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Study on spatio-temporal evolution of ecosystem services, spatio-temporal pattern of tradeoff/synergy relationship and its driving factors in Shendong mining area

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Objectives: The game between socio-economic development and ecological development has always been the core issue in coal areas, but the internal mechanism of tradeoff and cooperative dynamic change of ecosystem services in mining areas under long-term mineral resources development is still lacking in in-depth research.

Methods: Therefore, taking Shendong mining area as an example, this study used InVEST model to evaluate the changes of four major ecosystem service functions in Shendong mining area from 1990 to 2020, namely, water yield (WY), net primary productivity (NPP), soil conservation (SC) and habitat quality (HQ). Meanwhile, correlation analysis was used to explore the trade-off and synergistic relationship among these services. On this basis, the coupling effect between the four ecosystem services is further discussed by using the constraint line method. Finally, the key drivers of ecosystem service trade-offs/synergies in the region are explored by using geodetectors and the explanations of each influence factor for RMS errors are obtained.

Results: The results show that 1) from 1990 to 2020, the water yield and soil retention in the mining area decrease first and then increase, and the net primary productivity and habitat quality increase slowly, mainly in the southeast of the mining area. 2) In terms of constraint relationship, all the four ecosystem services showed hump-like constraint relationship, that is, there was obvious constraint threshold effect. 3) In the Shendong mining area, the synergistic relationship is the dominant relationship between ecosystem services, and the tradeoff effect mainly occurs between water yield and habitat quality. 4) In terms of the driving mechanism of tradeoff/synergy, land use type, temperature, and rainfall are the main factors that cause the spatial differentiation of tradeoff synergy intensity among ecosystem services in Shendong mining area.

Conclusions: The results of this study provide a scientific basis for the improvement of ecological environment and sustainable utilization of mineral resources under long-term exploitation.

KEYWORDS

ecosystem services, trade-offs/synergies, constraint line, hot spot analysis, geographical detector, Shendong mining area

1 Introduction

Ecosystems have a crucial role in providing necessary resources and habitats for human beings, serving as the fundamental basis for human life and development (Comberti et al., 2015; Reader et al., 2022). Ecosystem services (ESs) refer to the operations and processes of ecosystems that provide direct or indirect benefits to humans (Costanza et al., 2017). Due to the escalating global environmental concerns, there is a rising emphasis on the roles and alterations of ecosystem services (Naidoo et al., 2008). Based on the 2005 Millennium Ecosystem Assessment report, almost 60% of ecosystem services worldwide are experiencing significant degradation. The decline of ecosystem services will have a substantial effect on the harmonized growth of natural ecology and social economy, since it plays a crucial role in connecting mankind and nature (Fu et al., 2015; Delgado and Marín, 2020; Lyu et al., 2022). The dynamic link between ecological services has been influenced by their diversity, uneven spatial distribution, and selective human utilization. These changes are evident in the trade-offs and synergies that lead to mutual benefits (Wang J. et al., 2019; Xia et al., 2023). Trade-off refers to a situation in which the improvement of one ecosystem service results in the decline of other services (Zhang et al., 2020), whereas synergy refers to circumstances when two or more ecosystem services are simultaneously increased or reduced (Pan et al., 2020).

The function of ecosystem services is related to human welfare. At present, domestic and foreign scholars have made some achievements in the study of ecosystem services. Turner et al. (2014) revealed the scale effects of 11 ecosystem services in Denmark. Yu et al. (2021) explored the differences of tradeoff synergies among five ecosystem services, namely, NPP, food production, soil conservation, water resources supply and habitat quality, at global, integrated, sample interval and typical sample area scales in the Qinba Mountains. It is believed that the tradeoff synergy between services will change not only with time but also with scale, which is scale dependent. In mining areas, exploitation of mineral resources is one of the strongest human disturbances to terrestrial ecosystems, often leading to drastic changes in ecosystem services (Wu et al., 2021; Xiong et al., 2023). Surface mining damages topsoil, vegetation, topography, and other features, resulting in the removal or alteration of natural ecosystem areas (Xu et al., 2023), affecting their ability to provide ecosystem service value (ESV). In China, most mining areas are concentrated in arid and semi-arid regions (Yang et al., 2021). Understanding the impact of open-pit mining on ecological environment can provide guidance for ecological restoration of mining area and provide basis for sustainable management of mining area.

Open pit mining affects the ecosystem of a mine throughout its life cycle, from exploration and development to closure (Wang et al., 2024). In the initial stage of mining, the construction of infrastructure and roads will cause changes in land use, especially affecting the supply and regulation of ecosystem services (Boldy et al., 2021). In the process of mining, on the one hand, mining causes direct damage to the surface ecosystem, on the other hand, it also destroys the original water cycle process, resulting in the reduction of surface water system (Wu et al., 2024) and groundwater level (Luo et al., 2024), resulting in the decline of ecosystem regulation and support functions. After the end of mining, some waste rock piles and residues may cause water pollution and air pollution through the leaching process (Madejón et al., 2021), and may also cause spontaneous combustion of coal gangue (Fan et al., 2014), which further affects the ecosystem services of the mining area. On the other hand, land reclamation, ecological restoration, natural vegetation restoration and other processes will also promote the restoration of the mining area ecosystem (Li Y. et al., 2024). Therefore, the impact of mining on the environmental value of mining area is a long-term process, which presents different trends due to the different mining life cycle. There have been studies using LandTrendr algorithm to map ecosystem service changes caused by mining disturbance (Wang et al., 2020). Qian et al. (2018) selected six typical open-pit mining areas on the southern slope of Qilian Mountains to evaluate the ecological environment value of the mining areas from 1975 to 2016. The results show that with the expansion of the mining area scale, the regional ecological environment value gradually decreases. However, most previous studies reflected the impact of ecosystem services in mining areas through the ecosystem changes in a single year, but ignored the dynamic process of ecosystem services in mining areas, and few studies revealed the internal mechanism of tradeoff and collaborative dynamic changes of ecosystem services in mining areas under coal mining.

Several approaches have been developed to identify trade-offs and synergies between ecosystem services. For example, Spearman method and Pearson method are used for correlation analysis to judge the tradeoff and synergy between ecosystem services (Dade et al., 2019; Feng et al., 2022; Li and Luo, 2023), both of which provide a significance test to determine whether the correlation coefficient is significantly different from zero, which helps to judge whether the correlation between variables really exists. In addition, there are potential constraints between ecosystem services. By quantifying the complex nonlinear relationship between ecosystem services and constructing constraint lines, the coupling effect between ecosystem services is obtained. The mutual constraint between ecosystem services has gradually become an important reference for the change of ecosystem service functions. In addition to improving understanding of the interactions between ecosystem services, revealing how different drivers affect the relationships between ecosystem services can also provide recommendations for sustainable development. It has been proved that ecosystem services are significantly affected by climatic factors such as rainfall and temperature (Li Z. et al., 2022; Zhao and Dai, 2024). Socio-economic factors are also regarded as important drivers of ecosystem services (Li et al., 2021), and land use change related to human activities is considered to be the most prominent, important and direct driver (Mehring et al., 2017; Xu et al., 2020). At present, most of the studies on driving force only focus on the impact of driving factors on individual ecosystem services, while there are few studies on the driving mechanism of ecosystem service interaction, especially the driving force of social factors.

The Shendong mining area is characterized by its substantial coal reserves and exceptional coal quality, making it the largest mining area of the underground mine in China (Zhang et al., 2021). Nevertheless, the massive coal mining activities have greatly disturbed the fragile ecological environment in the Shendong mining area (Xu et al., 2021). As a result, it is imperative to promptly use scientific methods to reveal the connections between ecosystem services in this region. This will enable the improvement of a management system for the mining region that integrates environmentally-friendly mining operations and principles of sustainable development. The aim of this study is to thoroughly examine the spatial and temporal fluctuations in ecosystem services within the Shendong mining area and investigate the tradeoffs, synergies, and factors that influence these services. In order to accomplish this objective, a study was conducted from 1990 to 2020 focusing on four key ecosystem services: water yield, net primary productivity, soil conservation, and habitat quality. The findings seek to establish a robust basis for decision-making processes concerning the high-quality regional development and the effective management of ecosystem services.

