# Spatiotemporal Variation of Ecosystem Service Value in Loess Plateau Mining Areas: A Case Study of Pingshuo Mining Area Postprint

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## Abstract

Conducting spatiotemporal analysis of ecosystem service values in mining areas is of great significance for protecting the ecological environment of mining areas and enhancing ecosystem functions. Based on remote sensing data and land use data, and using methods such as 3S technology, the value equivalent method, and ecological contribution degree, this study investigates the ecosystem service value of Pingshuo Mining Area, a typical mining area on the Loess Plateau, from 1990 to 2020. The results show that: (1) From 1990 to 2020, the six land use types in Pingshuo Mining Area exhibited distinctly different area changes, with cultivated land showing the largest decrease (1122.72 $hm^2$) and construction land showing the largest increase (2044.23 $hm^2$). (2) The ecosystem service value of Pingshuo Mining Area showed a trend of first decreasing and then increasing, decreasing from 19562.43$×10^{4}$ yuan in 1990 to 11265.40$×10^{4}$ yuan in 2010, and then increasing to 15755.47$×10^{4}$ yuan in 2020. The main reason for the decline from 1990 to 2010 was the substantial reduction in ecosystem service values of construction land and grassland, while the main reason for the increase from 2010 to 2020 was the implementation of extensive ecological restoration and management projects in the mining area. (3) From 1990 to 2020, except for the increase in soil conservation value, all other individual ecosystem service values in Pingshuo Mining Area decreased to varying degrees, with water conservation, environmental purification, and biodiversity values showing relatively large reductions, decreasing by 115.84%, 69.92%, and 18.29%, respectively. (4) From 1990 to 2020, the spatial distribution of ecosystem service values in Pingshuo Mining Area exhibited a characteristic of being high in the north and south and low in the central region. (5) The ecological contribution degrees of grassland, construction land, and forestland in Pingshuo Mining Area were -41.52%, -34.49%, and -10.09%, respectively, and these three were the main contributing factors and sensitive factors.

## Full Text

# Spatiotemporal Changes in Ecosystem Service Value in the Loess Plateau Mining Area: A Case Study of the Pingshuo Mining Area

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**Abstract:** Spatiotemporal analysis of ecosystem service value (ESV) in mining areas is crucial for ecological environmental protection and functional enhancement. Based on remote sensing and land-use data, this study quantitatively assessed the ESV of the Pingshuo mining area—a typical mining region on the Loess Plateau—from 1990 to 2020 using 3S (GIS, RS, GPS) technology, the equivalent factor method, and ecological contribution rate analysis. The results revealed five key findings: (1) Land-use types changed significantly between 1990 and 2020, with farmland experiencing the largest decrease (1122.72 $hm^2$) while construction land showed the greatest increase (2044.23 $hm^2$). (2) Total ESV exhibited a declining-then-rising trend, decreasing from 19562.43$\times 10^{4}$ Yuan in 1990 to 11265.40$\times 10^{4}$ Yuan in 2010, primarily due to substantial reductions in ESV from construction land and grassland. The subsequent increase to 15755.47$\times 10^{4}$ Yuan by 2020 resulted from extensive ecological restoration programs implemented in the mining area. (3) Among individual ecosystem services, all components except soil retention showed varying degrees of decline, with water retention, environmental purification, and biodiversity values decreasing most dramatically by 115.84%, 69.92%, and 18.29%, respectively. (4) The spatial distribution of ESV in the Pingshuo mining area displayed a distinct pattern of high values in the north and south versus low values in the central region. (5) Grassland, construction land, and forestland demonstrated the highest ecological contribution rates at -41.52%, -34.49%, and -10.09%, respectively, identifying them as the primary contributing and sensitive factors driving ESV changes in the study area.

**Keywords:** ecosystem service value; spatiotemporal change; Pingshuo mining area; Loess Plateau

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## Introduction

Ecosystems constitute the foundation for human survival and development, providing essential environmental conditions and material resources. Ecosystem services refer to the diverse products and benefits that humans obtain directly or indirectly from ecosystem structures, processes, and functions, typically categorized into provisioning, supporting, regulating, and cultural services. These services serve as a critical bridge linking human activities with ecosystem processes, forming a central focus in human-environment system research.

