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Spatio-temporal Evolution and Driving Factors of Ecosystem Services in the Luo River Basin

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ABSTRACT

To assess the ecosystem service levels in the Luo River Basin and promote sustainable environmental development in the region, this study utilized land use and meteorological data from 2000 to 2020. The InVEST and optimal parameter Geodetector models were employed to analyze the spatiotemporal evolution and driving mechanisms of water yield, soil conservation, carbon storage, and habitat quality in the Luo River Basin. Spatially, water yield generally decreases from south to north, while soil conservation shows a more dispersed distribution of high values. Carbon storage and habitat quality exhibit a west-high and east-low distribution. Temporally, water yield, soil conservation, and carbon storage initially decreased before increasing, whereas habitat quality declined year by year. Annual precipitation and slope are the key factors influencing water yield and soil conservation, respectively, while land use types are the primary factors affecting carbon storage and habitat quality. The research findings provide valuable reference data for making ecological and environmental protection decisions in the Luo River Basin.

KEYWORDS

Ecosystem Service; Luo River Basin; Spatial-Temporal Evolution; Drivers; Optimal Parameter Geodetector.

1. INTRODUCTION

Ecosystem services are closely linked to human well-being and provide a wide range of direct and indirect benefits to human society[1]. However, with the intensification of urbanization and human activities, large areas of land have been converted for urban and infrastructure development, leading to changes in land use patterns and triggering various ecological and environmental problems such as biodiversity loss, water quality degradation, and soil erosion. These changes have weakened or even eliminated the ability of ecosystems to provide their original services. Therefore, it is crucial to implement measures to protect and restore ecosystem services.

Natural and social factors play critical roles in the study of the driving mechanisms of ecosystem services. These factors include natural elements such as climate, vegetation, topography, and elevation, as well as socioeconomic factors that represent human activities. The diverse natural environments and social characteristics of different regions lead to variations in the supply of ecosystem services, resulting in spatial heterogeneity in their distribution[2]. Current research on the relationship between ecosystem services and driving factors primarily focuses on single-angle analyses, such as urbanization[3], land use[4], or climate change[5]. Previous studies have commonly used methods such as random forests[6], logistic regression models[7], and geographically weighted regression [8]. However, the analysis of the impact of multi-factor interactions remains relatively limited. The optimal parameter Geodetector serves as an effective analytical tool to address these issues. It not only accounts for regional geographic differences but also identifies and interprets spatial patterns and characteristics, thereby enhancing the explanation and prediction of geographic phenomena. Additionally, it comprehensively considers multiple influencing factors, evaluates their relative contributions, and reveals the interactions between different factors.

The Luo River Basin was selected as the study area due to its rich resources, which are crucial to the economic and social development of Henan and Shaanxi provinces. In recent years, the increase in human activities has exacerbated the natural disasters faced by the Luo River Basin, including droughts, floods, and soil erosion, imposing significant stress on the ecological environment. Four ecosystem services were selected as the focus of this study—water yield (WY), soil conservation (SC), carbon storage (CS), and habitat quality (HQ). By analyzing the spatial and temporal variations and key influencing factors of ecosystem services in the Luo River Basin, the study aims to provide effective reference data for ecosystem management and conservation in the region and surrounding urban areas.

2. MATERIALS AND METHODS

2.1. Overview of the study area

The Luo River Basin (33°34′-35°4′N, 111°7′-112°58′E) is located in the provinces of Shaanxi and Henan, covering a total area of 18,881 km² with a length of 1,400 km (Figure 1). The basin's elevation ranges from 57 to 2,655 meters, characterized by a west-high-east-low topography, and it lies at the junction of the second and third topographic steps of China. The climate of the Luo River Basin is primarily characterized by a warm temperate monsoon climate and a temperate monsoon climate, with precipitation concentrated in the summer and autumn months, and an average annual precipitation of approximately 500-800 mm. As a crucial part of the Yellow River Basin, the Luo River Basin is not only central to the development of Chinese civilization but also a significant source of ecological resources, providing substantial ecological benefits.