2 Materials and methods

2.1 Study area

The Shendong mining region is located in Shenmu County, Yulin City, Shaanxi Province. It is situated between 109.83° and 110.34°E longitude and 39.56° and 39.19°N latitude. The mining area covers around 900 km^2 and has an average elevation of about 1,200 m (as shown in Figure 1). The study site is located in a temperate semi-arid continental monsoon climate zone. This environment is characterized by dry springs, abundant sunshine, and solar power. The area also experiences sandy winds that mainly blow from the northwest. Summers are extremely hot with intense rainfall, primarily in the form of heavy showers and thunderstorms from July to September. Autumns are pleasant and humid, with more rain and the formation of frost and ice. Winters are lengthy and dry, accompanied by prevailing northwest winds. The mining area is mainly covered with psammophytes and xerophytes, which are plants that can tolerate both droughts and low temperatures. As a result, the area has a shrub plant type landscape with a low population density (Chen Z. et al., 2023). The coal seam discovered in this mining area demonstrates consistent occurrence patterns and a straightforward structure that is well-suited for mechanized extraction methods, particularly shaft mining using the strike longwall caving technique (Xu et al., 2021). As a result, this region has become the largest coal production hub in China.

2.2 Data collection and preprocessing

The current investigation is centered on the Shendong mining area as the designated research location and obtained seven sets of environmental data in the years 1990, 1995, 2000, 2005, 2010, 2015, and 2020, respectively. The datasets included rainfall data, soil data, digital elevation model (DEM) data, land use data, and administrative vector boundary data (as shown in Table 1). All of these datasets were standardized in terms of spatial resolution and coordination system.

2.3 Research methods

2.3.1 Calculation of ecosystem service indicators

The Shendong mining region plays a vital role as a key coal producing hub in China. Nevertheless, the extended period of mineral exploitation has led to the land and vegetation degradation, and several related problems. Examining the alterations in ecosystem services can help us understand the effects of restoring and managing the ecological environment in mining sites, while also offering useful knowledge for future ecological restoration efforts. Therefore, this research aims to evaluate four crucial ecosystem services: water yield, soil conservation, carbon storage, and habitat quality. The next section provides a detailed description of the assessment methodologies used for each individual ecosystem service.

2.3.1.1 Water yield (WY)

The water production in the research area reflects the region's ability to provide water. The water production module of the InVEST model is determined through the application of the water balance principle, taking into account several aspects including vegetation cover, land use, terrain, soil texture, and other relevant variables (Chen Y. et al., 2023). Water yield is calculated using Eq. 1 as follows:

$$\boldsymbol{Y_x} = \left(\boldsymbol{1} - \frac{\boldsymbol{AET_x}}{\boldsymbol{P_x}}\right)\boldsymbol{P_x} \tag{1}$$

Where: Y_x is the water yield of the grid unit (mm); AET_x is the actual evapotranspiration of the grid cell (mm); and, P_x is the amount of rainfall on the pixel (mm).

2.3.1.2 Soil conservation (SC)

Soil conservation is influenced by both the potential and current soil erosion. The soil conservation in the watershed was calculated using the modified general soil loss equation (RUSLE) in this paper, as shown in Eq. 2:

$$\boldsymbol{SD} = \boldsymbol{RKLS} - \boldsymbol{USLE} = \boldsymbol{R} \times \boldsymbol{K} \times \boldsymbol{LS} \times (\boldsymbol{1} - \boldsymbol{P} \times \boldsymbol{C}) \tag{2}$$

SD in the formula is SC, $t/(hm^2 \cdot a)$; R is the rainfall erodivity factor, $MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$, calculated from the monthly rainfall data proposed by Wischmeier and Smith. (1978). K is soil erosibility factor $t \cdot h \cdot MJ^{-1} \cdot mm^{-1}$, calculated by EPIC model proposed by Williams et al. (1983). LS is the slope length and slope factor extracted from DEM by ArcGIS. C is the vegetation cover factor, which is calculated using the calculation method proposed by Chong. (2000). P is the current soil conservation measure factor.

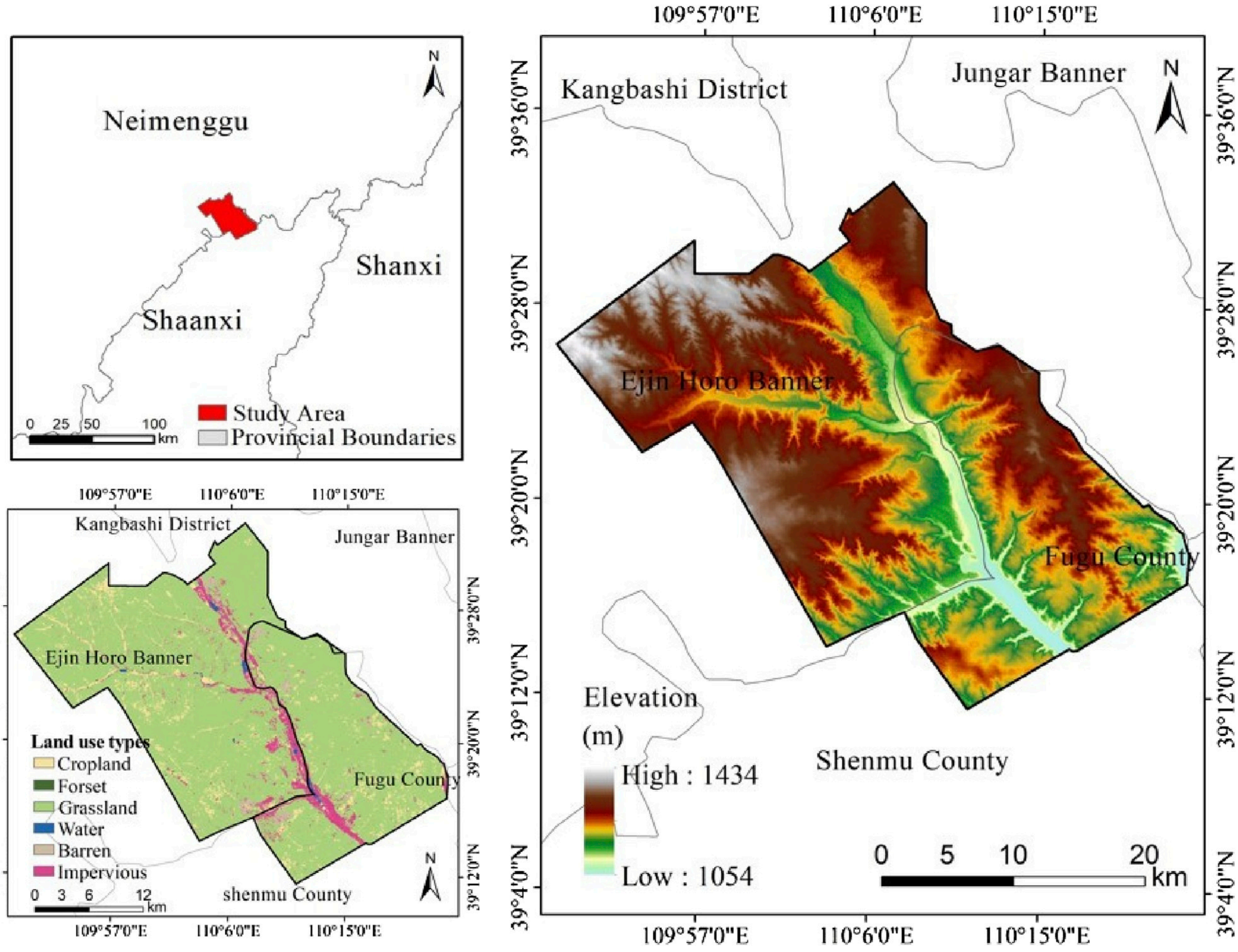


FIGURE 1
Map of the study region.

2.3.1.3 Net primary productivity (NPP)

The Carnegie-Ames-Stanford Approach (CASA) (Field et al., 1995) model was used to calculate the NPP value, as shown in Eqs 3–5:

$$\boldsymbol{NPP}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{APAR}(\boldsymbol{x},\boldsymbol{t}) \times \boldsymbol{\varepsilon}(\boldsymbol{x},\boldsymbol{t}) \tag{3}$$

$$\boldsymbol{APAR}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{SOL}(\boldsymbol{x},\boldsymbol{t}) \times \mathbf{0.5} \times \boldsymbol{FPAR}(\boldsymbol{x},\boldsymbol{t}) \tag{4}$$

$$\boldsymbol{\varepsilon}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{T}_{\boldsymbol{\varepsilon}1}(\boldsymbol{x},\boldsymbol{t}) \times \boldsymbol{T}_{\boldsymbol{\varepsilon}2}(\boldsymbol{x},\boldsymbol{t}) \times \boldsymbol{W}_{\boldsymbol{\varepsilon}}(\boldsymbol{x},\boldsymbol{t}) \times \boldsymbol{\varepsilon}_{\boldsymbol{max}} \tag{5}$$

Where, $NPP(x,t)$ is the NPP value (gC/(m^{2}yr)), and x, t are the position and time respectively; $APAR(x,t)$ is the Photosynthetically active radiation (MJ/m^2); $\varepsilon(x,t)$ is the actual light efficiency (gC/MJ); $SOL(x,t)$ is the total solar radiation (MJ/m^2); the numerical value 0.5 is the ratio of effective solar radiation to total solar radiation; $FPAR(x,t)$ is the fraction of photosynthetically active radiation absorbed by vegetation canopy; $T_{\varepsilon 1}(x,t)$ and $T_{\varepsilon 2}(x,t)$ is the temperature stress coefficient; and, $W_{\varepsilon}(x,t)$ *is* the water stress coefficient. Here ε_{max} is the maximum light energy utilization efficiency of a specific biome under ideal conditions.