Since the systematic conceptualization of "ecosystem services" by scholars such as Costanza and Daily, research on ecosystem services has gained widespread recognition across ecology, geography, and environmental science disciplines. Numerous studies have evaluated ecosystem service values across various spatial scales—from global and national to provincial, basin, and plateau levels—and across different ecosystem types including urban, farmland, river, forest, grassland, and wetland ecosystems. Recent research has expanded from natural ecosystems (e.g., wetlands) to semi-natural systems (e.g., farmland), yielding substantial academic achievements in value assessment, service classification, spatiotemporal patterns, trade-off/synergy relationships, and formation mechanisms.

Mining areas represent unique semi-natural, semi-artificial ecosystems centered on resource extraction. Long-term mining activities cause severe ecological and environmental problems including land destruction, soil erosion, water pollution, and vegetation degradation, which profoundly impact soil conservation, water yield, carbon storage, and habitat quality. However, existing ecosystem service research has largely overlooked these special ecosystems. The limited available studies on mining areas have focused primarily on land-use transformation, ecological vulnerability, and static or cross-sectional analyses at single time points, lacking long-term spatiotemporal pattern analysis of ecosystem service values. As mining areas continue to provide substantial resources and energy for socioeconomic development, research on their ecosystem services is gaining academic attention. There is an urgent need for fundamental studies on the dynamic changes in mining area ecosystem service values to better coordinate resource development with ecological conservation.

The Pingshuo mining area, China' s largest opencast coal mining region, exemplifies ecosystem changes in coal mining areas nationwide. Located on the edge of the Loess Plateau and within the northern agro-pastoral transition zone, it exhibits both ecological vulnerability and transitional characteristics, making it a representative and demonstrative case for ecosystem service research. This study utilizes remote sensing and land-use data to estimate the ecosystem service value of the Pingshuo mining area from 1990 to 2020 using the equivalent factor method and ecological contribution rate analysis. By quantitatively characterizing the spatiotemporal changes in ecosystem service values, this research not only provides references for land reclamation and ecological reconstruction in Loess Plateau mining areas but also broadens the scope of ecosystem service research.

### 1.1 Study Area

This study focuses on the Pingshuo mining area (112°10 ~112°28 E, 39°18 ~39°37 N) as a typical mining region on the Loess Plateau. Located in Shuozhou City, northern Shanxi Province, the area covers approximately 380 $km^2$. The region experiences a mid-temperate semi-arid continental monsoon climate with an average annual temperature of 5.0~7.5°C, annual precipitation of 410~450 mm, annual evaporation of 1750~2550 mm, and average wind speed of 2.5~5.0 $m \cdot s^{-1}$. The topography consists primarily of loess hills with extensive loess distribution. The main soil types are chestnut soil and cinnamon soil, characterized by low organic matter content, poor structure, and weak erosion resistance, resulting in severe water and wind erosion. This makes the area a typical ecologically fragile zone on the Loess Plateau.

As one of China' s five major opencast coal mining bases, the Pingshuo mining area represents the longest-operating and largest spatial-scale opencast coal mining region in the country. With proven geological reserves of approximately 12.6 billion tons, it was among the first batch of national coal planning zones. The mining area comprises three opencast mines (Antaibao, Donglutian, and Anjialing) and three modern underground mines with ten-million-ton capacity (Underground Mine No. 1, No. 2, and No. 3) [Figure 1: see original paper].

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### 1.2 Data Sources

This study utilized multiple datasets including land-use data, soil data, and socioeconomic statistics (Table 1). Land-use data were derived from Landsat TM and OLI imagery with spatial resolution. Using Erdas 9.1 software, multi-band remote sensing data fusion was performed with standard false-color composite (5-4-3 band combination), quadratic polynomial correction, and nearest-neighbor resampling, with correction errors controlled within one pixel. ArcMap 9.3 software enabled interactive visual interpretation and extraction of land-use types, with interpretation accuracy controlled above 85%. To enhance accuracy, field surveys were conducted on August 15, 2021, randomly sampling 50 points across different land-use types for ground-truth verification. All temporal interpretations achieved accuracy above 85%, meeting research requirements. Land-use was classified into six types: farmland, forestland, grassland, water bodies, construction land, and unused land.

