 are mainly concentrated in the eastern and central parts of the Gansu section and the southern part of the Ningxia section of the basin, located within the Loess Plateau ecological function protection zone. After years of key protection, governance, and management, the improvement trend in these areas is stable. Areas where land ecological quality shows non-significant decreasing trends are partially clustered in the southwestern part of the Qinghai section within the Yellow River source ecological function protection zone, and partially in the northwestern part of the

Inner Mongolia section. The land ecological quality in these areas may decline contiguously in the future, requiring strengthened protection and monitoring.

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