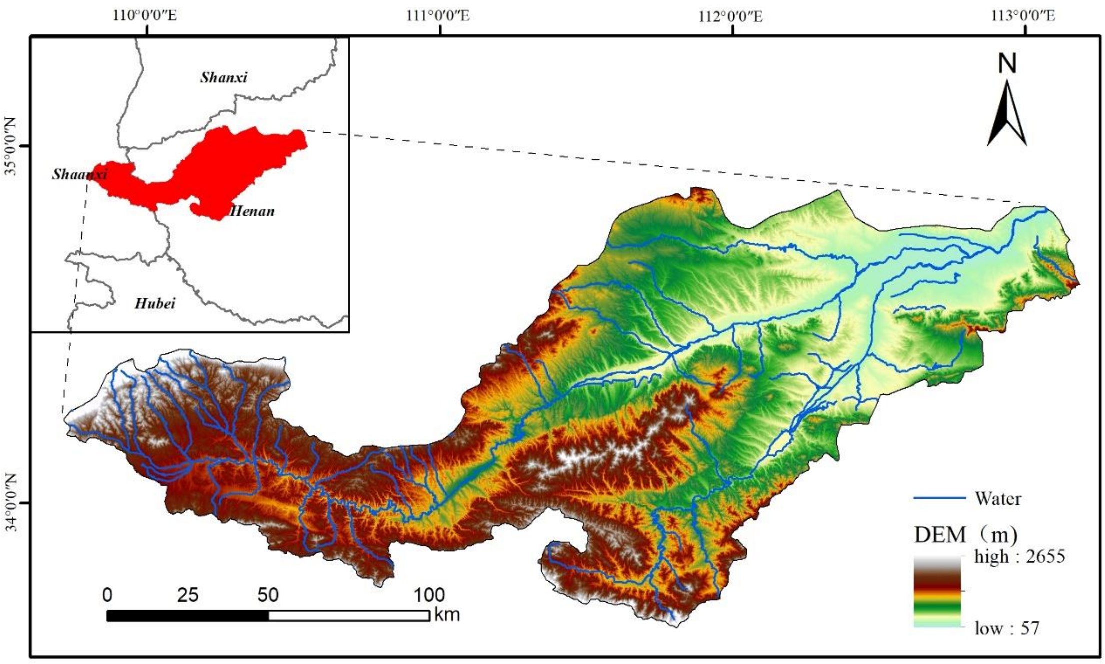

Figure 1. Study area location

2.2. Data source and processing

The main sources of data are shown in Table 1. The projection coordinate system is standardized using WGS-1984-UTM-Zone-49N.

Table 1 Data source

Date	type	Data source
Land use	Grid	Zenodo http:// zenodo.org/record/8176941
DEM	Grid	Geospatial data cloud https://www.gscloud.cn/search
Annual rainfall Annual temperature Annual evaporation	Grid	National Earth System Science Data Center http://www.geodata.cn/data/
Soil data	Grid	World Soil Database V1.2 http://www.ncdc.ac.cn
NDVI	Grid	MOD13A3 dataset https://search.earthdata.nasa.gov/searchNASA

2.3. Research methods

2.3.1. ESs Assessment Methodology

In this study, the physical quantities of four ecosystem services were quantitatively evaluated using the InVEST model. The basic calculations are summarized in Table 2.

Table 2 Quantitative evaluation methods for ESs

ESs	Calculation Formula
WY	$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \cdot P(x)$ (1) AET(x) : Actual annual evapotranspiration (mm); P(x) :Annual precipitation (mm)[2]
SC	$SDR = RKLS - USLE = R \times K \times LS \times (1 - C \times P)$ (2) R: the factor of rainfall erosion; K: soil erodibility factor; LS: slope length and slope factor; C: vegetation cover factor; P:soil-water conservation measure factor[9]
CS	$C_{total} = C_{above} + C_{below} + C_{soil} + C_{dead}$ (3) C_{above}、C_{below}、C_{soil} and C_{dead} represent the carbon density of aboveground biomass, belowground biomass, dead and soil organic matter, respectively[6]
HQ	$Q_{xj} = H_j \times (1 - \frac{D_{xj}}{D_{xj}+k})$ (4) H: habitat suitability; D: Degree of habitat degradation; K:semi-saturation factor; Z: normalization constants[10]

2.3.2. The optimal parameter Geodetector

The Geodetector model[11] can be used for quantitatively detecting spatial heterogeneity and identifying its driving forces. The q-statistic measures the explanatory power of a factor on the spatial heterogeneity of the dependent variable, with a range from 0 to 1; the higher the q-value, the stronger the explanatory power. The optimal parameter Geodetector[12] improves the accuracy of assessing the explanatory power of driving factors by discretizing continuous data and selecting appropriate discretization parameters. The expression is as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (5)$$

Where h is the number of layers, h=1,..., L is the stratification of ecosystem service function Y and influence factor X; Nh and N are the number of units in layer h and the whole region, respectively; σ_h^2 and σ^2 are the variance of the values of the dependent variable Y of the ecosystem service in layer h and the whole region, respectively.

