



# OPEN Evolution and driving mechanism of multiple ecosystem services in resource-based region of Northern China

Jinfeng Wang<sup>1</sup>, Ya Li<sup>1</sup>, Sheng Wang<sup>1✉</sup>, Qing Li<sup>2</sup>, Rende Wang<sup>2</sup>, Rui Zhang<sup>1</sup> & Xi Ge<sup>1</sup>

Understanding the spatiotemporal characteristics and comprehensive service capabilities of various ecosystem services is crucial for maintaining regional ecosystem security, and clarifying the driving mechanisms of ecosystem services plays a guarantee for achieving regional sustainable development. Based on the ecological issues of Shanxi Province (SXP) in China, an assessment system covering eight targeted ecosystem services were constructed to quantitatively analyze the spatio-temporal patterns and contribution rates of driving factors. The water conservation, sand fixation, environment purification and habitat quality in the Loess Hills of western SXP have improved, with significant increase in hotspots. The comprehensive service capacity of ecosystem services in the Fenwei Basin (central SXP) has deteriorated, and the coldspots have expanded. The water conservation, carbon storage, habitat quality and recreation culture in the Yanshan-Taihang Mountains (eastern SXP) were enhanced, while product supply, carbon storage and environment purification were deteriorated. Land use is the dominant influencing factor on product supply. Water and soil conservation, sand fixation, and environment purification are dominated by climate factors. Carbon storage, habitat quality and recreation culture are influenced by underlying surface conditions. The current study provided a research paradigm, which will help the government with appropriate management policies to ensure the effectiveness of ecological protection and restoration, and offers insights for facilitating ecological sustainability and economic transformation in resource-based regions worldwide.

**Keywords** Ecosystem services, Multiple ecosystem services landscape index, Hotspot analysis, Driving force, Resource-based area

Ecosystem services (ES) have enormous potential to impact natural resource management<sup>1</sup>. Developing scientific planning based on ES is an effective ecosystem management approach to promote human well-being and social sustainable development, which is of great significance to realize the common development of ecosystem and social interests<sup>2</sup>. With the progression of society, issues such as population growth, urban expansion and human-land contradictions have become increasingly prominent, and unsustainable human activities have led to the ES reduction of approximately 60%<sup>2</sup>. The contradiction between ecological carrying capacity and ecosystem service supply is increasing sharply, and the ecosystem sustainable development is influenced by multiple factors. Both natural and socio-economic factors can affect the distribution and supply of ecosystems and biodiversity. Understanding the ES status is a prerequisite for restoring and strengthening ecosystem stability, and identifying the dominant factors affecting ES is the key for subsequent implementation of ecosystem improvement and protection<sup>3–5</sup>.

The dynamic change of ES has attracted extensive attention worldwide, especially in resource-based regions. Baskent assessed the ecosystem services of Kumluca National Forest (Turkey), emphasized that the comprehensive quantification and assessment of ecosystem services could provide effective communication and good decision-making basis for sustainable forest resource management<sup>6</sup>. Whitney et al. reported that the variation in water resource was greatly influenced by climate change and forest disturbance in the Colorado River Basin<sup>7</sup>. Tuo et al. evaluated the grassland ecosystem services of northern China, providing technological support for the protection and restoration of northern grassland ecosystems<sup>8</sup>. Overall, most studies focus on regions dominated

<sup>1</sup>School of Geographical Science, Shanxi Normal University, Taiyuan 030031, China. <sup>2</sup>Institute of Geographical Sciences, Hebei Academy of Sciences, Hebei Technology Innovation Center for Geographic Information Application, Shijiazhuang 050011, China. ✉email: wangsheng@sxnu.edu.cn

by ecological resources, with little attention on the ecosystem of mineral resource regions. At present, studies on ES have shifted from concept, classification<sup>2,9</sup> and single indicator analysis<sup>10–12</sup> to the comprehensive study on multiple ES, interrelationships and driving factors<sup>13,14</sup>. Ecosystem service assessment relied heavily on statistics previously. Statistical approaches were easily affected by subjectivity, and their reliability was uncertain. With the wide application of 3 S technology, the comprehensive assessment models of ESs have developed rapidly. These models can not only depict spatio-temporal patterns of ESs in detail, but also explore future dynamics, thus providing scientific basis for formulating adaptive countermeasures<sup>11,13</sup>. By integrating the ecosystem regulation, supply, support and cultural services, the comprehensive capacity of the regional ecosystem will be continuously improved<sup>15,16</sup>. After comprehending the spatiotemporal pattern of ES, scholars have begun to pay attention to the response of ecosystem service evolution to human activities and natural environment<sup>17,18</sup>. Some studies have used traditional linear regression<sup>19</sup>, geographically weighted regression<sup>20</sup> and geographic detectors<sup>21</sup> to explore the ES drivers. These methods exhibit limited efficacy on capturing the complex interactions among multiple factors and are predominantly employed for qualitative analysis. The random forest method can train the sample data, which is more consistent with reality<sup>22</sup>. By calculating the contribution rate of various driving forces to ES, this method realizes the quantitative analysis on the comprehensive influence of multiple factors, which is crucial for fully understanding the impact mechanism of regional ES and implementing policy measures in accordance with local conditions.