Soil data were obtained from the Harmonized World Soil Database (HWSD) Chinese soil dataset with 1 km resolution. Socioeconomic data including crop types, areas, yields, and prices were sourced from the *Shuozhou Statistical Yearbook*, *National Agricultural Product Cost-Benefit Data Compilation*, and field investigations.

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### 1.3 Methods

**1.3.1 Ecosystem Service Value Estimation** Drawing upon the principles and methods of ecosystem service value assessment by Costanza and Daily, Xie Gaodi' s team revised the ecosystem service value equivalent factor table for China' s terrestrial ecosystems through expert questionnaires, addressing underestimation of farmland and overestimation of wetlands. In 2015, the team further updated the equivalent factor table using literature review, expert knowledge, and biomass data, which represents the most scientific and systematic equivalent factor table currently available in China.

One equivalent factor represents the economic value of natural grain yield per unit area. Considering the spatiotemporal heterogeneity of ecosystem services, this study adopted the average grain yield of the Pingshuo mining area from 2015 to 2020 (5425.50 $\mathrm{kg \cdot hm^{-2}}$) and the 2020 national minimum corn purchase price (2.2 $\mathrm{Yuan \cdot kg^{-1}}$), as corn is the main crop in the area. The calculated equivalent factor for the Pingshuo mining area is 1705.35 $\mathrm{Yuan \cdot hm^{-2}}$. Based on the equivalent factor table and local natural conditions, with construction land values referencing Long Jinghua et al., ecosystem service value coefficients for each land-use type were established (Table 2). The formulas for calculating ecosystem service value are:

$$ESV = \sum (A_x \times VC_x)$$

$$ESV_y = \sum (A_x \times VC_{xy})$$

where $ESV$ and $ESV_y$ represent the total ecosystem service value and the value of service $y$ ($\mathrm{Yuan \cdot yr^{-1}}$), respectively; $A_x$ is the area of land-use type $x$ ($\mathrm{hm^2}$); and $VC_x$ and $VC_{xy}$ are the ecosystem service value coefficients for land-use type $x$ and service $y$, respectively ($\mathrm{Yuan \cdot hm^{-2} \cdot yr^{-1}}$).

**1.3.2 Ecological Contribution Rate** The ecological contribution rate ($CR_{it}$) quantifies how changes in a particular land-use type' s ecosystem service value affect the total service value change during period $t$, revealing major contributing and sensitive factors. The calculation formula is:

$$CR_{it} = \frac{\Delta ESV_{it}}{\Delta ESV_t} \times 100\%$$

where $CR_{it}$ is the ecological contribution rate of ecosystem $i$ during period $t$; $\Delta ESV_{it}$ is the change in ecosystem service value for land-use type $i$ during period $t$ ($\mathrm{Yuan \cdot yr^{-1}}$); and $n$ represents the number of land-use types.

**1.3.3 Sensitivity Analysis** The sensitivity index ($CS$) from economics, based on elasticity coefficients, was introduced to quantitatively describe the dependency of ecosystem service value changes on value coefficients, thereby reducing uncertainty. Value coefficients for each land-use type were adjusted by $±$50% to calculate the sensitivity index:

$$CS = \left| \frac{(ESV' - ESV)/ESV}{(VC_i' - VC_i)/VC_i} \right|$$

where $CS$ is the sensitivity index; $ESV$ and $ESV'$ are the ecosystem service values before and after coefficient adjustment ($\text{Yuan} \cdot \text{yr}^{-1}$); and $VC_i$ and $VC_i'$ are the ecosystem service value coefficients before and after adjustment for land-use type $i$ ($\text{Yuan} \cdot \text{hm}^{-2} \cdot \text{yr}^{-1}$). When $CS < 1$, the value coefficient is inelastic and results are credible; when $CS > 1$, the coefficient is elastic and results are less accurate. The closer $|CS|$ is to 1, the higher the accuracy.