3. RESULTS AND ANALYSIS

3.1. Characteristics of spatial and temporal changes in land use

Spatially, the land use types in the Luo River Basin are predominantly arable land and forest land, accounting for over 85% of the total basin area. Arable land is mainly distributed in the middle and lower reaches of the basin, centered around Luoyang City, while grasslands are primarily found in the middle reaches of the Luo River. Due to the illegal occupation of large areas of arable land and grasslands by urban expansion, the total arable land area decreased by 813.91 km², and the grassland area decreased by 561.00 km² between 2000 and 2020. In contrast, due to the implementation of the "Grain-for-Green" policy and forestry ecological construction, the area of forest land increased by a total of 781.93 km², primarily in the upper reaches of the Luo River. Construction land is mainly distributed in the lower reaches of the Luo River, forming central urban areas such as Luoyang City and Yanshi City, with a total area increase of 561.24 km². Additionally, with the development of hydraulic construction and fishery production, the number of reservoirs and ponds in the basin has increased, leading to a continuous expansion of water areas. These water bodies are primarily located in the Luhun Reservoir in the middle reaches of the Yi River within Luoyang. Over the past 20 years, the total water area has increased by 31.53 km². The area of unused land is relatively small and is mainly located around construction areas. Between 2000 and 2020, the land use type area transfers in the Luo River Basin (Table 3) show that the top three changes were: arable land to forest land (594.48 km²), arable land to construction land (572.49 km²), and grassland to forest land (469.87 km²). Due to various human activities, the land use coverage has undergone significant changes.

Table 3 Transfer matrix of land use types in the Luo River Basin, 2000-2020 (km²)

2000\2020	Cropland	Forest	Grasslands	Waters	Unused	Construction	Total	Total transfers
cropland	7509.04	594.48	130.17	18.72	0.07	572.49	8824.96	1315.93
Forest	227.60	7593.85	48.09	0.23	0.03	6.85	7876.65	282.80
Grasslands	259.20	469.87	485.51	1.12	0.18	9.10	1224.98	739.47
Waters	8.18	0.37	0.16	54.55	0.02	3.63	66.91	12.36
Unused	0.00	0.00	0.01	0.00	0.00	0.06	0.08	0.08
Construction	7.02	0.02	0.03	23.82	0.00	760.18	791.07	30.89
Total	8011.05	8658.58	663.98	98.44	0.31	1352.31	18784.65	2381.52
Total transfers	502.01	1064.73	178.47	43.89	0.30	592.13	2381.52	—

3.2. Characterization of spatial and temporal changes in ecosystem services

From 2000 to 2020, the average water yield exhibited a trend of first decreasing and then increasing (Figure 2). In 2020, the water yield decreased by 45.24 mm compared to 2000. The high-value areas are primarily in the southern part of the basin, such as Luanchuan County and Songxian County, while the low-value areas are mainly in the northern part of the downstream region, including Shanzhou District and Mianchi County. Overall, there is a gradual decrease from northwest to southeast. During the study period, the average annual precipitation across the five stages was 783.86 mm, 754.83 mm, 729.10 mm, 695.67 mm, and 738.59 mm, respectively. A comparison reveals that the trend in water yield corresponds closely with changes in precipitation. Over the 20 years, areas with an increase in water yield per unit area were primarily located in the northwestern part of the basin, including Mianchi County, Shanzhou District, and Huazhou District. Conversely, areas with a decrease in water yield were mainly in the northeastern part of the basin, east of Yiyang County. The carbon storage initially showed a slight decrease followed by a gradual increase, resulting in an overall growth trend with an increase of 8.88%. Over the 20 years, the spatial distribution of carbon storage in the Luo River Basin remained consistent, characterized by higher values in the central and southern regions and lower values in the northwest. Across the entire basin, carbon storage generally exhibited an increasing trend, particularly in forested areas, indicating that the carbon storage capacity of forests is continuously strengthening. The areas with decreased carbon storage were primarily concentrated in built-up land, where economic development and urban expansion led to the reduction of farmland and forests, resulting in decreased biomass and carbon storage.

