Assessment of Ecosystem Services and Multi-scenario Prediction in the Yellow River Basin Based on the PLUS Model: A Case Study of the Shaanxi Section (Postprint)

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Abstract

Long-term supply and maximization of ecosystem services constitute important prerequisites for sustainable social development, necessitating accurate understanding of ecosystem service change trends. Based on multi-source data and employing methodologies including the InVEST model and ecosystem service assessment system construction, this study comprehensively analyzed the spatiotemporal evolution characteristics of various ecosystem service types in the Shaanxi section of the Yellow River Basin from 2000 to 2020, and simulated and predicted land use and ecosystem service changes for 2035 using the PLUS model. The results indicate: (1) The comprehensive ecosystem service value in the Shaanxi section of the Yellow River Basin from 2000 to 2020 exhibited an overall distribution pattern of "high in the south and low in the north," with advantageous areas for individual ecosystem services similarly concentrated in the southern part of the study area. (2) During 2000–2020, the comprehensive ecosystem service value in the study area demonstrated a trend of initial decline followed by significant increase, with high-value zones expanding progressively from south to north; except for soil conservation services, all other ecosystem service types showed certain degrees of improvement during the study period, with pronounced spatial differentiation among various ecosystem services. (3) Compared with the natural development scenario, forestland area increased substantially under the ecological protection scenario, with notable improvements in service levels in the central-northern region of the study area; under the construction priority scenario, construction land area expanded considerably, with distinct clustering of areas experiencing decreased service levels along the Yellow River water system; under the sustainable development scenario, both forestland and construction land expanded, with significant improvements in service levels in the northern part of the study area. The research findings

can provide scientific references for ecological comprehensive management and high-quality development of the Yellow River Basin.

Full Text

Abstract

The long-term supply and optimization of ecosystem services are critical prerequisites for sustainable social development, necessitating accurate understanding of InVEST model-based ecosystem service change trends. Using multi-source data and integrating the InVEST model with ecosystem service evaluation system construction methodologies, this study comprehensively analyzes the spatiotemporal evolution characteristics of various ecosystem service types in the Shaanxi section of the Yellow River Basin from 2000 to 2020, and simulates and predicts land use and ecosystem service changes for 2035. Results indicate: (1) From 2000 to 2020, the comprehensive ecosystem service value in the Shaanxi section of the Yellow River Basin exhibited an overall "high in the south, low in the north" distribution pattern, with dominant areas for each ecosystem service similarly concentrated in the southern part of the study area. (2) During 2000–2020, the comprehensive ecosystem service value initially declined then rose significantly, with high-value areas expanding from south to north. Except for soil conservation services, all other ecosystem service values improved to varying degrees, demonstrating pronounced spatial differentiation among services. (3) Compared with the natural development scenario, ecological protection scenarios showed significant forest area increases and marked service level improvements in the central-northern regions; construction priority scenarios featured substantial built-up area expansion with clustered areas of declining service levels along the Yellow River water system; sustainable development scenarios saw expansion of both forest land and built-up areas, with notable service level improvements in the northern part of the study area. These findings provide scientific references for comprehensive ecological management and high-quality development in the Yellow River Basin.

Keywords: ecosystem services evaluation; PLUS model; multi-scenario simulation; Yellow River Basin; Shaanxi section

Introduction

Ecosystem services represent the environmental conditions and utilities formed and maintained by ecosystems for human survival and development, encompassing the products and services humans obtain from ecosystem functions. Rapid societal development has led to ecosystem-provided human welfare becoming insufficient to meet demands, intensifying resource consumption and ultimately impacting and degrading ecosystems. Mitigating the effects of human activities and climate change on ecosystem services through land use planning and regulation represents an important pathway for achieving ecological protection, high-quality development, ecological civilization advancement, and human welfare improvement. Since "ecosystem services" was formally introduced as a technical term in 1981, research content, methods, scales, and simulation models in this field have gradually matured, yielding numerous research achievements. Studies have examined spatiotemporal distribution characteristics of ecosystem service functions, trade-offs and synergies, supply-demand balance, and value assessment. Although substantial ecosystem services research exists domestically and internationally, most remains tracking-oriented without further exploring interrelationships among ecosystem services. Due to complex interaction mechanisms among ecosystem services, current research lacks in-depth quantitative analysis of these interactions. Investigating ecosystem service combinations and interaction intensities for zoning enables precise discussion of zonal control measures tailored to regional characteristics. Methodologically, approaches include mathematical statistical analysis, multi-scenario simulation, and driving factor analysis. Spatially, research has focused primarily on economically developed eastern Chinese cities, urban agglomerations, and coastal areas, with insufficient research on the Yellow River Basin to support its sustainable development. Regarding simulation models, most previously employed models could only obtain future land use data based on past trends, whereas the PLUS model simulates patch-level land use changes, accurately revealing nonlinear relationships underlying land use transformations and more precisely disclosing potential impacts of future land use on ecosystem service functions under different scenarios. This method has been rarely applied in regional ecosystem service predictions.

