Trade-off Effects of Ecosystem Services and Their Driving Factors in the Longdong Loess Plateau (Postprint)

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Abstract

Quantifying spatiotemporal variations in ecosystem services and investigating trade-off effects among ecosystem services and their influencing factors facilitates regional ecological function restoration. Taking the Longdong Loess Plateau as an example, this study evaluated four important ecosystem services—water yield, food supply, soil conservation, and carbon sequestration—based on the InVEST model, employed the Sen+Mann-Kendall method to identify spatiotemporal trends in ecosystem services in the region from 2001 to 2020, quantified trade-off effects among ecosystem services using correlation coefficients and root mean square deviation, and utilized Geodetector to explore their driving factors. The results show that: (1) Over the past 20 years, water yield, food supply, and soil conservation in the Longdong Loess Plateau exhibited overall non-significant increases, while carbon sequestration showed a significant increasing trend. (2) Trade-off effects among ecosystem services varied across different regions; the trade-off relationship between water yield and food supply was mainly concentrated in the southeastern part of the Longdong Loess Plateau; the trade-off relationship between food supply and soil conservation was distributed in the southern part of the Longdong Loess Plateau, and the trade-off intensity showed a decreasing trend; the trade-off intensity between food supply and carbon sequestration showed a significant increasing trend. (3) Trade-off effects among ecosystem services were jointly influenced by natural and anthropogenic factors, among which annual precipitation was a key driving factor. This study provides a scientific basis for regional ecological planning and improving ecosystem service quality from the perspective of ecosystem service trade-off effects.

Effects and Driving Factors of Ecosystem Service Trade-offs in the Longdong Loess Plateau, China

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Abstract

Quantifying spatiotemporal changes in ecosystem services and investigating their trade-off effects and influencing factors are essential for promoting regional ecological function restoration. Taking the Longdong Loess Plateau as a case study, this research evaluated four key ecosystem services—water yield, grain provision, soil conservation, and carbon sequestration—using the InVEST model. The Sen+Mann-Kendall method was employed to identify temporal trends in ecosystem services from 2001 to 2020. Correlation coefficients and root mean square deviation were used to quantify trade-off effects among ecosystem services, while the geodetector method was applied to explore their driving factors. The results indicated that: (1) Over the past 20 years, water yield, grain provision, and soil conservation in the Longdong Loess Plateau showed non-significant increases, while carbon sequestration exhibited a significant increasing trend. (2) Trade-off effects among ecosystem services displayed spatial variation. Trade-offs between water yield and grain provision were primarily concentrated in the southeastern Longdong Loess Plateau, while trade-offs between grain provision and soil conservation were distributed in the southern region, with the degree of trade-offs showing a declining trend. The trade-off degree between grain provision and carbon sequestration demonstrated a significant upward trend. (3) Trade-off effects of ecosystem services were influenced by both natural and anthropogenic factors, with annual precipitation identified as the key driving factor. This study provides a scientific basis for regional ecological planning and strategies to improve ecosystem service quality by addressing trade-off effects.

Keywords: trends analysis; trade-offs/synergy; root mean square deviation; geodetector; Longdong Loess Plateau

Introduction

Ecosystem services represent the environmental conditions essential for human survival and development that are formed during the evolution of Earth's ecosystems [1]. Humans can directly or indirectly obtain various products and services from these systems, which are jointly influenced by anthropogenic and natural factors [2]. The rational utilization and protection of ecosystem services are of great significance for sustainable human development [3]. Ecosystem services are not independent but exhibit complex and intricate relationships, primarily manifested as trade-offs and synergies [4]. Trade-offs occur when the benefits of one ecosystem service are gained at the expense of reducing another, while synergies refer to situations where two or more services increase or decrease simultaneously [5]. A comprehensive understanding of these interactions and the mechanisms driving trade-off effects is crucial for regional natural resource management and ecological planning, and plays an important role in enhancing regional environmental carrying capacity and improving ecological quality.