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## 2 Results and Analysis

Remote sensing image interpretation yielded land-use maps (Figure 2) and statistical tables (Table 3) for the Pingshuo mining area from 1990 to 2020. Over the past 30 years, the spatial distribution pattern of six land-use types remained largely consistent, with farmland consistently dominating and showing minimal spatial distribution change. Construction land and unused land emerged in central areas and gradually expanded eastward and northeastward. Forestland and grassland were mainly distributed around Underground Mine No. 1 and No. 3, though forestland and grassland around Mine No. 1 converted to farmland, while those around Mine No. 3 gradually transformed into construction land and unused land. This pattern reflects the transition from agriculture-dominated to agro-industrial-mining integrated land use, creating a semi-natural, semi-artificial ecosystem structure.

From 2010 to 2020, intensified land reclamation and ecological restoration efforts gradually restored degraded areas to farmland, forestland, and grassland, achieving a transformation from wasteland to green landscapes.

### 2.1 Spatiotemporal Changes in Land Use

In terms of magnitude, farmland constituted the largest area in 1990, accounting for 71.83% of the total mining area. With expanded coal mining and urban development, farmland, grassland, and forestland decreased by 1122.72 $\text{hm}^2$, 965.30 $\text{hm}^2$, and 3761.27 $\text{hm}^2$, respectively, by 2020. In contrast, construction land, unused land, and water bodies increased, with construction land showing the most dramatic expansion from 930.06 $\text{hm}^2$ to 6735.56 $\text{hm}^2$—a net increase of 5805.50 $\text{hm}^2$. In terms of change rates, construction land exhibited the most significant change, increasing from 2.45% to 7.83% of total area. Farmland

and grassland followed with change rates of -2.95% and -2.54%, respectively, while forestland and water bodies showed less pronounced changes at -5.38% and 5.38%.

### 2.2 Changes in Ecosystem Service Value

**2.2.1 Temporal Changes in Total Value** Driven by large-scale coal resource extraction, total ecosystem service value in the Pingshuo mining area decreased from 19562.43$\times10^{4}$ Yuan in 1990 to 11265.40$\times10^{4}$ Yuan in 2010, with a change of -8306.96$\times10^{4}$ Yuan (-42.46%). Construction land and grassland contributed most to this decline with changes of -7116.53$\times10^{4}$ Yuan and -427.47$\times10^{4}$ Yuan, respectively, representing change rates of -75.49% and -5.83%. From 2010 to 2020, total value increased to 15755.47$\times10^{4}$ Yuan, with a change of 4490.07$\times10^{4}$ Yuan (39.85%). Construction land and farmland showed the largest changes at 2634.47$\times10^{4}$ Yuan and -2250.29$\times10^{4}$ Yuan, with rates of 55.84% and -32.61%, respectively.

Overall, the mining area's ecosystem service value experienced a decline followed by an increase, with the 1990–2010 decrease primarily caused by substantial reductions in construction land and grassland values, while the 2010–2020 increase stemmed from extensive ecological restoration programs. Although forestland, unused land, and water bodies showed positive changes, their small areas and limited change magnitude had minimal impact on total value. The reduction in grassland area coupled with expansion of construction land, combined with their high ecosystem service value coefficients, resulted in large value changes (totaling -3155.62$\times10^{4}$ Yuan), making them the main drivers of total value decline.

**2.2.2 Temporal Changes in Individual Service Values** Among individual ecosystem service value changes from 1990 to 2020, all components except soil retention decreased to varying degrees. Water retention, environmental purification, and biodiversity values showed the most significant declines at 115.84%, 69.92%, and 18.29%, respectively. In the 1990–2010 period, water retention, environmental purification, and climate regulation decreased most dramatically by 4496.92$\times10^{4}$ Yuan, 1325.72$\times10^{4}$ Yuan, and 697.63$\times10^{4}$ Yuan. From 2010 to 2020, all individual service values except soil retention increased, with water retention, environmental purification, and gas regulation showing the largest gains of 3103.54$\times10^{4}$ Yuan, 905.05$\times10^{4}$ Yuan, and 625.29$\times10^{4}$ Yuan. Overall, the decline in regulating service values drove the reduction in total ecosystem service value, while changes in soil retention value reflected reduced water and soil erosion from construction land.