Soil conservation initially showed a decreasing trend, followed by an increase, but overall, it exhibited a declining pattern. From 2000 to 2015, the average soil conservation decreased by 45.77 tons, representing a reduction of 16.19%, while from 2015 to 2020, it increased by 24.03 tons, reflecting a growth of 10.14%. The soil conservation capacity was strongest in 2000 and weakest in 2015. The study found that soil conservation was largely concentrated in low-value areas, with regions of strong soil conservation capacity being relatively scattered. Over the 20 years, the areas with significant decreases in soil conservation were mainly located in the central and southern parts of the basin, which were similar in distribution to areas with strong soil conservation capacity within the basin. Additionally, some scattered areas with reductions were found in the eastern region. In contrast, areas with significant increases in soil conservation were primarily dispersed in the western part of the basin. Habitat quality showed a year-by-year decline, decreasing from 0.47 to 0.44, a reduction of 6.38%. Over the 20 years, the overall spatial distribution of habitat quality in the Luo River Basin remained similar, with high values concentrated in the central and western regions, particularly in Luan County and eastern Lushi County. Low-value areas were primarily located in the northeastern part, around Luoyang City and its surrounding towns. The consistency of high-value areas with forested regions indicates a close relationship between habitat quality and land use types.

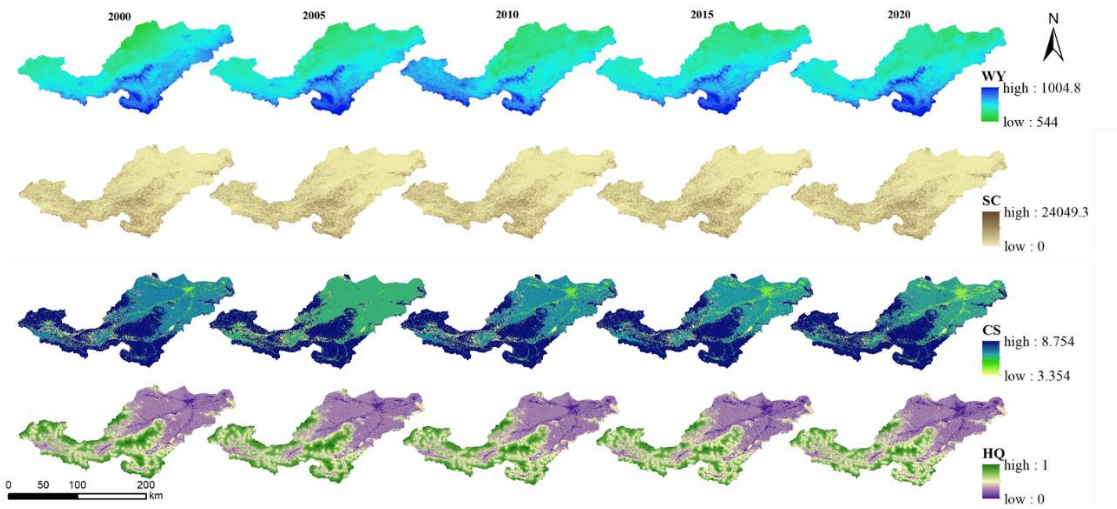

Figure 2 Spatial distribution of ecosystem services in the Luo River Basin, 2000-2020

3.3. Analysis of Factors Influencing Ecosystem Services

The optimal parameter Geodetector model[12]was employed to comprehensively assess the vulnerability of the watershed's ecological environment to natural factors and human activities. Four ecosystem services were selected as dependent variables (Y), and nine influencing factors were chosen as potential predictors, covering six aspects: topography, climate, land use types, vegetation, and socioeconomic factors. Specifically, the independent variables (X) include elevation (X1), slope (X2), annual precipitation (X3), annual mean temperature (X4), annual potential evapotranspiration (X5), land use type (X6), normalized difference vegetation index (NDVI) (X7), gross domestic product (GDP) (X8), and population density (X9).

According to the factor detection results (Table 2), the primary influencing factor for water yield was X3, with an explanatory power of 0.845, indicating that rainfall is the main source of water for the ecosystem. The primary influencing factor for carbon storage is X6, with an explanatory power of 1, demonstrating that land use type is the decisive factor affecting the spatial heterogeneity of carbon storage. The primary influencing factor for soil conservation is X2, with an explanatory power of 0.132. For habitat quality, the main influencing factor is also X6, with an explanatory power of 0.825. Although habitat quality is less affected by social factors, societal development still impacts the living environment for organisms. Among the ecosystem services, X8 is consistently the factor with the smallest impact. The interaction detection results (Figure 3) show that the q-values for the interactions between factors are all higher than those for single-factor detection, indicating that factor interactions can enhance the explanatory power of individual factors on ecosystem services. The interaction detection results indicate bilinear or nonlinear enhancement. The interaction between X8 and X9 shows an increased explanatory power, but the enhancement effect is not significant, suggesting that natural factors have a greater influence on ecosystem services compared to social factors.