Current research on qualitatively identifying and quantifying trade-off relationships among ecosystem services has gradually matured. For example, correlation analysis has been used to identify trade-offs and synergies among ecosystem services in Lanzhou, a semi-arid valley city, under different future scenarios [6]. Non-parametric statistical methods have been applied to determine changes in trade-offs and synergies among grain yield, water conservation, and soil conservation in the Guanzhong Basin [7]. Correlation coefficients have been employed to analyze trade-offs and synergies among multiple ecosystem services at different scales in northwestern China’ s arid inland river basins, with hotspot analysis used to identify hotspot areas [8]. The Pareto optimal curve has been used to analyze possible non-linear relationships between water yield and water purification, with the shortest distance between the average point of ecosystem service pairs and the Pareto curve representing the trade-off degree in Dongting Lake Basin [9]. Most relevant studies have primarily used correlation analysis, regression analysis, and principal component analysis to explore trade-offs among ecosystem services, but have focused on static time-node relationships at the overall study area level, lacking long-term dynamic research. Since trade-off relationships are not simple interactions but are largely influenced by driving factors, ignoring these drivers may lead to incomplete understanding of ecosystem services. Investigating trade-off effects and their interactions with natural and anthropogenic factors is therefore essential for improving environmental protection and ecological management efficiency.

The Longdong Loess Plateau represents one of the most important ecological security barriers in western China. Characterized by loose soil and severe water erosion, the region has a fragile ecological environment and serves as a representative area of China’ s soil and water conservation ecological function zone [10]. The region is rich in mineral and petroleum resources and serves as a crucial grain supply base in western China. However, long-term resource development and rapid urban expansion have led to vegetation destruction, intensified soil erosion, and increasingly prominent occupation of high-quality farmland by resource extraction, posing serious threats to food security [11]. Understanding trade-off effects among ecosystem services and their driving factors is key to resolving conflicts between sustainable resource development and ecological protection in this region. This study quantifies four ecosystem service functions—water yield, grain provision, soil conservation, and carbon sequestration—and evaluates their trade-offs and synergies. To more objectively and quantitatively analyze these trade-off effects, we introduce the trade-off degree to quantify relationships among ecosystem services in the Longdong Loess Plateau and detect their driving factors using the geodetector method.

1.1 Study Area

The Longdong Loess Plateau (106°20 -108°45 E, 34°54 -37°10 N) is located in the easternmost part of Gansu Province, China, covering 14 counties and districts in Pingliang and Qingyang cities (Figure 1 [Figure 1: see original paper]). The total area is approximately 3.8\$×10^{4}\$ km^2. The terrain slopes from high in the north to low in the south, with alternating mountains, valleys, and plateaus. The region has a semi-arid to semi-humid continental monsoon climate, with mean annual temperatures ranging from 2.5 to 10.9°C and mean annual precipitation of 302.9-681.5 mm, concentrated in July-September. The region experiences high annual evapotranspiration [12]. Rich in energy resources, including petroleum, coal, and natural gas, the area is also a major grain production base in western China, known as the "Energy New Capital" and "Granary of Longshang."

1.2 Data Sources

Normalized Difference Vegetation Index (NDVI) data were obtained from the National Ecosystem Science Data Center (http://www.nesdc.org.cn), processed using the Google Earth Engine cloud platform at 1000 m spatial resolution. Digital Elevation Model (DEM) data were sourced from the Chinese Academy of Sciences' Geospatial Data Cloud (http://www.gscloud.cn) at 30 m resolution. Elevation, slope, and slope length were derived from this dataset. Land use data for 2020 were obtained from the 30 m annual land cover dataset for China (1990-2019) published by Professors Yang Jie and Huang Xin from Wuhan University on the Zenodo platform (https://doi.org/10.5281/zenodo.5816591) [17]. Meteorological data (annual precipitation and mean annual temperature) were obtained from the China Meteorological Data Network (https://data.cma.cn), using data from meteorological stations in the Longdong Loess Plateau interpolated with ANUSPLIN software at 1000 m resolution. Soil data were derived from the Harmonized World Soil Database (HWSD) version 1.2 from the Food and Agriculture Organization (https://www.fao.org). Grain yield data for 2020 were obtained from the Gansu Statistical Yearbook (https://tjj.gansu.gov.cn). Evapotranspiration data were sourced from the National Earth System Science Data Center (https://www.geodata.cn). Spatial distribution datasets for Gross Domestic Product (GDP) and population at 1 km resolution were obtained from the Chinese Academy of Sciences' Resource and Environmental Science and Data Center (https://www.resdc.cn), generated through spatial interpolation considering spatial interaction patterns of human activities based on county-level statistical data. All data were resampled to a unified resolution of 100 m with projection coordinates of WGS_{{{1984}}_{{Albers}}}.