### 2.3 Spatial Changes in Ecosystem Service Value

Using ArcGIS 10.2 raster statistics, ecosystem service values were classified into five categories to reflect spatial changes (Figure 3). Overall, the Pingshuo mining area exhibited a distinct spatial pattern of high values in the north and south versus low values in the center, consistent with the distribution of forestland, grassland, and construction land. High-value areas were distributed in southern and northern regions, peaking around Underground Mine No. 1. Low-value areas aligned with construction land and unused land distribution, primarily located in central Anjialing Opencast Mine, northern Donglutian Opencast Mine, and southeastern Anjialing. Medium-value areas were widely distributed across central and south-central regions.

From 1990 to 2000, minimal spatial distribution change occurred as coal mining impacts had not yet fully manifested. From 2000 to 2010, continuous mining at Antaibao and development of Donglutian converted large farmland areas to construction land, expanding low-value zones. From 2010 to 2020, low-value areas contracted due to vigorous ecological restoration and land reclamation that restored some construction land to farmland and forest-grassland. Continued environmental management is expected to further reverse the declining trend in ecosystem service values.

### 2.4 Ecological Contribution Rate

Analysis of ecological contribution rates for different land-use types from 1990 to 2020 revealed that grassland, construction land, and forestland had the greatest impact at -41.52%, -34.49%, and -10.09%, respectively (Table 6). These three land-use types represent the primary contributing and sensitive factors. The combined ecological contribution rate of these three types reached -91.71%, while water bodies and unused land contributed positively at 4.13%. Land-use types causing value loss (construction land, grassland, forestland, farmland) had a combined contribution of -95.84%, while those generating value gains (water bodies, unused land) contributed 4.13%. The substantial land-use changes occurred under constant total area, with policy-driven expansion of construction land for industrial facilities and infrastructure to support coal production growth from 8.1 million tons to 125 million tons and population increase of 7,200.

### 2.5 Sensitivity Analysis

Sensitivity index calculations (Table 7) showed significant variation among land-use types but minimal interannual differences within the same type. All sensitivity indices were less than 1, indicating inelasticity of total ecosystem service value to value coefficients and confirming result credibility. Farmland showed the highest sensitivity index (0.584–0.884), meaning a 1% increase in its value coefficient would increase total value by 0.584–0.884%. Unused land exhibited the lowest sensitivity index (near 0.04), indicating minimal fluctuation. These results demonstrate that the value coefficients used in this study are appropriate for the Pingshuo mining area.

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## 3 Discussion

This study addresses the research gap regarding ecosystem services in mining areas by analyzing long-term (1990–2020) spatiotemporal patterns of ecosystem service values. The findings align with land-use change research by Zhu Jiulong and Long Jinghua et al. While the equivalent factor method by Costanza and the updated equivalent factor table by Xie Gaodi et al. are credible for large-scale studies, their application to small-scale mining areas requires local calibration. This study modified the equivalent factors using 2015–2020 grain values from the Pingshuo mining area, yielding more accurate, comprehensive, and analytical results than static estimation methods.

The spatiotemporal pattern of ecosystem services in the Pingshuo mining area —characterized by an initial decline followed by recovery and a spatial distribution of high values in the north/south and low values in the center—demonstrates distinct regional characteristics and the necessity of ecological management. Mining ecosystems comprise multiple subsystems with interconnected services, where changes in one service affect others positively or negatively. Future research should employ more sophisticated data and models to explore the driving mechanisms of land-use and ecosystem service changes, providing scientific foundations for reclamation, ecological reconstruction, and management policy formulation.

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## 4 Conclusions

This study analyzed spatiotemporal changes in ecosystem service value in the Pingshuo mining area from 1990 to 2020, yielding three main conclusions:

(1) Farmland, grassland, and forestland areas decreased by 1122.72 $hm^2$, 965.30 $hm^2$, and 3761.27 $hm^2$, respectively, while construction land expanded dramatically by 2044.23 $hm^2$, reflecting the transition from agriculture-dominated to agro-industrial-mining integrated land use.