2.3.1.4 Habitat quality (HQ)

This study utilizes the habitat quality module of the InVEST model to quantitatively assess the potential level of habitat quality in the Shendong mining area. The model uses land use data and pertinent factors that threaten biodiversity to evaluate the quality of the habitat in the Shendong mining area. This provides information about the current biodiversity status and the area's ability to support the living circumstances of different species. The habitat quality is quantified on a scale of 0–1, where higher values represent better quality and lower ones represent poorer quality (Wei et al., 2023; Zheng et al., 2023). In this study, the habitat quality of Shendong mining area was divided into four levels from high to low: high (0.6–0.8), medium (0.4–0.6), low (0.2–0.4) and low (0–0.2). The specific habitat quality assessment calculation formula is shown in Eq. 6:

$$\boldsymbol{Q}_{\boldsymbol{xj}} = \boldsymbol{H}_{\boldsymbol{j}}\left[\mathbf{1} - \left(\frac{\boldsymbol{D}_{\boldsymbol{xj}}^{\boldsymbol{z}}}{\boldsymbol{D}_{\boldsymbol{xj}}^{\boldsymbol{z}} + \boldsymbol{K}^{\boldsymbol{z}}}\right)\right] \tag{6}$$

Where: Q_{xj} represents the habitat quality of grid x in habitat type *j*; H_j is the habitat suitability of habitat *j*; D_{xj} refers to the habitat degradation index of grid x in habitat type *j*; the half-saturation constant, denoted as k, is typically equal to half of the maximum degradation index; and, z is a standardized constant that serves as the default parameter of the system.

TABLE 1 Data sources and pre-treatment.

Data type	Data sources and processing methods
Rainfall and temperature	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (https://www.resdc.cn)
Soil	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn), National Data Center for Tibetan Plateau Science (http://data.tpdc.ac.cn), and National Earth System Science Data Center (http://www.geodata.cn), The soil data with a resolution of 30 m was obtained by ArcGIS resampling
DEM	GDEM data products with spatial resolution of 30 m from geospatial data cloud (https://www.gscloud.cn)
Solar radiation	earth's resources data cloud data set (http://gis5g.com/data/trsj), the spatial resolution of 1 km
Land use	China land cover dataset (CLCD) data set (http://zenodo.org/record/5210928#.YuXtgtBBw2y), the data the spatial resolution of 30 m
Administrative vector boundary data	From Resources and Environmental Sciences and Data Center, Chinese Academy of Sciences (https://www.resdc.cn)

The habitat quality module integrates the impact distance and magnitude of threat sources on habitat quality, together with the vulnerability of each habitat to these threats. The information is displayed in Tables 2, 3. In the research area, threat factors were chosen based on the first-level ground classification, taking into account the specific situation. The values for other parameters were obtained using the model manual and applicable literature guidelines.

2.3.2 Identification of ecosystem service hotspots

The spatial distribution pattern of ecosystem services' cold and hot spots is determined by using the Getis-OrdG_i* tool in ArcGIS 10.7 software to analyze the spatial supply differences of ecosystem services in the Shandong mining area (Peeters et al., 2015). In order to provide a clearer understanding of this spatial distribution pattern, an analysis was performed to identify cold and hot spots based on the annual mean data of four ecosystem services at a grid size of 1 km. The regions that surpassed their averages during the study period were identified as hotspots for each specific service. These hotspots were then superimposed using ArcGIS software. Areas that have more than one type of service are called hotspot areas for 1, 2, 3, and 4 types of ecosystem services, respectively. On the other hand, regions that do not have more than one type of service are classified as non-hotspot areas. as shown in Eqs 7–9:

$$G_i^{*} = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{x}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\left[n\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right] \Big/ (n-1)}} \tag{7}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_1 \tag{8}$$

$$S = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n} x_i^2 - (x)^{-2}} \tag{9}$$

Where n is the number of grids in the study area; x_i is the ecosystem service of grid i and j respectively; $w_{i,j}$ is the average value of ecosystem services; and, $\bar{x}$ is the space weight matrix.

2.3.3 Ecosystem service tradeoff and synergy analysis

The fishing net generation tool in ArcGIS was employed in this study to provide random locations and establish sampling points at intervals of 1 km. The correlation between four categories of ecosystem services in the Shendong mining area was quantified using Pearson correlation analysis. The findings were visually evaluated for assessing the extent of correlation between these variables. The calculation formula is as Eq. 10:

$$P_{X,Y} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}\sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}} \tag{10}$$

Where X and Y are variables, and n is the total number data points. When $P_{XY} = 0$, X and Y are not linearly correlated; When $P_{XY} = 0$, the correlation coefficient between the two ecosystem services is positive and significant ($p < 0.01$), denoting that the two ecosystem services are synergistic. In contrast and as a tradeoff relationship, the correlation increases with increasing proximity of P_{XY} to ± 1.

2.3.4 Constraint line definition and extraction

The interconnections among the variables in complex ecosystems frequently lead to a dispersed cloud-like distribution of data points (Zhao and Dai, 2024). Constraint lines are the underlying boundaries from this distribution that provide ecological information. Constraint lines are meant to reduce the impact of limiting factors and optimize the value of the response variable by reducing the influence of multiple factors (Zhang et al., 2024). More and more, the constraint line approach is used to investigate trade-offs or synergies between pairs of ecosystem services (Hao et al., 2017). In this work, we provide a two-dimensional coordinate system for each ecosystem service (X) reacting to another ecosystem service (Y) by employing the horizontal and vertical axes. Concurrently, we define constraint lines between various ecosystem services by using a quantile partitioning approach where 100 columns are produced in the scatter plot by dividing the range of ecosystem services on the X-axis into 100 intervals. We choose as boundary points a quantile cutoff at 99.8% within each column to lessen the impact of outliers. As such, for fitting each constraint line, about 100 boundary points are obtained. Coresponding constraint lines can be obtained by using Origin's fitting function based on shape and goodness-of-fit (R^2) analysis of scattered data points.

TABLE 2 The weight and the maximum influence distance of the threat source.

Threats source	Maximum distance of influence	Weight	Spatial decay type
Cropland	2.6	0.26	exponential
Construction land	5.8	0.73	linear
Barren land	2	0.25	exponential

TABLE 3 Sensitivity of each land use type to threat sources.

Land use type	Habitat suit- ability	Sensitivity		
		Cropland	Construction land	Barren land
Cropland	0.3	0	0.6	0.5
Forestland	0.9	0.8	0.7	0.4
Shrubland	0.9	0.8	0.7	0.4
Grassland	0.7	0.6	0.6	0.3
Water body	0.75	0.5	0.6	0.1
Snow	0.75	0.5	0.6	0.1
Barren land	0	0	0.2	0.1
Construction land	0	0	0	0
Wetland	0.8	0.5	0.6	0.1

2.3.5 Trade-offs and identification of key synergy drivers

The geographical detector is a method used to identify the spatial differentiation characteristics and their primary driving forces. Its fundamental concept suggests that if the spatial distribution patterns of the independent and dependent variables are similar, then the independent variable will significantly influence the dependent variable. This approach comprises four modules: risk detection, factor detection, ecological detection, and interaction detection. In this study, through the factor detection module, we analyze the key influencing factors of ecosystem service tradeoff synergy in Shendong mining area. It's calculated as Eq. 11.

$$\boldsymbol{q} = \mathbf{1} - \frac{\sum_{h=1}^{L} \boldsymbol{N}_h^2}{\boldsymbol{N}\boldsymbol{\sigma}^2} \tag{11}$$

Where q represents the interpretation degree of influencing factors on water yield, ranging from 0 to 1 [0, 1]. Here, a higher value indicates a stronger impact of these factors on the spatial distribution of water yield; h is the number of partitions, and L is the number of influencing factors among samples; N and N_h are the number of units in the whole area and in each layer, respectively; σ and σ_h are the variances of the whole area and layer h.

3 Results

3.1 Temporal and spatial changes of ecosystem services

This study utilized the InVEST model and spatial mapping method of ArcGIS software to evaluate four ecosystem services (water yield, NPP, soil conservation, and habitat quality) in the Shendong mining area. The assessment was conducted for the years 1990, 1995, 2000, 2005, 2010, 2015, and 2020. Each service displayed oscillations in its spatiotemporal features. The main findings are as follows.