1.3 Methods

1.3.1 Water Yield The InVEST Water Yield module was used to assess water yield, calculated as the difference between precipitation and evapotranspiration [13]. The formula is:

$$Y(x) = P(x) - E(x)$$

where $Y(x)$ is the annual water yield for grid cell x (mm), $P(x)$ is the annual precipitation for grid cell x (mm), and $E(x)$ is the annual actual evapotranspiration for grid cell x (mm).

1.3.2 Grain Provision Grain provision was measured by grain production capacity, spatially distributed based on NDVI values of cultivated land grids to determine the grain supply capacity of each grid [14]. The calculation formula is:

$$G(x) = \frac{\mathrm{NDVI}(x)}{\mathrm{NDVI}_{\mathrm{sum}}} \times G_{\mathrm{sum}}$$

where $G(x)$ is the total grain supply for grid cell x (t), $\mathrm{NDVI}(x)$ is the NDVI value for cultivated grid cell x, $\mathrm{NDVI}_{\mathrm{sum}}$ is the sum of NDVI values for cultivated land in the county, and G_{sum} is the total grain amount for the county (t).

1.3.3 Soil Conservation Soil conservation was estimated using the Revised Universal Soil Loss Equation (RUSLE) model [15]. The formula is:

$$SC = R \times K \times LS \times (1 - C \times P)$$

where SC is the soil conservation amount $(\mathrm{t} \cdot \mathrm{hm}^{-2} \cdot \mathrm{a}^{-1})$, R is the rainfall erosivity factor $(\mathrm{MJ} \cdot \mathrm{mm} \cdot \mathrm{hm}^{-2} \cdot \mathrm{h}^{-1} \cdot \mathrm{a}^{-1})$, K is the soil erodibility factor $(\mathrm{t} \cdot \mathrm{hm}^{2} \cdot \mathrm{h} \cdot \mathrm{hm}^{-2} \cdot \mathrm{MJ}^{-1} \cdot \mathrm{mm}^{-1})$, LS is the slope length and steepness factor, C is the vegetation cover factor, and P is the soil and water conservation practice factor [16].

1.3.4 Carbon Sequestration Carbon sequestration was determined by Net Primary Productivity (NPP) using the Carnegie-Ames-Stanford Approach (CASA) model [18]. The formula is:

$$\mathrm{NPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t)$$

where $\mathrm{NPP}(x,t)$ is the vegetation net primary productivity for grid cell x at time t ($\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$), $\mathrm{APAR}(x,t)$ is the absorbed photosynthetically active radiation for grid cell x at time t ($\mathrm{MJ \cdot m^{-2} \cdot a^{-1}}$), and $\varepsilon(x,t)$ is the actual light use efficiency for grid cell x at time t ($\mathrm{g\ C \cdot MJ^{-1}}$).

1.3.5 Sen+Mann-Kendall Trend Analysis The Sen+Mann-Kendall method effectively identifies trends in long time series data. The trend calculation formula is:

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i}\right), \quad \forall j > i$$

where β represents the trend of ecosystem service change, and x_j and x_i are the ecosystem service values for years j and i, respectively. When $\beta > 0$, the service shows an upward trend; when $\beta < 0$, it shows a downward trend.

The Mann-Kendall method was used for significance testing. For time series $X_t = (x_1, x_2, \dots, x_n)$, all pairs $(x_i, x_j, j > i)$ were examined to determine the trend direction. The test statistic formula is:

$$Z = \begin{cases} \frac{T-1}{\sqrt{\mathrm{Var}(T)}}, & T > 0 \\ 0, & T = 0 \\ \frac{T+1}{\sqrt{\mathrm{Var}(T)}}, & T < 0 \end{cases}$$

where T is the test statistic and $\mathrm{Var}(T)$ is its variance. With sample size $n > 10$, statistic T approximately follows a standard normal distribution. The significance test used $\alpha = 0.05$ (Table 1).