The Shaanxi section of the Yellow River Basin, as a key area in the Yellow River Basin's high-quality development strategy, suffers severe ecological degradation. Global climate change and unregulated human activities have caused significant changes in ecosystem services in this region. This study selects the Shaanxi section of the Yellow River Basin as the research area, aiming to analyze spatiotemporal evolution characteristics of ecosystem services from 2000 to 2020, identify dominant areas for each ecosystem service, simulate comprehensive ecosystem service spatial distribution patterns under natural development, ecological protection, construction priority, and sustainable development scenarios for 2035 using the PLUS model, overlay dominant areas to analyze different ecosystem service combinations and interaction intensities, and finally propose zonal control recommendations.

1.1 Study Area Overview

The Shaanxi section of the Yellow River Basin (33°21 –39°35 N, 106°26 –111°15 E) is located in central-northern Shaanxi Province, within the middle reaches of the Yellow River, with a total length of 719 km and a drainage area of approximately 13.28$\times10^{4}$ km^2. Elevation ranges from 313 to 3753 m, with terrain sloping from high in the north to low in the south. The study area features a temperate monsoon climate with distinct seasons and moderate temperatures, with annual average temperature of 7–14°C, annual precipitation of 340–1240 mm, and annual evapotranspiration of 448–533 mm. Spanning a large north-south distance with numerous tributaries, complex geological conditions, and diverse ecological types, the region represents the core area for ecological protection and economic development in Shaanxi Province. Rich in mineral resources with good agricultural foundations, obvious location advantages, and a complete industrial system, the area possesses substantial development potential.

1.2 Data Sources

This study selected land use data, annual precipitation data, nighttime light data, and population density data for 2000–2020 from the Chinese Academy of Sciences Resource and Environmental Science Data Center (https://www.resdc.cn). Land use data had a spatial resolution of 30 m, while other data were at 1 km resolution. Population density data were obtained from WorldPop (https://www.worldpop.org). Elevation data were sourced from the Chinese Geospatial Data Cloud (http://www.gscloud.cn) at 30 m resolution. Net Primary Productivity (NPP), Normalized Difference Vegetation Index (NDVI), and evapotranspiration data were obtained from NASA EarthData (https://modis.gsfc.nasa.gov) at 500 m resolution. Municipal grain yield and population data were sourced from respective city statistical yearbooks. The overall accuracy of the selected datasets was 88.95%, meeting research requirements.

1.3 Research Methods

Based on existing research, this study selected five ecosystem services to construct an evaluation index system: carbon storage, soil conservation, water supply, food production, and residential resource support. The InVEST model was used to evaluate these services for 2000–2020, and the PLUS model was employed to predict ecosystem service functions under four scenarios (natural development, ecological protection, construction priority, and sustainable development) for 2035.

1.3.1 Ecosystem Service Evaluation System Construction Carbon Storage (CS) refers to the ability of vegetation to sequester carbon through photosynthesis. Research indicates that 1 kg of dry matter can sequester 1.63 kg of carbon. The formula is:

$$CS = NPP \times 1.63$$

where NPP is net primary productivity ($\mathrm{gC \cdot m^{-2} \cdot a^{-1}}$), calculated as:

$$NPP = APAR \times \varepsilon$$

where $APAR$ is photosynthetically active radiation and ε is light use efficiency.

Soil Conservation (SC) refers to the ecosystem's capacity to maintain soil functions. This study uses the RUSLE model to calculate soil conservation capacity:

$$SC = A_p - A_a = R \times K \times L \times S \times (1 - C \times P)$$

where SC is soil conservation amount ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$); A_p is potential soil erosion ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$); A_a is actual soil erosion ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$); R is rainfall erosivity index; K is soil erodibility factor; L and S are slope length and slope steepness factors; C is vegetation cover and management factor; and P is soil and water conservation practice factor.