3.1.1 Temporal changes of ecosystem services

Table 4 shows that the annual water production of the Shendong mining area had a pattern of initial decline followed by subsequent growth between 1990 and 2020. In 2005, the water production reached its lowest point. From 1990 to 2005, the total water production decreased by 10.57×10^7 m^3. However, from 2005 to 2020, there was an upward trend in water production. The water production service in the mining area has been mostly influenced by the fluctuations in rainfall and mining activity between 1990 and 2020. The total water production rose from 17.01×10^7 m^3 in 1990 to 21.82×10^7 m^3 in 2020, representing an increase of 4.61×10^7 m^3 or 26.79%. From 1990 to 2020, the average annual NPP of the Shendong mining area showed a notable and consistent increase. More precisely, the average annual NPP value of the Shendong mining area experienced a 12.65 gc/m^2 growth between 1990 and 1995. The average annual NPP of the Shendong mining area experienced a decline between 1995 and 2000, primarily due to extensive mining activity. The data suggests that the early phase of mining has had a noticeable impact on the growth of vegetation, and the average annual NPP in the mining area has experienced a considerable increase from 112.63 gc/m^2 in 2000 to 304.80 gc/m^2 in 2020. This could be attributed to the enhancement of ecological environment quality resulting from land reclamation programs implemented in mining regions in recent years. The soil conservation services in the Shendong mining area had fluctuations between 1990 and 2020, mostly influenced by variations in rainfall patterns and changes in land use. Initially, there was a decline in soil conservation efforts, followed by subsequent improvements. Between 1990 and 2020, the soil conservation capacity experienced a significant increase of 1.74 × 10^6 t, representing a growth of 37.83%. According to the results of classified statistical analysis, the habitat quality of Shendong mining area is shown in Table 5; Based on the findings of the statistical analysis, the percentage of low grade and relatively low grade habitat area has consistently dropped from 1990 to 2020. Specifically, the proportion of low-quality habitat area decreased from 19.29% in 1990 to 9.12% in 2020, resulting in a total decrease of 10.17%. The percentage of land area with relatively low habitat quality declined from 55.71% in 1990 to 43.59% in 2020, resulting in a total reduction of 12.12%. Over time, there has been a consistent increase in the area of habitats with middle and higher grades. The fraction of areas with middle habitat quality has dramatically risen from 24.99% in 1990 to 47.25% in 2020, resulting in a total increase of 22.26%. Overall, the ecological conditions in the Shendong mining area exhibited a gradual improvement from 1990 to 2020. Between 1990 and 2020, there was an initial decline followed by an increase in water yield and soil retention in mining regions. Conversely, there was an increase in NPP and habitat quality during the same period.

3.1.2 Spatial distribution characteristics of ecosystem services

Figure 2 illustrates the spatial distribution features of different ecosystem services. The chart clearly demonstrates that water production services in the Shendong mining area have a dispersed pattern, with the majority of high-value locations concentrated in the southeastern region and low-value areas scattered throughout the central urban area. In 1995, a substantial amount of rainfall led to a rise in the overall water production in the mining region. Between 2000 and 2005, a decrease in rainfall, population increase, and expansion of urban areas resulted in a drop in overall water output, especially in the central urban zone. Between 1990 and 2020, there has been a gradual growth in NPP in the Shendong mining area. Significantly, the NPP remains relatively constant inside the center metropolitan area, but shows substantial fluctuations and enhancements in other regions. From 1990 to 2020, there have been few changes in the spatial distribution of soil conservation services in the Shendong mining area. The regions with high-value soil conservation services are mostly located in the northwestern, southwestern, and certain southeastern parts, while the northeastern sections of the mining site have low-value areas. Between 1990 and 2020, the habitat quality in different sections of the Shendong mining area showed both consistency and fluctuation, as shown in Figure 2. The landscape is characterized by the presence of high-value areas, mostly consisting of woodland and grassland. These regions have been less affected by human activities, leading to a greater level of habitat quality. In contrast, places of low value are mainly located in the northwestern portions and central urban zones, where there is a high prevalence of building land usage, empty land, and cultivated fields. These locations have lower habitat quality because they are more susceptible to external disturbances.

3.2 Identification of ecosystem service hotspots

This study examines the aggregation patterns and temporal variations in ecosystem services within the study area by analyzing the spatio-temporal evolution characteristics and conducting an evaluation of cold and hot spots (as shown in Figures 3, 4). In 1990, non-hot spots were scattered throughout the mining area, accounting for 38.57% of the total area. The majority of hot spots were located in the southeast region, with category 1 hot spots accounting for the biggest percentage (42.62%) and category 4 hot spots representing a smaller fraction (0.07%). In 2000, the decrease of non-hot spot area accounted for 7.64%. However, a new hot spot emerged in the southwest region, where type 2 hot spots covered the largest area (44.48%). Additionally, there were slight increases in the areas occupied by type 3 and type 4 hot spots. By 2010, the proportion of non-hot spot locations had declined even further compared to the year 2000, accounting for only 10.26%. The spatial distribution of hot spots in the mining area has migrated predominantly towards the eastern, southern, and southeastern regions. The prevalence of type 2 hot spots remained high at 40.67%, however type 3 and type 4 hot spots extended towards the eastern region of the mining area. The areal ratio experienced an increase of 9.04% and 1.02%, respectively. In 2020, the non-hot spot area constituted 21.29% of the overall area, mainly distributed in the western section of the mining area. The highest number of hot spot locations was still comprised of type 2, while type 3 and type 4 hot spot areas showed negligible changes compared to 2010. Over the past 3 decades, substantial changes have taken place in the hot spot zones of the Shendong mining sector. Between 1990 and 2020, there has been a gradual decline in both non-hot spot and type 1 hot spot regions, whereas type 2, type 3, and type 4 hot spots have Steadily expanded.

3.3 Temporal variations and constraint effect analysis of ecosystem service trade-offs and synergies

3.3.1 Temporal changes of ecosystem service trade-offs and synergies

The measurement of the Spearman coefficient for 1,500 randomly selected samples provided information about the association and strength of the four ecosystem services (as shown in Figure 5). The four types of services in the mining sector primarily exhibit synergistic and mutually advantageous relationships. Between 1990 and 2020, there was a notable and positive association between the quality of the habitat, soil conservation and water yield. Furthermore, in 2020, the interdependence between habitat quality and water yield was much more pronounced. The correlation coefficient between soil conservation and water yield peaked at its highest value in 1990 and 2000, at 0.26. The trade-off intensity between net primary productivity, habitat quality, and soil protection varied slightly between 1990 and 2020. It is important to mention that there was a mutually beneficial relationship between the quality of the habitat

TABLE 4 Individual ES supply and its change pattern in the Shendong Mining Area from 1990 to 2020.

ES	1990	1995	2000	2005	2010	2015	2020
WY($1 \times 10^7 m^3$)	17.21	21.07	7.99	6.64	17.10	14.82	21.82
NPP(gc/m^2)	105.10	117.75	112.63	208.60	254.70	307.80	304.80
SC($1 \times 10^6 t$)	4.60	5.55	2.57	2.01	4.51	5.55	6.34

TABLE 5 Changes in area proportions of different habitat quality grades in the Shendong Mining Area from 1990 to 2020.

Level of habitat	Index range	The proportions of habitat quality grades in different years (%)						
		1990	1995	2000	2005	2010	2015	2020
Low	0–0.2	19.2936	17.1053	12.2956	10.9116	9.1557	7.6091	9.1212
Relatively low	0.2–0.4	55.7086	54.4847	51.4884	47.3616	42.0641	39.0332	43.5948
Middle	0.4–0.6	24.9946	28.3731	36.1697	41.7219	48.7766	53.3507	47.2516
Relatively high	0.6–0.8	0.0032	0.0369	0.0464	0.0049	0.0036	0.0071	0.0323