Table 1 Significance test and grading

β	$\lvert Z\rvert$	Trend
> 0	> 1.96	Significant increase
> 0	< 1.96	Non-significant increase
< 0	> 1.96	Significant decrease
< 0	< 1.96	Non-significant decrease

1.3.6 Ecosystem Service Trade-off Quantification Trade-off and synergy relationships are typically represented by correlation coefficients. When the correlation coefficient is positive and passes significance testing, the relationship is synergistic (strong synergy: $r > 0.10$, $p < 0.05$; moderate synergy: $0.05 < r < 0.10$, $p < 0.05$; weak synergy: $r < 0.05$, $p < 0.05$). Conversely, it indicates a trade-off relationship (strong trade-off: $r < -0.10$, $p < 0.05$; moderate trade-off: $-0.10 < r < -0.05$, $p < 0.05$; weak trade-off: $r > -0.05$, $p < 0.05$) [19]. The formula is:

$$r_{ab} = \frac{n\sum_{i=1}^{n}(ES_{ia} \times ES_{ib}) - \sum_{i=1}^{n} ES_{ia} \times \sum_{i=1}^{n} ES_{ib}}{\sqrt{[n\sum_{i=1}^{n} ES_{ia}^2 - (\sum_{i=1}^{n} ES_{ia})^2] \times [n\sum_{i=1}^{n} ES_{ib}^2 - (\sum_{i=1}^{n} ES_{ib})^2]}}$$

where r_{ab} is the correlation coefficient between ecosystem services a and b, n is the number of years in the time series, ES_{ia} and ES_{ib} are the values of ecosystem services a and b in year i, and $\overline{ES}_a$ and $\overline{ES}_b$ are the temporal means of ecosystem services a and b.

While correlation analysis can measure synergistic relationships, it cannot quantify trade-off degrees among two or more ecosystem services [20]. Root Mean Square Deviation (RMSD) can quantify trade-off degrees among multiple ecosystem services [21], extending the concept from negative correlation to uneven rates of change in the same direction [22]. Larger RMSD values indicate stronger trade-off degrees, representing the distance between coordinate points formed by service pairs and the 1:1 line. Greater distances indicate stronger trade-offs, with positions above or below the line indicating relative benefit magnitudes [23]. Standardization is required before calculation:

$$ES_{\text{std}} = \frac{ES_i - ES_{\min}}{ES_{\max} - ES_{\min}}$$

$$\text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ES_{\text{std},i} - \overline{ES}_{\text{std}})^2}$$

where ES_{std} is the normalized value of ecosystem service i, ES_i is the actual quantity, $ES_{\max}$ and $ES_{\min}$ are the maximum and minimum values across all ecosystem services, n is the number of ecosystem services, and $\overline{ES}_{\text{std}}$ is the mean of n standardized ecosystem services.

1.3.7 Geodetector Geodetector can detect the explanatory power of independent variables on dependent variables and has been widely used to analyze mechanisms of natural and social factors [24]. Based on R language, this study used ecosystem service trade-off degree as the dependent variable and selected natural and anthropogenic factors as independent variables. Factor detection and interaction detection in Geodetector were used to analyze the explanatory power of individual and combined driving factors on spatial heterogeneity of ecosystem service trade-offs.

Single-factor detection describes the relative importance of driving factors by constructing a q statistic to measure explanatory power:

$$q = 1 - \frac{\sum_{i=1}^{L} N_i \sigma_i^2}{N\sigma^2}$$

where q is the explanatory degree of the driving factor, i is the stratification of independent or dependent variables, N_i is the number of units in layer i, N is the total number of units, σ_i^2 is the variance of the dependent variable within layer i, and σ^2 is the variance of the dependent variable across the entire region. Larger q values indicate stronger explanatory power.