Water Supply (WS) refers to the capacity of a region to retain groundwater and surface water within the system over a certain space and time. This study uses the InVEST Water Yield module based on water balance principles:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x = \left(\frac{w_x \times R_x}{w_x \times R_x + 1}\right) \times R_x$$

where Y_x is annual water yield for grid cell x (mm); P_x is annual precipitation for grid cell x (mm); AET_x is actual evapotranspiration coefficient; w_x is vegetation regulation coefficient; and R_x is dryness index.

Food Production (FP) refers to food provision capacity, calculated as the ratio of grain yield to cultivated land area for each district/county:

$$FP = \frac{GY}{CL}$$

where GY is total grain yield (t) and CL is cultivated land area ($\mathrm{hm^2}$).

Residential Resource Support (RRS) is closely related to population and nighttime light intensity, with nighttime lighting serving as an effective data source for human activity monitoring. This study obtained municipal population data from statistical yearbooks and allocated it to residential grids within jurisdictions based on nighttime light intensity differences to represent residential resource support.

Standardization Processing: To enable overlay analysis and ensure result comparability, ecosystem service threshold ranges were standardized to 0–1. The formula is:

$$ES_i = \frac{E_i - E_{min}}{E_{max} - E_{min}}$$

where ES_i is the standardized result for grid cell i; E_i is the actual ecosystem service value; and E_{max} and E_{min} are the maximum and minimum ecosystem service values in the study area.

Dominant Area Delineation: Dominant areas refer to regions where ecosystem services play critical roles. Based on existing research, areas within the top 20% of standardized results are designated as dominant areas (assigned value 1), with other areas assigned 0.

1.3.2 Integrated Ecosystem Service Assessment System Construction

Integrated Ecosystem Service Estimation: To compare total ecosystem service indicators, this study adopts the "integrated ecosystem service" concept, requiring weight definition to determine each service's importance. Using the Analytic Hierarchy Process (AHP), weights were determined as: carbon storage (0.25), soil conservation (0.20), water supply (0.20), food production (0.20), and residential resource support (0.15).

1.3.3 Land Use and Ecosystem Service Multi-Scenario Simulation

Based on historical land use change trends and objectives, this study uses the PLUS model to predict target-year land use scenarios. The model achieved Kappa coefficients exceeding 0.75, meeting research requirements. Four scenarios were established: natural development, ecological protection, construction priority, and sustainable development (Table 1).

Natural Development: Maintains development trends without considering future planning or restricting special rules. All land types except construction land and water bodies can convert to each other.

Ecological Protection: Pursues high ecological benefits by restricting conversion from high to low ecological benefit land. Forest and grassland expansion is prioritized.

Construction Priority: Emphasizes economic development by setting economically valuable land as high priority, following low-to-high conversion principles.

Sustainable Development: Balances economic development and ecological protection, organically integrating requirements and coupling human-land relationships.

2.1 Ecosystem Service Spatial Distribution Patterns

The spatial distribution patterns of ecosystem services in 2020 are shown in Figure 2. Carbon storage services exhibited a "high in the south, low in the north" pattern. The "dry belt" area north of the Wei River is an important quarrying zone with weak carbon sequestration function, showing low-value clusters in northern Yulin and Yan'an regions. However, forest land and dry farmland have relatively high carbon sequestration capacity, resulting in generally higher carbon storage service values in areas south of central Yan'an. Soil conservation, influenced by topography and vegetation cover, showed lowest values in northwestern Yulin and the Guanzhong Plain (Xi'an, Xianyang, Weinan) due to gentle slopes and low vegetation coverage. The Qinling mountainous area, with abundant forest resources, exhibited the highest soil conservation service values. Water supply services increased from northwest to southeast, with optimal services in the Qinling Mountains where forest and grass resources are concentrated and rainfall is abundant. Northwestern Yulin, affected by the Mu Us Sandy Land with extensive unused land and scarce precipitation, showed the poorest water supply. Food production displayed an alternating high-low distribution, with high values mainly in the Yan'an Loess Plateau region with good tillage layers and strong food provision capacity. The Qinling Mountains, with superior ecological resources, also demonstrated strong food production functions. The Guanzhong Plain urban agglomeration, with favorable terrain and irrigation conditions, showed high-value clusters around urban areas. Residential resource support services were primarily influenced by built-up area, population, and economic activity, predominantly distributed in the flat Guanzhong Plain suitable for development. Yulin and Yan'an cities, constrained by terrain conditions, had limited and scattered available construction land.