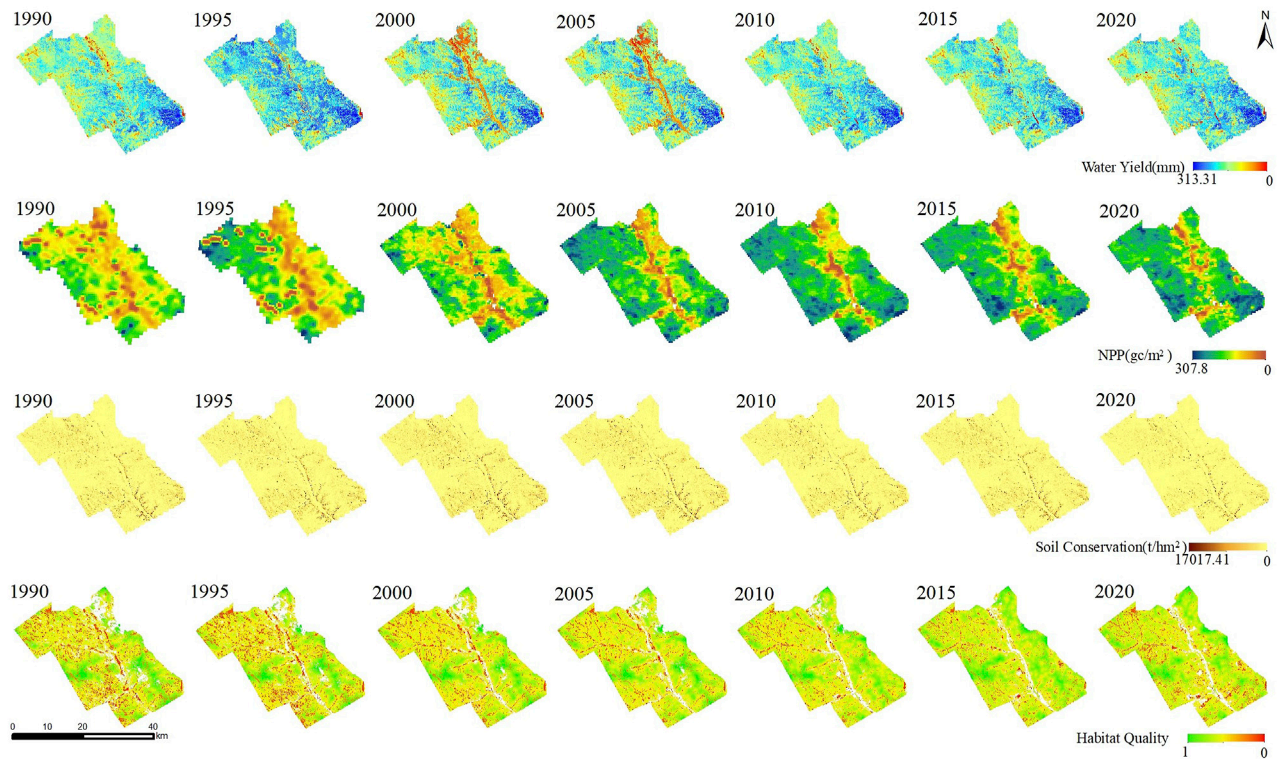


FIGURE 2
Spatiotemporal distribution of ecosystem services.

and the services provided by NPP before 2000. However, after 2000, there was a less favorable tradeoff relationship, with the strength of the tradeoff reaching its highest point in 2005 (−0.11). Furthermore, there was a limited correlation between NPP and water production in 2005, but in other years there was a limited positive interaction. The level of synergy, which was quite low, peaked in 2010 with a value of 0.072.

3.3.2 The constraint impact of trade-offs and synergies in ecosystem services

Between 1990 and 2020, the constraint lines of the six pairs of ecosystem services consistently showed a downward parabolic linear trend (as shown in Figure 6). To clarify, to the left of the threshold line, there is a direct relationship between pairs of ecosystem services, meaning that a rise in one service corresponds to an

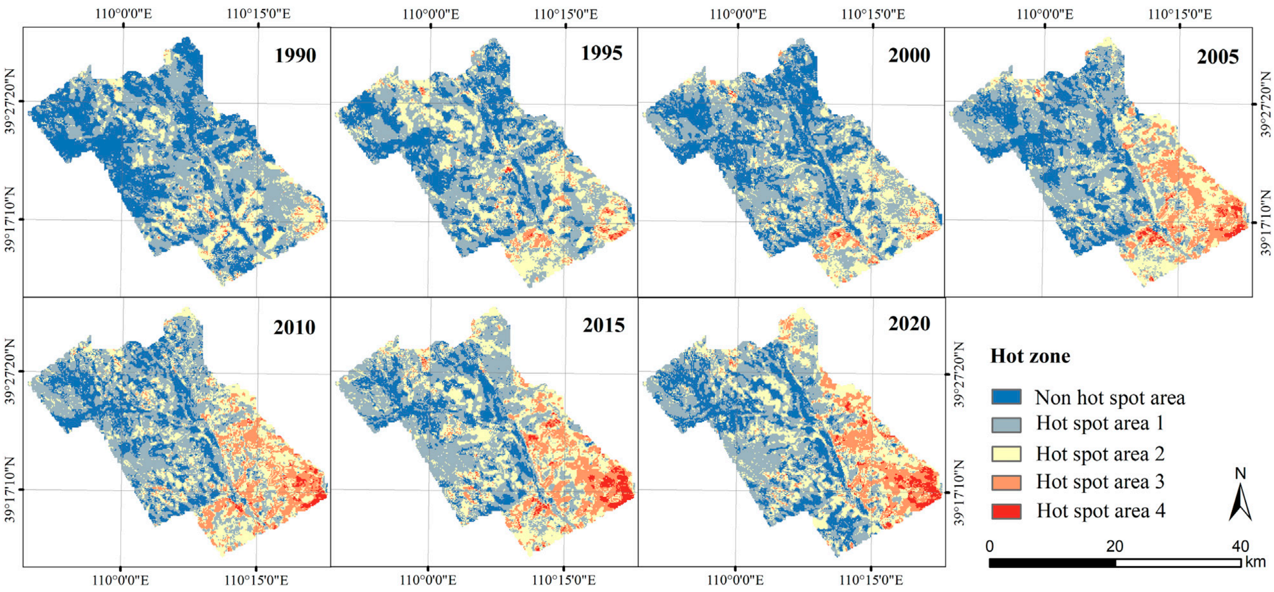


FIGURE 3
Changes in the areal ratio of hotspot areas of ecosystem services on the Shendong Mining Area from 1990 to 2020.

increase in another service. On the other hand, to the right of the threshold line, an increase in one service leads to a drop in another one. Over time, the constraint relationship becomes increasingly constricting. Figure 6 shows that there are two pairs of ecosystem services: habitat quality and net primary productivity, and habitat quality and soil conservation. The threshold value for habitat quality in relation to NPP and soil conservation fluctuates around 0.40. To the right of the threshold line, there is a growing limitation imposed by habitat quality on both NPP and soil conservation. The thresholds for NPP, soil conservation, and water production ecological services lie within the range of 200–250 gc/m^2. This implies that when NPP rises, the limitations on soil conservation and water production initially reduce, but eventually start to grow again. Moreover, when the water yield level exceeds 270.00 mm, there is a progressively stronger constraint imposed by water yield on both soil conservation and habitat quality.

3.4 Spatial pattern of ecosystem service trade-offs and synergies

This study identified the spatial differentiation characteristics of ecosystem service relationships and their areal proportions in the Shendong mining area (as shown in Figure 7). The findings indicated that there was a predominant spatial synergy between NPP and habitat quality, with a synergistic area comprising 73.30%. The synergistic area was predominantly found in the northwest, northeast, and southwest parts of the mining area, whereas a tradeoff area, which made up 26.80% of the total, was principally situated in the southeast. The most significant synergistic association was found between soil conservation and habitat quality, with a synergistic area comprising 70.30%. The distribution of this region was primarily concentrated in the western and northeastern parts of the mining area, with a smaller tradeoff area predominantly found in the southeast. The synergistic relationship between NPP and soil conservation had a significantly greater scope compared to its tradeoff counterpart. Specifically, it encompassed 93.20% of the overall mining site, while tradeoffs were mostly focused inside its central metropolitan zone. From a spatial perspective, there was a strong correlation of 82.90% between NPP and water production in the mining zone. Additionally, there was a tradeoff of 17.10% between these two factors, which was distributed throughout the entire area. In terms of the relationship between water yield and soil conservation across space, there was a high level of synergy (98.00%) and a minimal level of tradeoffs (1.90%). In this context, a significant level of synergy accounted for a substantial chunk of 45.70%, while a smaller level of synergy comprised around 52.30%. Lastly, it is vital to note that water yield showed both synergy (42.00%) and tradeoff (57.00%) in terms of habitat quality.