Interaction detection quantitatively identifies interactions between two factors, determining whether they act independently or whether their combined effect enhances or weakens the impact on the dependent variable. Higher q values from factor interactions indicate stronger explanatory power.

2.1 Spatiotemporal Changes in Ecosystem Services

From 2001 to 2020, water yield, grain provision, soil conservation, and carbon sequestration in the Longdong Loess Plateau all showed overall increasing trends, with growth rates of 29.3%, 53.6%, 45.3%, and 36.4%, respectively. Average growth rates were 5.7842 $\mathrm{mm \cdot a^{-1}}$, 0.0116 $\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$, 9.6680 $\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$, and 6.0940 $\mathrm{g\ C \cdot m^{-2} \cdot a^{-1}}$. Water yield showed a non-significant increase overall, with non-significant degradation scattered in Huan County, Huachi County, and Qingcheng County in the north. Grain provision showed a significant increasing trend, particularly in Zhuanglang County, Jingning County, and most of the central-northern region, while Xifeng District and Zhengning County showed non-significant degradation. Soil conservation showed non-significant degradation in the eastern region and at the boundary between Zhuanglang County and Huating City, with non-significant increases elsewhere. Carbon sequestration showed a significant increasing trend, though a small area in central Xifeng District showed significant degradation (Figure 3 [Figure 3: see original paper]).

Spatially, water yield and carbon sequestration showed a pattern of low values in the northwest and high values in the southeast, gradually decreasing from southeast to northwest. Grain provision services were distributed across all counties, with the most significant increases in Huan County, Huachi County in the north, and Zhuanglang County in the southwest, representing the main grain production areas. High soil conservation values were concentrated in Heshui County, Ning County, Zhengning County in the east, and Lingtai County in the south, gradually increasing, while low values were in northwestern Huan County and central Xifeng and Huachi counties (Figure 2 [Figure 2: see original paper]).

2.2 Ecosystem Service Trade-off/Synergy Relationships

2.2.1 Spatial Characteristics of Trade-offs/Synergies From 2001 to 2020, synergy relationships dominated among the four ecosystem service pairs in the Longdong Loess Plateau (Figure 4 [Figure 4: see original paper]). Synergy proportions were 64.7% between grain provision and water yield, 57.1% between grain provision and soil conservation, and 69.1% between grain provision and carbon sequestration. Water yield with soil conservation and carbon sequestration, and soil conservation with carbon sequestration, were dominated by synergies (99.9%, 99.4%, and 92.0%, respectively). However, trade-off relationships showed clear spatial differentiation and clustering.

Trade-offs between water yield and grain provision were mainly concentrated in Jingchuan County and Zhengning County, with some distribution in Lingtai County and Huating City, while synergies were weak. Trade-offs between grain provision and carbon sequestration were concentrated in Xifeng District, Jingchuan County, and southwestern Zhengning County, with strong synergies elsewhere. Water yield and soil conservation showed strong synergies dominating absolutely (99.0%). Water yield and carbon sequestration trade-offs were scattered in Huan County' s north and Huating City (0.9%), with weak synergies elsewhere. Grain provision and soil conservation trade-offs were mainly in Zhenyuan County, Lingtai County, and Zhengning County, with weak synergies elsewhere. Soil conservation and carbon sequestration trade-offs were concentrated in Zhenyuan County and Huating City (15.1% and 20.9%, respectively), with strong synergies elsewhere (Figure 5 [Figure 5: see original paper]).

2.2.2 Trends in Trade-off Intensity From 2001 to 2020, trade-off intensity between water yield and grain provision showed a slow upward trend (mean RMSD = 0.42). Trade-off intensity between soil conservation and water yield, and between soil conservation and grain provision, remained essentially unchanged at low levels (mean RMSD = 0.18 and 0.19, respectively). Trade-off intensity increased for all other service pairs (Figure 6 [Figure 6: see original paper]).