Temporal changes in ecosystem services are shown in Table 2. Overall, carbon storage, water supply, and residential resource support services showed upward trends from 2000 to 2020 without impacting the growth of comprehensive ecosystem service values in 2020. Comprehensive ecosystem service function declined notably in 2000–2010 but improved significantly in 2010–2020, with high-value areas continuously expanding northward. Except for soil conservation, other ecosystem service values improved during the study period, with significant spatial differentiation among services.

Dominant area distributions for each ecosystem service in 2020 are shown in Figure 3. Carbon storage dominant areas were concentrated south of central Yan'an, with additional areas in the Qinling Mountains. Water supply service dominant areas clustered in the Guanzhong Plain cities, with other areas in Yan'an. Food production dominant areas were distributed similarly to soil conservation. Residential resource support service dominant areas were mainly in urban built-up zones, most prominently in Xi'an.

2.2 Integrated Ecosystem Service Spatiotemporal Distribution Characteristics

The integrated ecosystem service value improved significantly from 2000 to 2020, maintaining a "high in the south, low in the north" spatial distribution pattern (Figure 4). Minimum values were primarily distributed in northwestern Yulin, deep in the Mu Us Desert interior. After years of large-scale sand control and afforestation campaigns, comprehensive ecosystem services in this area improved. The "dry belt" area north of the Wei River also exhibited low integrated ecosystem service values due to intensive ore mining. The Qinling Mountains, with abundant natural resources and good ecological conditions, maintained high comprehensive ecosystem service values throughout the study period.

2.3 Multi-Scenario Simulation Analysis

2.3.1 Land Use Multi-Scenario Simulation

Land use changes under natural development, ecological protection, construction priority, and sustainable development scenarios were predicted for 2035. Under natural development, forest area increased while grassland decreased, with built-up area rising by only 0.57%. Ecological protection scenarios showed significant forest area increases and built-up area reductions of 0.92%, emphasizing inventory revitalization and development reduction. Construction priority scenarios represented the most aggressive development pattern, with substantial built-up area expansion radiating outward from Xi'an. Sustainable development scenarios balanced development and protection, with significant increases in both built-up and ecological land areas. Overall change hotspots were concentrated in Guanzhong Plain cities (Xi'an, Xianyang), with relatively fewer changes in northern Shaanxi, mainly around existing urban built-up areas (Figure 5).

Dynamic land use area changes under different scenarios are shown in Table 3. Compared with 2020, natural development maintained historical trends with orderly conversion of cultivated and unused land to built-up areas and mutual conversion between forest and grassland, with change hotspots primarily in urban built-up zones. Ecological protection strictly limited urban spatial expansion, focusing on internal improvement and ecological land area increases, manifested as increased forest and grassland areas in central-southern regions. Construction priority showed the most radical development pattern, with built-up area proportion increasing by 0.56% mainly from cultivated land and forest. Sustainable development saw increases in both forest (0.91%) and built-up areas (0.57%), but significant decreases in cultivated land and grassland (0.92% and 0.56% respectively).

2.3.2 Integrated Ecosystem Service Multi-Scenario Simulation

Using the natural breaks method, integrated ecosystem service levels were classified into low, relatively low, medium, relatively high, and high categories for 2035 scenario simulation (Figure 6). Area proportions for each level are shown in Table 4. Compared with 2020, all four scenarios showed different trends while maintaining the "high in the south, low in the north" pattern. Natural development showed decreased medium-level area with increased high and low-level proportions. Ecological protection exhibited significant high-level area proportion increases and notable medium-level decreases. Construction priority showed minimal high-level area change, mainly converting medium levels to relatively low and low levels. Sustainable development followed similar trends as ecological protection but with lower high-level area proportion increases.

Overlaying natural development with the other three scenarios identified change hotspots (Figure 7). Compared with natural development, ecological protection showed service level improvement areas mainly in ecologically fragile northwestern Yulin and central-southern Yan'an, with notable improvements in central-northern regions. Construction priority showed clustered areas of declining service levels along the Yellow River water system, with improvements only in parts of Baoji and Xianyang. Sustainable development showed significant service level improvements in northern Yan'an and most of Yulin, while the Guanzhong Plain exhibited a "hot southwest, cold northeast" pattern. Overall, northern Shaanxi performed better under ecological protection and sustainable development scenarios than construction priority, related to its development model and energy extraction dependence. Guanzhong Plain cities need to focus on sustainable development, transforming economic growth models to explore high-quality development pathways.