(2) Total ecosystem service value decreased from 19562.43$\times10^{4}$ Yuan in 1990 to 11265.40$\times10^{4}$ Yuan in 2010, then increased to 15755.47$\times10^{4}$ Yuan in 2020. Except for soil retention, all individual ecosystem service values decreased, with water retention, environmental purification, and biodiversity showing the most significant declines.

(3) The spatial distribution of ecosystem service value exhibited high values in the north and south versus low values in the center, consistent with the distribution of forestland, grassland, and construction land. Grassland, construction land, and forestland emerged as the main contributing and

sensitive factors, with ecological contribution rates of -41.52%, -34.49%, and -10.09%, respectively.

## References

[1] Xie Gaodi, Zhang Caixia, Zhang Changsun, et al. The value of ecosystem services in China[J]. Resources Science, 2015, 37(9): 1740-1746.

[2] MA (Millennium ecosystem assessment). Ecosystems and human being[M]. Washington, DC: Island Press, 2005.

[3] Qian Caiyun, Gong Jie, Zhang Jinxi, et al. Change and tradeoffs synergies analysis on watershed ecosystem services: A case study of Bailongjiang Watershed, Gansu[J]. Acta Geographica Sinica, 2018, 73(5): 868-879.

[4] Daily G C. Nature' s services: Societal dependence on natural ecosystems[M]. Washington DC: Island Press, 1997.

[5] Costanza R, d' Arge R, Groot R. The value of the world' s ecosystem services and natural capital[J]. Nature, 1997, 387(6630): 253-260.

[6] Ma Lina, Zhang Feiyun, Zhai Yuxin, et al. Temporal and spatial evolution of ecosystem service value under land use change in Xinjiang from 1980 to 2020[J]. Arid Land Geography, 2023, 46(2): 253-263.

[7] Yuan Y, Bai Z K, Zhang J J, et al. Investigating the trade-offs between the supply and demand for ecosystem services for regional spatial management[J]. Journal of Environmental Management, 2023, 325: 116591, doi: 10.1016/j.jenvman.2022.116591.

[8] Shen Jiaying, Liu Hui, Wen Xiaole, et al. Ecosystem service evaluation of high standard farmland: Taking some area of the Tong' an Town, Yongtai County, Fujian Province as an Example[J]. Journal of Subtropical Resources and Environment, 2019, 14(4): 86-92.

[9] Hao Mengya, Ren Zhiyuan, Sun Yijie, et al. The dynamic analysis of trade-off and synergy of ecosystem services in the Guanzhong Basin[J]. Geographical Research, 2017, 36(3): 592-602.

[10] Wang Xiaozhen, Wu Jianzhao, Wu Puxia, et al. Spatial and temporal distribution and trade-off of water conservation, soil conservation and NPP services in the ecosystems of the Loess Plateau from 2000 to 2015[J]. Journal of Soil and Water Conservation, 2021, 35(4): 114-121.

[11] Ma S H, Wen Z Z. Optimization of land use structure to balance economic benefits and ecosystem services under uncertainties: A case study in Wuhan, China[J]. Journal of Cleaner Production, 2021, 311: 127537, doi: 10.1016/j.jclepro.2021.127537.

[12] Yang M H, Gao X D, Kadambot H M, et al. Spatiotemporal exploration of ecosystem service, urbanization, and their interactive coercing relationship in the Yellow River Basin over the past 40 years[J]. Science of the Total Environment, 2023, 858: 159757, doi: 10.1016/j.scitotenv.2022.159757.

[13] Bai Zhongke, Zhao Jingkui, Li Jinchuan, et al. Ecosystem damage in a large opencast coal mine: A case study on Pingshuo surface coal mine, China[J]. Acta Ecologica Sinica, 1999, 19(6): 870-875.

[14] Zhu Jiulong. Analysis of dynamic evolution process of ecosystem service value of Yima coal mining area in Henan Province[J]. Areal Research and Development, 2016, 35(2): 145-149.

[15] Qi Xinxian, Huang Xianjin, Lai Li. An empirical study of Meta-analytical value transfer of forest ecosystem services in China[J]. Scientia Geographica Sinica, 2018, 38(4): 522-530.