Table 2 Detection results of ecosystem service factors

driving factor	WY	SC	CS	HQ
X1	0.3628*	0.0913*	0.3089*	0.7037*
X2	0.1772	0.1325*	0.2767*	0.4577*
X3	0.8448*	0.0774*	0.2765*	0.4612*
X4	0.2887*	0.0849*	0.2539*	0.5243*
X5	0.3920*	0.0918*	0.3207*	0.6656*
X6	0.1765	0.0798*	1.0000*	0.8247*
X7	0.3807*	0.0902*	0.3845*	0.6564*
X8	0.0007	0.0012	0.0152	0.0161*
X9	0.0241	0.0094	0.0847	0.0970*

Note: with * passes the test of significance

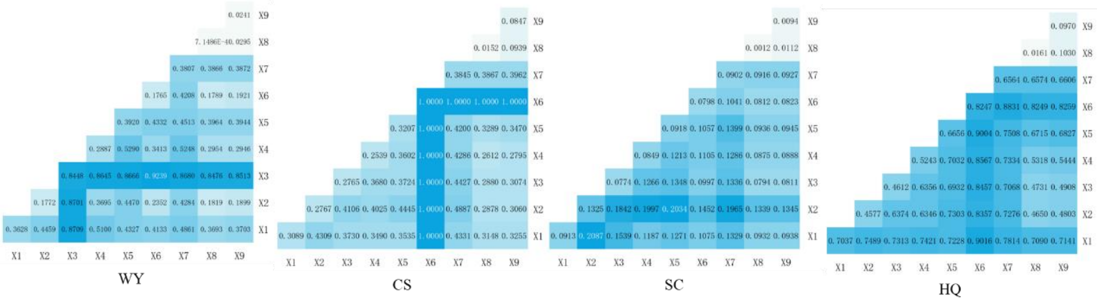

Figure. 3 Interaction detection results of ecosystem service drivers

4. DISCUSSIONS

Between 2000 and 2020, the Luo River Basin primarily experienced conversions among arable land, forest land, and grassland. The white paper Twenty Years of Returning Farmland to Forest and Grassland in China (1999-2019) reveals that over this period, China implemented policies to return a total of 515 million mu of farmland to forests and grasslands, significantly increasing forest coverage and markedly improving the ecological environment. The mass migration of rural laborers to urban areas for work has led to a sharp decline in rural populations and significant abandonment of arable land. To prevent land from lying fallow, some farmers have planted trees on their fields, resulting in localized instances of "returning farmland to forest." To implement the delineation of the three control lines and prioritize the ecological conservation of arable and forest lands, it is necessary to ensure that all farmland is preserved and that land occupation and compensation are balanced, while also vigorously promoting forestry ecological construction.

The study found that between 2000 and 2020, water yield, soil conservation, and carbon storage in the Luo River Basin initially declined and then increased, while habitat quality showed a consistent downward trend, indicating a deterioration in ecological environmental quality. The fluctuation in water yield, characterized by an initial decrease followed by an increase, is closely linked to rainfall, with precipitation being the primary influencing factor. This finding is consistent with the results of Peng et al. [13], indicating that water yield is largely influenced by natural factors. Therefore, efforts should be made to strengthen the protection of natural ecosystems and reduce human interference. The primary factor influencing soil conservation is slope, which is consistent with the findings of Wang et al. [14]. The study shows that terrain has a significant impact, with smaller slopes leading to stronger soil conservation capabilities. However, in areas with low slopes, frequent human activities and significant surface disruption result in relatively weaker soil conservation capabilities. The primary factors influencing carbon storage and habitat quality are land use types, consistent with the findings of Wang [9] and Zhang [10]. Forests and croplands are the primary carbon storage areas. Strengthening forest development and protection, while appropriately controlling construction land, will optimize land use structure and provide a scientific basis for regional ecological management and land use planning in the future.

5. CONCLUSION

This study focuses on the Luo River Basin to analyze land use type changes from 2000 to 2020. Using the InVEST model and geographical detectors, the study explores the spatiotemporal variations and influencing factors of four ecosystem services in the study area. The results are as follows:

(1) Between 2000 and 2020, the area of arable land converted to other land types was 1,315.93 km^2, with this converted area accounting for more than half of the total land conversion. At the same time, the area of construction land continuously increased, encroaching on arable land.

(2) Between 2000 and 2020, the ecosystem services of water yield, soil conservation, and carbon storage in the Luo River Basin initially decreased and then increased, while habitat quality exhibited a consistent decline, indicating overall ecological degradation.

(3) Natural factors play a dominant role in influencing ecosystem services, with the impact of interactions being significantly greater than that of individual factors. These interactions exhibit characteristics of either two-factor enhancement or non-linear enhancement. Therefore, it is essential to strengthen natural ecological protection and reduce human interference.

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