2.4 Zoning and Management Recommendations

By overlaying ecosystem service dominant areas with predicted ecosystem service evaluation results, the study area was classified into seven zones (Figure 8). Targeted prevention measures were proposed to maximize regional advantages and adapt to local conditions.

Ecological Stability Zone: High ecosystem regulation services require strengthened vegetation protection to maintain ecological stability.

Ecological Restoration Zone: High vegetation cover and soil retention but lower carbon sequestration than ecological stability zones require afforestation with water-storage and carbon-sequestration species.

Suburban Development Zone: Located in western Guanzhong Plain, favorable for providing adequate food and living space, should practice agricultural intensification and avoid large heavy industry development.

Urban Agglomeration Zone: Central human activity areas bearing socioeconomic functions require rational urban planning, optimized population structure, and enhanced internal ecological security.

Agricultural Advantage Zone: Good water supply and food production services facilitate crop cultivation but with weaker production capacity than suburban development zones, requiring high-standard farmland development.

Agricultural Development Zone: Constrained by environment with food production as the main service, suitable for agricultural product processing development.

Northern Ecological Breeding Zone: Poor environmental conditions with many areas lacking favorable ecosystem services, requiring improvement in forest quality and soil-water conservation capacity.

3 Discussion

Residential resource support showed significant growth trends among all ecosystem services. However, Zhang et al. noted that urban ecosystems are highly vulnerable and dependent on external material inflows for stability. Once external supply becomes insufficient, the ecosystem may collapse. Rapid urban development continuously increases demand for external land and materials, pressuring surrounding areas, reducing ecosystem service levels and diversity, and indirectly causing significant declines in soil conservation services in 2020. This aligns with Fang Lulu et al.'s findings on water yield and soil conservation service trends in the Yellow River Basin. Water supply services showed overall declining trends with obvious fluctuations during the study period, consistent with Yang Jie et al.'s research on water yield services and Tong Rui et al.'s analysis of evapotranspiration spatiotemporal variation characteristics in the Yellow River Basin. Therefore, upgrading soil conservation and water supply services should provide guarantees for normal ecosystem functioning, with ecology-dominated soil conservation and carbon sequestration improvements being crucial for Yellow River Basin protection. Overall, integrated ecosystem service functions in the study area continued improving, similar to Zhu Chunxia et al.'s conclusions on spatiotemporal evolution of ecosystem services in the Yellow River Basin.

Overlaying predicted target-year ecosystem service dominant areas to analyze different service combinations and interaction intensities provides more comprehensive understanding of ecosystem services in the Yellow River Basin (Shaanxi section). Clarifying landscape ecological risk impacts on ecosystem services or ecological processes and their benefits represents a meaningful exploration that expands the ecological connotation of landscape ecological risk. Based on current ecosystem conditions, collaborative socio-ecological development decisions focusing on ecosystem service spatial supply-demand matching can promote sustainable Yellow River Basin development.

4 Conclusion

From 2000 to 2020, except for soil conservation services which showed certain declines, all other ecosystem service values in the Shaanxi section of the Yellow River Basin maintained upward trends. The comprehensive ecosystem service value declined significantly during 2000–2010 but improved substantially during 2010–2020, resulting in overall notable improvement during the study period.

Ecosystem services in the study area from 2000 to 2020 exhibited significant spatial differentiation. Carbon storage services showed a "high in the south, low in the north" pattern. Areas with gentle slopes and low vegetation cover had the lowest soil conservation service values, while forest-rich regions had the highest. Water supply services were highest in the Qinling Mountains, gradually decreasing from southeast to northwest. The flat, slightly eroded Loess Plateau of Yan'an represents good cultivation areas with high food production service values. Residential resource support was mainly distributed in the Guanzhong Plain urban agglomeration.

Land use simulation results for 2035 showed: natural development scenarios maintained original trends with orderly built-up area growth; ecological protection scenarios significantly increased forest area proportion with decreased built-up area; construction priority scenarios substantially expanded built-up area mainly from cultivated land and forest; sustainable development scenarios achieved balanced growth in both forest and built-up areas.

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Note: Figure translations are in progress. See original paper for figures.