3.5 Ecosystem service tradeoff and synergistic relationship driving factors

The root-mean-square error was used to quantify the tradeoff synergies between ecosystem services in the Shendong mining area over a period of 7 years. The geographic detector was then used to analyze the impact of each element on the root-mean-square error (as shown in Figure 8). The land use type was found to have the greatest impact on the pairs of NPP and habitat quality services, NPP and soil conservation services, NPP and water yield services, as well as water yield and soil conservation services (0.1593, 0.2699, 0.0778, 0.1811). The temperature (0.0828) was the main determining factor for both soil

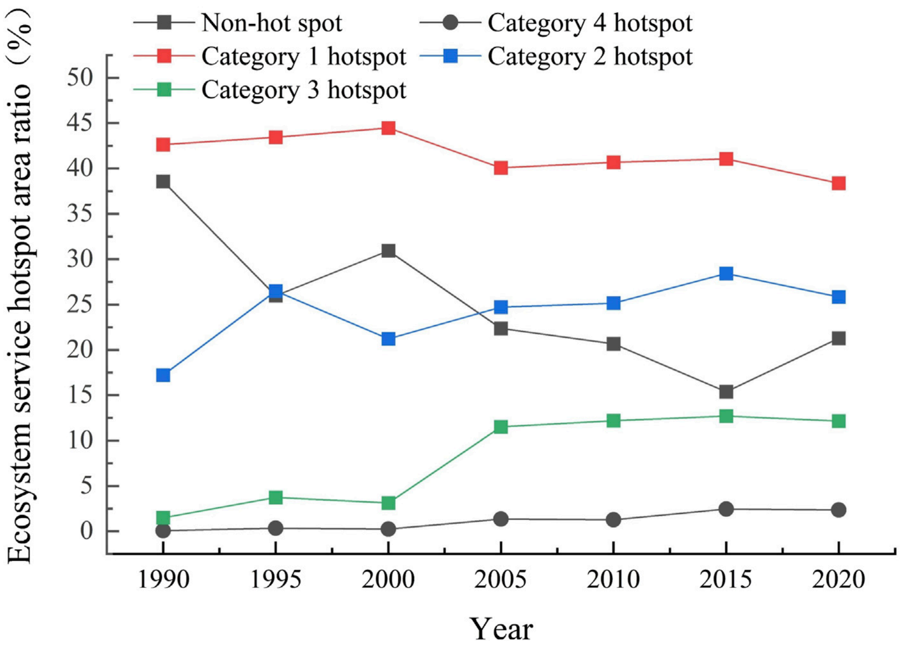
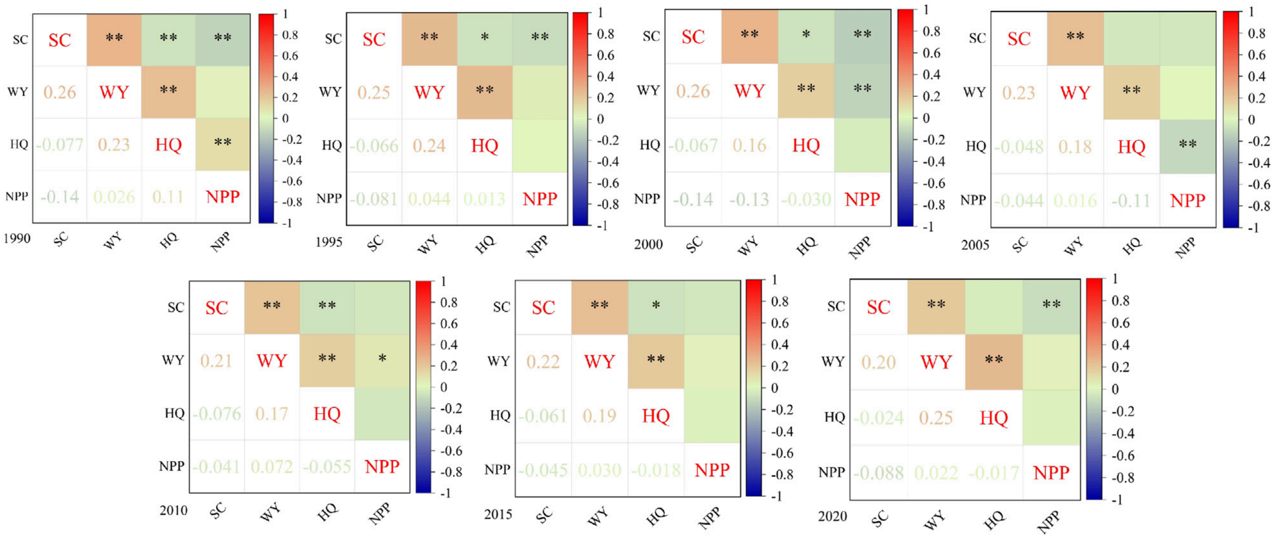


FIGURE 4
Changes in the areal ratio of hotspot areas of ecosystem services on the Shendong Mining Area from 1990 to 2020.



Note: * indicates significant at the 0.05 level, ** indicates significant at the 0.01 level. NPP: Primary Production; SC: Soil Conservation; HQ: Habitat Quality; WY: Water Yield.

FIGURE 5
Correlation coefficient of ecosystem services in the Shendong Mining Area from 1990 to 2020.

conservation and habitat quality service pairs, while it had a similar impact on water yield and habitat quality service pairs (0.0523). Within the study region, a notable synergistic correlation was seen between water yield and soil conservation services. The land use type (0.1811), temperature (0.0915), and kNDVI (0.0786) were found as crucial elements influencing this specific combination of services. The primary determinants impacting the correlation between water yield and habitat quality were temperature (0.0523) and rainfall (0.0435). The overall results suggest that there was a notable trade-off among ecosystem services throughout the whole study area. The study identified land use type (0.1593) and temperature (0.0603) as significant factors influencing NPP, in addition to habitat quality. Specifically, the

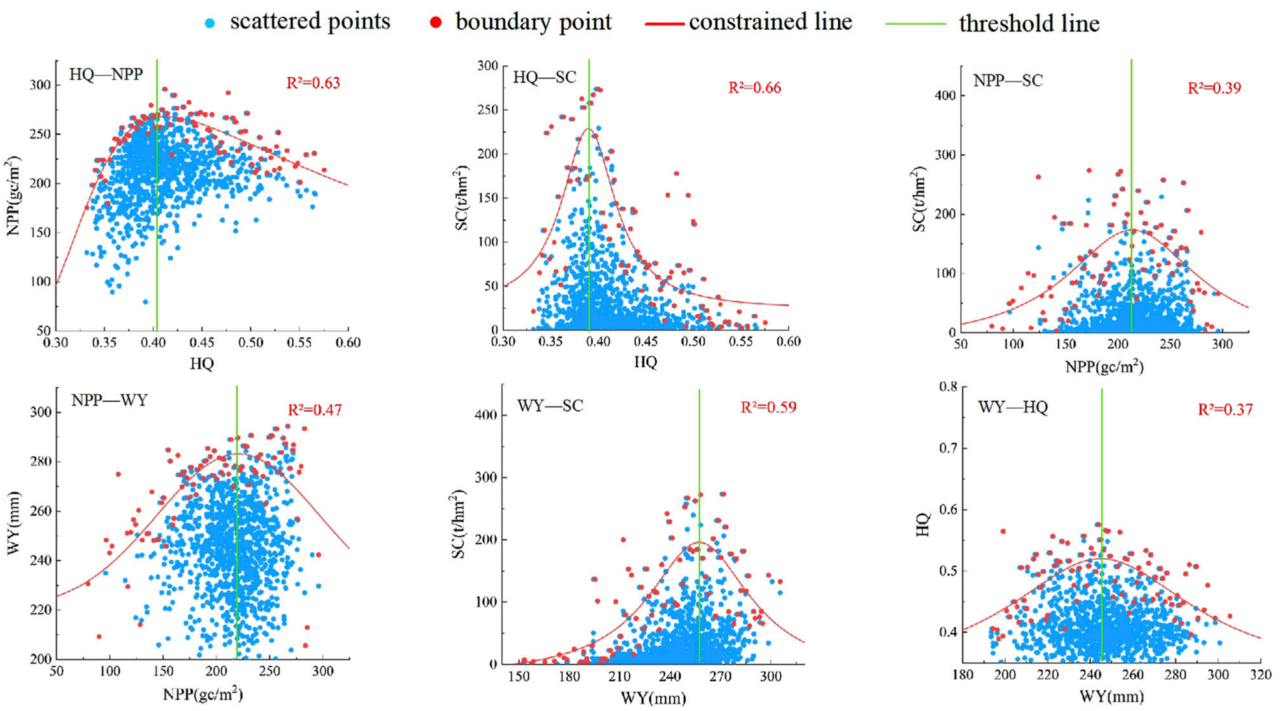


FIGURE 6
Nonlinear constraint relationships between pairs of ecosystem services.

cooperative development areas were primarily comprised of grassland and forest land, indicating that low temperatures are not conducive to their cooperative development. Land use type was found to have the greatest influence (0.2699) on the relationship between NPP and soil conservation, whereas temperature (0.0268) and DEM (0.0706) had relatively smaller effects. When examining the relationship between NPP and water production service pairs, it was found that land use type (0.0778) had the most influence, while temperature had the least influence with a q value of only 0.0136. The primary factors driving geographic heterogeneity in tradeoff synergistic intensity among ecosystem services in the Shendong mining area are land use type, temperature, and rainfall.