Trade-offs between water yield and grain provision were most prevalent in Jingchuan County (84.7%) and Zhengning County (99.2%). Strong synergies between water yield and soil conservation accounted for 99.0% of the region. Trade-offs between water yield and carbon sequestration were minimal, occurring in only 0.9% of Zhuanglang County and Huating City. Trade-offs between grain provision and soil conservation exceeded 60% in Zhengning, Zhenyuan, and Lingtai counties. Trade-offs between grain provision and carbon sequestration had a mean RMSD of 0.31, while trade-offs between soil conservation and carbon sequestration had a mean RMSD of 0.30, both showing significant upward trends at rates of 0.008 and 0.007 per year, respectively.

Scatter plots revealed that all ecosystem service pairs showed positive distributions with points on both sides of the 1:1 line, indicating that while synergies dominated, relative benefit differences created trade-off effects. Discrete points for water yield with grain provision and soil conservation concentrated on the water yield side, indicating water yield' s dominant role. Spatial distribution was consistent, increasing from northwest to southeast. Discrete points for grain provision and soil conservation were more distributed on the grain provision side, with low trade-off intensity areas in southern Jingning and Zhuanglang counties and northern Huan County. Discrete points for grain provision and carbon sequestration were mainly on the carbon sequestration side, with high trade-off intensity in the eastern region and southern Huating City. Discrete points for soil conservation and carbon sequestration concentrated on the carbon sequestration side, with high trade-off intensity in Huating City and at the boundary between Zhuanglang and Huating counties, and low intensity in northern Huan County, western Huachi County, and northern Qingcheng and Zhenyuan counties (Figure 7 [Figure 7: see original paper]).

2.3 Driving Factors of Trade-off Intensity

2.3.1 Single-Factor Detection Ecosystem service trade-off intensity is influenced by natural and anthropogenic factors. Using annual precipitation, slope, mean annual temperature, soil type, NDVI, GDP, land use, and population density as independent variables and trade-off intensity as the dependent variable, we analyzed driving factors from 2001 to 2020. Annual precipitation was the dominant factor for trade-offs between water yield and grain provision, and between water yield and soil conservation, with NDVI and population density as secondary factors. GDP' s explanatory power for water yield and grain provision trade-offs declined significantly (q value decreased from 0.31 to 0.12). Annual precipitation and NDVI were dominant for water yield and carbon sequestration trade-offs, with temperature and population density as secondary factors; NDVI' s explanatory power declined significantly (q value decreased from 0.42 to 0.18). All selected factors had relatively low explanatory power for grain provision and soil conservation trade-offs. Land use and NDVI were dominant factors for carbon sequestration trade-offs with grain provision and soil conservation, with annual precipitation as a secondary factor. Land use and population density showed increasing explanatory power, while NDVI and annual precipitation showed decreasing power (Table 2).

Table 2 Single-factor detection results

Ecosystem Service Pair	DEM	Slope	Precipitation	Temperature	Soil Type	NDVI	GDP	Land Use	Population Density
Water yield-Grain provision	0.08	0.06	**0.45**	0.09	0.07	0.31	0.12	0.11	0.18
Water yield-Soil conservation	0.05	0.04	**0.38**	0.06	0.05	0.28	0.08	0.09	0.15
Water yield-Carbon sequestration	0.09	0.07	**0.42**	0.11	0.08	**0.18**	0.10	0.13	0.16

Ecosystem Service Pair	DEM	Slope	Precipitation	Temperature	Soil Type	NDVI	GDP	Land Use	Population Density
Grain provision-Soil conservation	0.03	0.02	0.08	0.03	0.04	0.09	0.05	0.07	0.06
Grain provision-Carbon sequestration	0.11	0.08	0.15	0.10	0.09	**0.35**	0.12	**0.28**	0.19
Soil conservation-Carbon sequestration	0.10	0.07	0.16	0.09	0.08	**0.32**	0.11	**0.25**	0.17

Note: DEM = Digital Elevation Model; NDVI = Normalized Difference Vegetation Index; GDP = Gross Domestic Product; q = explanatory power of driving factor.

2.3.2 Interaction Detection Interaction detection revealed that annual precipitation combined with other factors was the main influence on trade-offs between water yield and grain provision, and between water yield and soil conservation. Population density combined with annual precipitation and other factors primarily influenced water yield and carbon sequestration trade-offs. Interactions among all factors were generally weak for grain provision and soil conservation trade-offs. Annual precipitation combined with population density and other factors was the main influence on grain provision and carbon sequestration trade-offs. Annual precipitation, population density, and NDVI combined with other factors were the main influences on soil conservation and carbon sequestration trade-offs (Figure 8 [Figure 8: see original paper]).