Mineral resources exploitation will inevitably cause ecological damage and environmental pollution. How to deal with the harmonious relationship between ecological protection and social economy is a common issue faced by resource-based regions<sup>23,24</sup>. SXP is a representative region of mineral resources in China and even the world. It has abundant resources (especially coal), nearly 60% of the land has mineral distribution, which is an important coal-steel industrial base. Under the development of resource-based economy, land use structure changes, water resources, soil interior and forest vegetation are seriously damaged, and the soil carbon sink function strongly declines<sup>25</sup>. The decrease in biomass and productivity has accelerated the degradation of product supply and habitat<sup>26</sup>. SXP is located in the Loess Hilly and Gully region, and the wind-water complex erosion is serious. Severe soil erosion area is  $10.8 \times 10^4$  km<sup>2</sup>, accounting for 69%<sup>27</sup>. Non-sustainable human activities (such as grassland degradation and farmland cultivation) have led to the rapid southward expansion of sandy desertification in the northern SXP, with frequent sandstorms and dust-floating weather<sup>28</sup>. 80% of SXP is mountainous, having rich ecological resources (such as Wutai Mountain and Taihang Grand Canyon) and splendid culture (such as “Sanjin Culture”). The resources development and protection are significant challenge faced by the local government. Therefore, SXP is the ideal mineral resource-based region for studying the evolution and driving mechanism of multiple ecosystem services.

Previous studies on ES were fragmented and focused on the changes in single ES at local areas (such as coal mining area and forests) or watershed scales in SXP<sup>29,30</sup>, which to some extent ignores the “whole system consciousness” reflected by ES and cannot describe in detail the complex interdependent relationship between human society and the entire ecosystem<sup>31</sup>. In view of the ecological problems faced by SXP, including supply reduction, water and soil loss, soil degradation, vegetation destruction, biodiversity loss, and cultural landscape protection, etc., a set of index and model system covering eight targeted ESs (product supplies: PSS, water conservations: WCS, soil conservations: SCS, carbon storages: CSS, sand fixations: SFS, environment purifications: EPS, habitat qualities: HQS, and recreation cultures: RCS) was built to quantitatively analyze the spatio-temporal patterns and contributions of influencing factors for each ES. A research paradigm of “Index System Construction - Ecosystem Services Comprehensive Assessment - Driving Force Quantitative Analysis - Propose Policy Recommendations” was provided for ES governance in resource-based regions. The current study will help local government on formulating effective regional ecological protection/recovery management strategies, and provide important reference for achieving ecological sustainability, and high-quality economic transformation and development in resource-based regions worldwide.

## Study area

SXP (34.34°N–40.44°N, 110.14°E–114.33°E, Fig. 1) is the mineral resource-based region of northern China, with the area of  $15.67 \times 10^4$  km<sup>2</sup>. More than 80% are mountains and hills, and the plains are in the intermountain valley areas. SXP is the temperate continental monsoon climate, with average annual precipitation and temperature of 554 mm and 3.4–14.7 °C, respectively. Under the impact of climate, the vegetation type is mainly deciduous broad-leaved forest and coniferous broad-leaved mixed forest in the south, and is temperate scrub and semi-arid grassland in the north, which is an important part of the sandstorm source control project. According to the ecological zoning from the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences (CAS), SXP is divided into three ecological regions and nine ecological subregions (Table S1 in Supplementary Information) in combination with the ecosystem structure, climate, topography and vegetation.