4 Discussion

Unsustainable human activities are disrupting and regulating the stability of ecosystems with increasing intensity, and may even lead to the structural collapse and functional decline of ecosystems (Zhang et al., 2008; Liu et al., 2024). As an important regional ecological fragile zone and key management area in China, the construction and optimization of the ecosystem in Shendong mining area is necessary (Lulu et al., 2021). In view of the lack of comprehensive evaluation of ecosystem services in mining areas in relevant studies, this study comprehensively measured the ecosystem service function of Shendong mining area by coupling individual ecosystem services, and considered the change rule of ecosystem services in the study area and the tradeoff and synergy between ecosystem services from the mining area scale. The driving mechanism of ecosystem service trade-offs and synergies in Shendong mining area was analyzed with the help of geodetector system, which made up the gap in the research of ecosystem services in mining area.

4.1 Evolutionary characteristics of ecosystem service functions

A comprehensive analysis was undertaken on the changes in ecosystem services in the Shendong mining area using a combination of remote sensing data and field investigation. The results showed notable fluctuations in both temporal and spatial dimensions. Soil conservation and water yield first decreased before later showing successive increments, but NPP and habitat quality demonstrated modest enhancements. From 1990 to 2020, there was a gradual increase in the expansion of these four categories of ecosystem services. Prior research has demonstrated that the ecological environment quality, vegetation cover, and soil moisture in the Shendong mining area have exhibited favorable patterns. Hao et al. (2022) observed a consistent improvement in the quality of the ecological environment in this region from 1995 to 2020. This suggests that the enhancement of ecosystem services is a direct result of the increased ecological environment quality. The findings of this study on the improvement of ecosystem services over a period of 30 years are consistent with earlier research results, therefore mutually confirming their conclusions.

In the early stage of coal mining, most of the ecosystem in the mining area is in its initial stage, and the original ecosystem is less

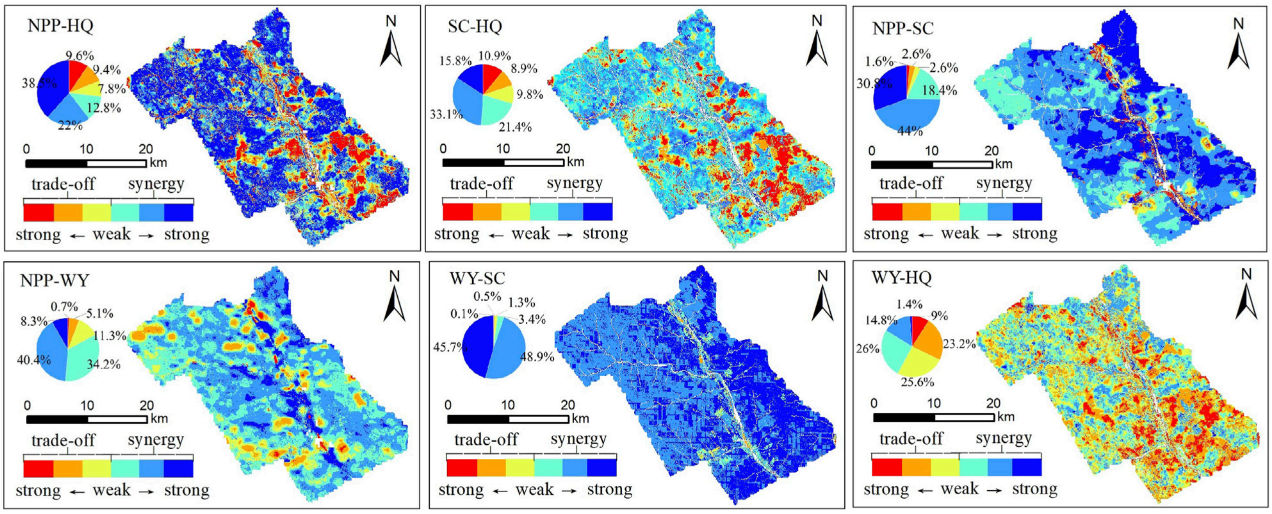


FIGURE 7
Intensity analysis of Slightly Improved to Significantly Improved.

affected by human activities (Boldy et al., 2021). In the stage of accelerated and stable development of coal mining, ecological problems become prominent and the ecosystem is seriously damaged, resulting in lower water yield and soil conservation at the beginning. With the ecological restoration in the later stage, the positive succession of the damaged ecosystem is realized and the negative succession of the ecosystem is slowed down (Li B. V. et al., 2024). In the stage of coal mine development decline and closure, ecological restoration is the main, supplemented by economic development, the mining area ecosystem will continue to recover. Under the ecological restoration project, measures such as afforestation and returning farmland to forest can increase land cover, reduce soil erosion, improve soil water retention capacity, and contribute to the conservation of water resources and the increase of water yield (Chen S. et al., 2023).

4.2 The spatial and temporal differentiation of trade-offs and synergies in ecosystem services

At present, the assessment of tradeoffs and synergies among ecosystem services is mainly based on static analysis, which examines the spatial correlation of a particular year or the temporal correlation within a limited time period. Nevertheless, there is a deficiency in conducting spatio-temporal analysis utilizing long-term time series data, and there is a requirement for more comprehensive spatial analysis to examine the tradeoffs and synergies (Jia et al., 2014; Wang L. et al., 2019).

In coal mining areas, the essence of ecosystem service trade-offs and synergies is the balance between mineral resource development and ecological environmental protection. In other non-mineral resource development areas, ecosystem services are usually interdependent (Chen and Chi, 2023), and the complex relationship between ecosystem services leads to trade-offs and synergies. However, the tradeoff and synergistic relationship between ecosystem services in Shendong mining area in different periods and Spaces is complex and inconsistent. For example, habitat quality and water production services show a significant synergistic relationship in time, but show a tradeoff relationship in space, which is due to the destruction of ecological environment caused by mining activities in the time scale, leading to the decline of habitat quality (Wang et al., 2021). At the same time, in order to meet the needs of production and life in mining areas, the demand for water resources increases, leading to the shortage of water resources and the decline of water production services. At the same time, under the implementation of different ecological restoration projects, land cover increases and soil erosion decreases, which greatly improves water production services and vegetation improvement (Li et al., 2020), so that water production services and habitat quality services are synergistic in time.

The spatial scale is based on the analysis of long-term dynamic changes of ecosystem services in grid plots. In some areas of mining areas, mining activities will lead to changes in land use and land cover, and directly affect the spatial distribution of ecosystem services (Cetin et al., 2023). The ecological and environmental characteristics (such as terrain, soil type, vegetation cover, etc.) in different regions will be affected by mining activities (Zhou et al., 2019), resulting in spatial heterogeneity of ecosystem services, that is, a trade-off between habitat quality and water yield in space. In addition, the ecosystem services of adjacent plots may show trade-offs or synergies. For example, land restoration in one area may improve soil conservation and habitat quality (Hua et al., 2024), while adjacent areas may face a decline in ecosystem services as a result of mining activities. This is not the same as the general mechanism of ecosystem services tradeoff synergies in the region, and the relationship between