[16] Xue Zhanjin, Qin Zuodong, Cheng Fangqin. Spatial-temporal patterns and driving factors of aeolian desertification in northwest Shanxi Province[J]. China Environmental Science, 2020, 40(12): 5428-5435.

[17] Zhang Yiran, Zhou Demin, Liu Miao. Ecosystem service valuation research of Chinese inland wetlands based on case study[J]. Acta Ecologica Sinica, 2015, 35(13): 4279-4286.

[18] Xie Gaodi, Lu Chunxia, Leng Yunfa. Ecological assets valuation of the Tibetan Plateau[J]. Journal of Natural Resources, 2003, 18(2): 189-196.

[19] Jiang Bo, Chen Yuyuan, Xiao Yang, et al. Evaluation of the economic value of final ecosystem services from the Baiyangdian wetland[J]. Acta Ecologica Sinica, 2017, 37(8): 2497-2505.

[20] Lester S E, Costello C. Evaluating tradeoffs among ecosystem services to inform marine spatial planning[J]. Marine Policy, 2013, 38: 80-89.

[21] Li F Z, Yin X X, Shao M. Natural and anthropogenic factors on China' s ecosystem services: Comparison and spillover effect perspective[J]. Journal of Environmental Management, 2022, 324: 116064, doi: 10.1016/j.jenvman.2022.116064.

[22] Huo Ran, Xu Xiangyang, Gao Junlian, et al. Spatial patterns of ecosystem services and their relationships with residents' well-being in coal resource-based cities[J]. Chinese Journal of Soil Science, 2020, 51(1): 31-39.

[23] Xue Minggao, Xing Lu, Wang Xiaoyan. Spatial correction and evaluation of ecosystem services in China[J]. China Land Science, 2018, 32(9): 81-88.

[24] Deng Chuxiong, Zhong Xiaolong, Xie Binggeng, et al. Spatial and temporal changes of land ecosystem service value in Dongting Lake area[J]. Geographical Research, 2019, 38(4): 844-855.

[25] Long Jinghua, Zhang Wei, Fu Yanhua, et al. The value of ecosystem services in Hegang coal mining area[J]. Acta Ecologica Sinica, 2021, 41(5): 1728-1737.

[26] Huang Muyi, Fang Bin, Yue Wenze, et al. Spatial differentiation of ecosystem service values and its geographical detection in Chaohu Basin during 1995–2017[J]. Geographical Research, 2019, 38(11): 2790-2803.

[27] Zhang Fa, Rusuli Yusufujiang, Tuersun Aierken. Spatiotemporal change of ecosystem service value in Bosten Lake watershed based on land use[J]. Acta Ecologica Sinica, 2021, 41(13): 5254-5265.

[28] Pan H H, Wang J Q, Du Z Q, et al. Spatiotemporal evolution of ecosystem services and its potential drivers in coalfields of Shanxi Province, China[J]. Ecological Indicators, 2023, 148: 110109, doi: 10.1016/j.ecolind.2023.110109.

[29] Blanco C F, Marques A, Bodegom P M. An integrated framework to assess impacts on ecosystem services in LCA demonstrated by a case study of mining in Chile[J]. Ecosystem Services, 2018, 30: 106-115.

[30] Maestre F T, Bagousse P Y, Delgado B M, et al. Grazing and ecosystem service delivery in global drylands[J]. Science, 2022, 378: 915-920.

[31] Xue Z J, Qin Z D, Li H J, et al. Evaluation of aeolian desertification from 1975 to 2010 and its causes in northwest Shanxi Province, China[J]. Global Planetary and Change, 2013, 107: 102-108.

[32] Xie Gaodi, Zhen Lin, Lu Chunxia, et al. Expert knowledge based valuation method of ecosystem services in China[J]. Journal of Natural Resources, 2008, 23(5): 911-919.

[33] Xie Gaodi, Zhang Caixia, Zhang Leiming, et al. Improvement of the evaluation method for ecosystem service value based on per unit area[J]. Journal of Natural Resources, 2015, 30(8): 1243-1254.

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