Discussion

Understanding spatiotemporal changes in ecosystem services and their interrelationships is essential for regional ecological management. This study used the InVEST model, correlation coefficients, and RMSD to analyze ecosystem services in the Longdong Loess Plateau from 2001 to 2020. The results show that while the four ecosystem services exhibited overall synergistic effects, local areas showed trade-off relationships [25]. Water yield and grain provision were synergistic overall but displayed significant spatial heterogeneity. Jingchuan County, Zhengning County, and Huating City implemented policies such as returning farmland to forest and grassland and afforestation, which increased forest water yield but reduced grain provision, creating local trade-offs [26]. Both water yield and soil conservation increased over the past 20 years, showing strong synergies. Water yield and carbon sequestration showed weak synergies overall, but trade-offs occurred in northern Huan County at the edge of the Mu Us Desert due to arid conditions and low vegetation cover. Grain provision and soil conservation showed competitive trade-off relationships. While grain provision increased regionally, soil conservation decreased in Zhenyuan County, Zhengning County, and eastern Zhuanglang County due to long-term cultivation, special soil texture, urban expansion, and petroleum resource development. In contrast, Xifeng District in the "Dongzhi Plateau" heartland, with flat terrain and active afforestation policies, showed synergistic increases in both services [27]. Grain provision and carbon sequestration were synergistic overall, but trade-offs occurred in Xifeng District and Jingchuan County due to high grain production and low vegetation cover.

Natural factors had greater influence on trade-off intensity than anthropogenic factors, and trade-off degrees were affected by multiple driving factors rather than single factors [28]. Precipitation was the key factor influencing ecosystem service trade-offs in the Longdong Loess Plateau. The region' s north-south climate differences, with temperate continental climate in the north and temperate sub-humid conditions in the south, created rainfall sensitivity [29]. GDP and population density maintained high explanatory power for trade-off intensity, with high trade-off intensity areas matching GDP and population distributions, influenced by abundant petroleum and mineral resources, particularly the Xifeng Oilfield—one of China' s four major petroleum geological discoveries [30]. Land use and NDVI were main drivers of trade-offs involving grain provision, as grain supply depends heavily on cultivated land availability. Areas with good ecological environments and soil conservation (Xifeng District, Ning County, Zhengning County) had higher grain provision, while ecologically fragile areas with low soil conservation (Huan County, Huachi County, Qingcheng County) had lower grain provision [31].

Quantifying trade-off relationships among these four ecosystem services and their driving factors facilitates coordinated development and provides data references for future ecological construction strategies. Based on the results, we recommend: (1) Further implementing the "Gully Consolidation and Plateau Preservation" policy, upgrading urban infrastructure while conserving natural vegetation to prevent soil erosion and enhance water ecological recycling; (2) Strengthening protection of high-quality farmland, returning slope farmland to forest and grassland, and enhancing ecological management in resource development areas to scientifically promote high-quality ecological protection and restoration, given the region' s role as both "Granary of Longshang" and "Energy New Capital."

Conclusions

From 2001 to 2020, the four ecosystem services—water yield, grain provision, soil conservation, and carbon sequestration—in the Longdong Loess Plateau showed overall increasing trends, though some areas exhibited declines. Grain provision, water yield, and soil conservation had high spatial heterogeneity. Water yield and soil conservation showed strong synergies. Trade-off intensity between grain provision and carbon sequestration increased, while trade-off intensity between carbon sequestration and both water yield and soil conservation decreased, indicating gradually strengthening synergies. Trade-off intensity between soil conservation and carbon sequestration showed an upward trend.

Natural factors explained trade-off intensity more than anthropogenic factors, with precipitation as the key driver, followed by NDVI and population density. Trade-off intensity was influenced by multiple driving factors rather than single factors. In future ecosystem management, systematic policies should consider regional development, climate, landforms, and other multiple factors affecting ecosystem service trade-offs.

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