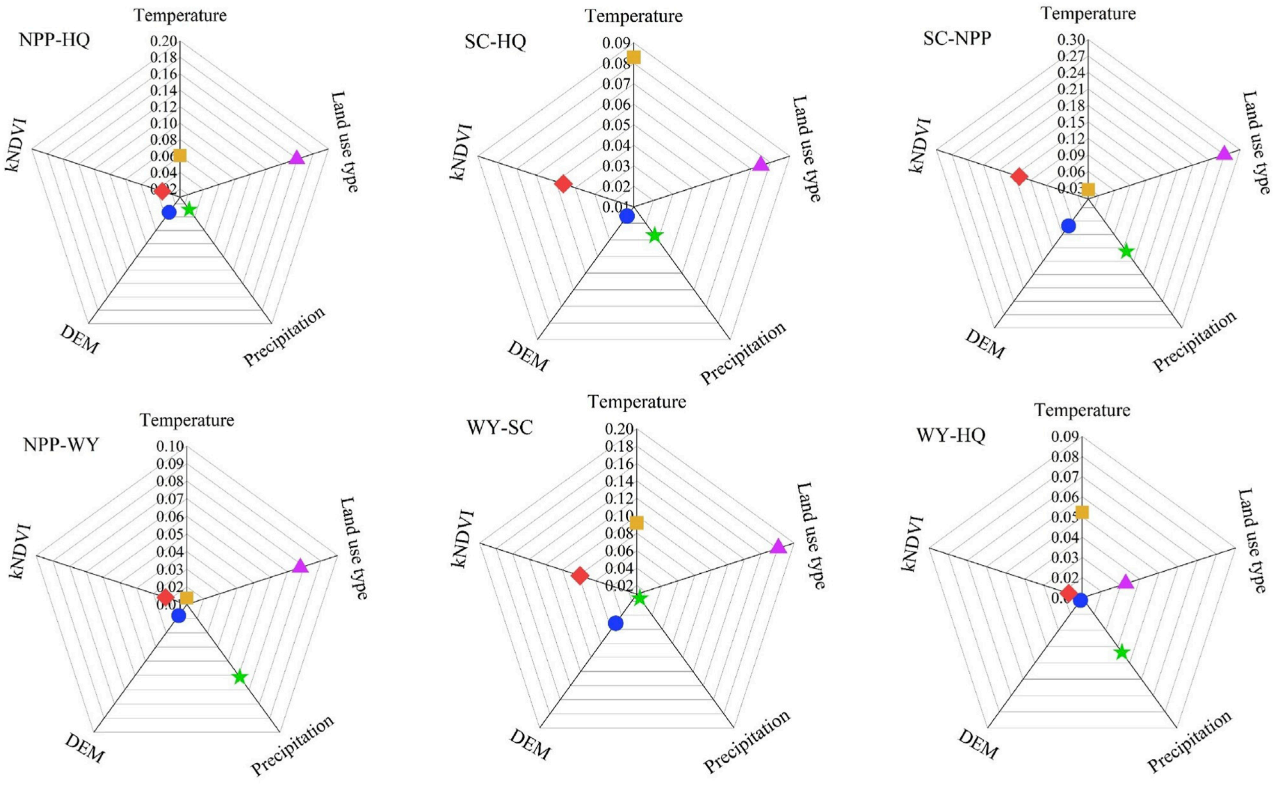


FIGURE 8
Single factor detection of the trade-off and synergies intensity among ecosystem services.

ecosystem services may change over time and over mining activities. In some cases, trade-offs may shift to synergies through long-term ecological restoration and sustainable land management. According to this study, regions with high ecosystem service supply tradeoff intensity have low demand synergy intensity. On the contrary, regions with low supply tradeoff intensity have higher demand synergy intensity, indicating that there is a correlation between ecosystem service supply tradeoff and demand synergy, which reveals the spatial difference between the output and supply of ecosystem services in mining areas.

4.3 The driving mechanism of ecosystem service tradeoff and synergy

The variations in environmental conditions within the study area of the Shendong mining area are influenced by its geographical location. This study employs the spatial detector system to examine the underlying factors that drive trade-offs and synergies in ecosystem services within the Shendong mining area. Moreover, its objective is to impartially assess the outcomes of implementing measures for ecological protection in mining and ascertain whether the study region has been impacted by mining activities. According to Tang et al. (2023), there is a strong relationship between changes in soil moisture in the mining area and both land cover and mining activities. This relationship is consistent with the reported trade-off and synergy of ecosystem services in the Shendong mining area. The correlations between these parameters are mostly controlled by natural variables such as land use type, temperature, and rainfall. The results of the spatial detector analysis show that land use type is a key element in explaining the trade-offs and synergies between ecosystem services. This is probably because changes in land use type directly affect different ecosystem services, which are essential for evaluating the model. The results are consistent with the study conducted by Li J. et al. (2022) in the China–Mongolia–Russia economic corridor. Furthermore, trade-off connections among ecosystem services can be influenced by geographical characteristics like as rainfall, kNDVI (Normalized Difference Vegetation Index), temperature, and DEM (Digital Elevation Model). The severity of surface runoff and soil loss is influenced by rainfall and elevation (Liu et al., 2022), whereas alterations in plant coverage have a direct impact on carbon storage levels and habitat quality in mining sites. These results demonstrate that changes in land use play a significant role in the trade-offs and synergies of ecosystem services during ecological restoration initiatives.

This study examined the driving mechanism behind the intricate interaction among various ecosystem services. However, it suffered from methodological and data limitations, as it included an excessive number of natural environment indicators as driving factors while neglecting human actions. Trade-offs or synergies can manifest in many ways across different spatial scales.

4.4 Limitations and recommendations

Initially, it is important to acknowledge that the InVEST model possesses certain constraints. For example, the necessary biophysical parameter is a broader representation of the real land surface. The water production module utilizes the simplified Budyko water-energy balance equation, disregarding the delicate balance caused by geology and complex land use patterns (Wu et al., 2021). In addition, the habitat module fails to account for the impact of climate conditions on the survival of species. Furthermore, it is imperative that this study includes a more extensive array of ecosystem services for thorough examination. Furthermore, ecosystem services are significantly impacted by both human activities and natural elements such as land utilization, climate, and terrain. Therefore, it is essential to identify the key factors that drive these services. To summarize, it is important to focus on enhancing model principles and validating parameters when assessing future trends across various scenarios. This will enable the simulation of the underlying mechanism that drives the ecological environment. Ultimately, this will establish a solid scientific foundation for ecosystem services and facilitate the promotion of high-quality sustainable development in the Shendong mining area.

Considering these factors, including the mining area's field characteristics and the distribution of ecosystem service activities, the following recommendations are proposed: These guidelines can optimize the sustainable exploitation of land resources and serve as valuable references for land use planning and ecosystem conservation. 1) The ability to manage land should be consistently improved, specifically by decreasing unregulated land reclamation activities and preventing significant land degradation that results in soil erosion. 2) The results suggest that there is a trade-off between the amount of water used each year and the storage of carbon, the quality of habitats, and the conservation of soil. This trade-off can be explained by the fact that water resources are used during the process of afforestation. Furthermore, the selection of unsuitable plant species can also cause water loss, which in turn leads to soil dryness. Hence, it is imperative for municipal authorities to give precedence to plants with reduced water demands while carrying out vegetation restoration initiatives. In addition, the implementation of water retention agents, conservation tillage practices, and agroforestry systems could effectively decrease water consumption while enhancing the overall ecosystem quality. 3) It is necessary to develop adaptable ecological compensation systems that take into account the distinct characteristics of various land use patterns and their respective significance in delivering ecosystem services. Concurrently, policymakers should prioritize environmental conservation when designing development sites or establishing economic objectives.

5 Conclusion

This study investigated and mapped the spatial and temporal evolution of ecosystem services in Shendong mining area. On this basis, the paper explores the changes of ecosystem service functions in mining areas, and makes a comprehensive analysis of the ecosystem service functions and their tradeoffs and synergies in Shendong mining area. The research on the synergies of regional ecosystem service function changes and tradeoffs in coal mines is of great significance for promoting ecological environment protection and sustainable development, and also provides a new research perspective and methodology. The application field of ecosystem services research has been broadened. The research conclusions are as follows:

(1) Different ecosystem services in the mining area have significant fluctuations in time. From 1990 to 2020, both water production and soil conservation in the mining area show a "V" -shaped change trend of first decreasing and then increasing, and the decreasing area is closely related to the mining development area. Under the intervention of ecological restoration in mining area, the net primary productivity and habitat quality increased slowly. Spatially, the high-value ecosystem service areas were mainly concentrated in the southeast of the study area, showing significant spatial heterogeneity.

(2) The dynamic changes of hot spots in the mining area during the past 30 years are significant. From 1990 to 2020, the areas of non-hot spots and type 1 hot spots gradually decrease, while the areas of type 2, type 3 and type 4 hot spots fluctuate and grow slowly. Through the evaluation and quantification of various ecosystem service functions in the mining area, it is found that the ecosystem service in the southeast of the mining area is excellent (hot spot), while the ecosystem service in the northwest of the mining area is relatively weak (non-hot spot).

(3) The spatial differentiation of ecosystem services in Shendong mining area showed that there were significant synergistic relationships between carbon storage and habitat quality, soil conservation and habitat quality, and water production and habitat quality in 42.20%, 70.30%, and 98.00% regions, respectively, mainly distributed in the western, northeastern and central towns of the mining area. The synergistic area between carbon storage and soil conservation accounted for 67.00%, and that between carbon storage and water yield accounted for 49.10%. The tradeoff relationship is mainly distributed in the southeast of the mining area. Moreover, through constraint effect analysis, the constraint line of each ecosystem service pair is hump-shaped, that is, the relationship between ecosystem services changes from positive correlation to negative correlation. And there is an obvious threshold effect, when the threshold is exceeded, the constraint effect between ecosystem services intensifies.

(4) The trade-offs and synergies among ecosystem services in Shendong mining area were mainly driven by land use type, temperature and rainfall. Among them, land use type is the main factor affecting net primary productivity and habitat quality, net primary productivity and soil conservation, water yield and soil conservation, and water yield and habitat quality service pairs. The effects of temperature on soil conservation and habitat quality service pair, water yield and habitat quality service pair

were significant. The synergistic relationship is mainly the relationship between water yield and soil conservation service pair.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZC: Conceptualization, Supervision, Validation, Visualization, Writing–review and editing. ZZ: Conceptualization, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. XZ: Writing–review and editing, Writing–original draft, Formal Analysis. YJ: Validation, Writing–original draft. YC: Software, Writing–original draft. SW: Supervision, Writing–review and editing. HZ: Funding acquisition, Project administration, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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