## Materials and methods

### Data sources

The data mainly include meteorological, LUCC, NDVI, Digital Elevation Model (DEM), soil and statistical datasets. The meteorological data include daily air temperature (AT), precipitation (P), total solar radiation (TSR), and potential evapotranspiration (PE) of 76 stations in and around SXP; The hourly wind speed (WS) data is selected from 56 stations around SXP, and is used to calculate the cumulative time of each grade WS which was greater than or equal to the critical erosion WS ( $5 \text{ m s}^{-1}$ ) during wind erosion activities. The statistical datasets were obtained from the Statistical Yearbook of SXP, including water and sediment volume, municipal production (food production, fisheries, animal husbandry, timber), and tourism income. The water resources

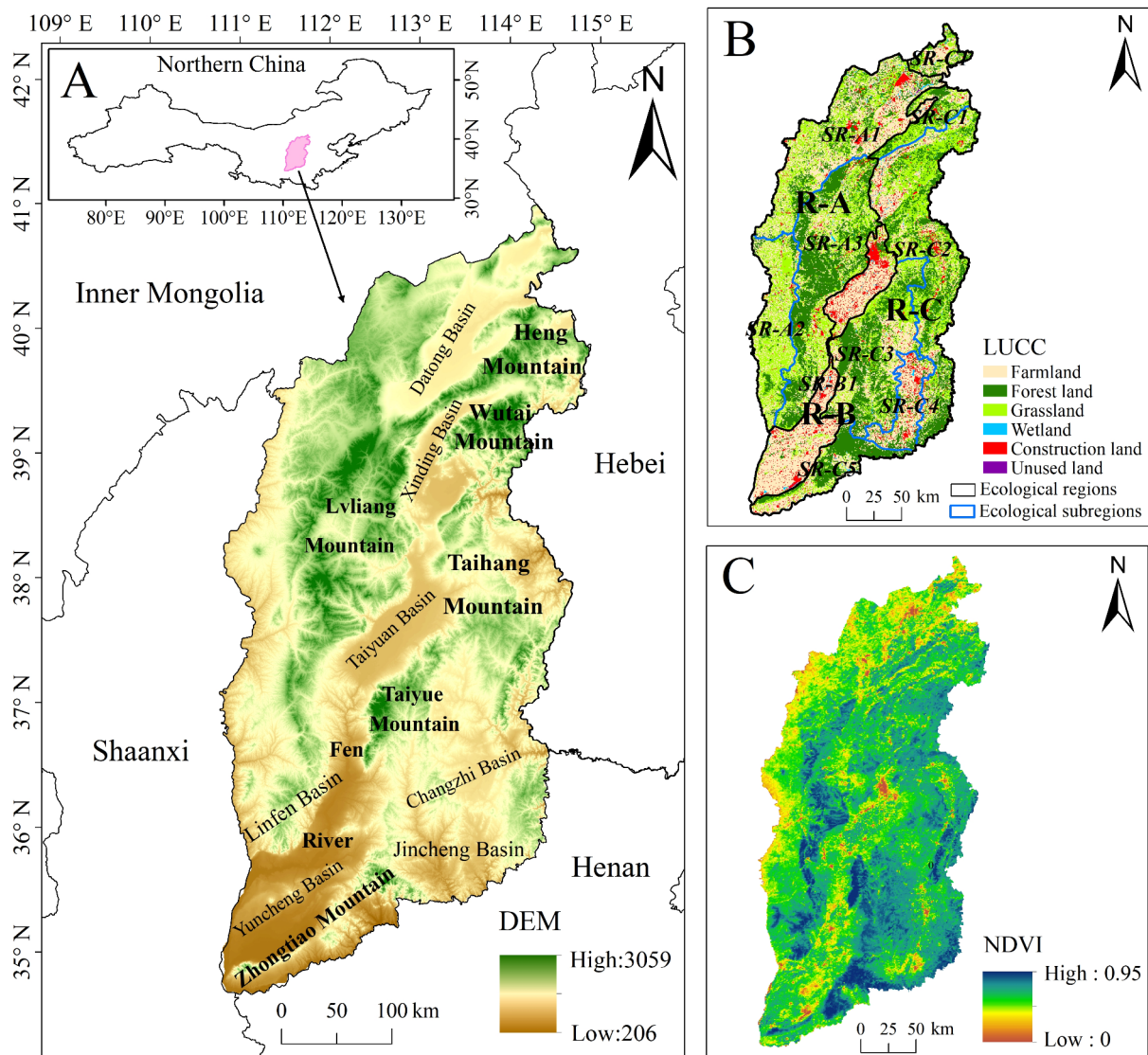


**Fig. 1.** (a) Location of the SXP; spatial distribution of (b) the Land Use and Cover Change (LUCC) and (c) Normalized Difference Vegetation Index (NDVI). The base maps of (a), (b) and (c) are DEM data from National Aeronautics and Space Administration, LUCC data from China Land Cover Dataset of Wuhan University and NDVI data from the Resource and Environment Science Data Center, respectively. All creations are completed in ArcGIS10.8 (<http://arc.cnglyh.com/>). The resolutions of all the maps were 1 km×1 km.

and sediment volume data were obtained from the Shanxi Water Resources Bulletin in Shanxi Provincial Department of Water Resources. The detailed information is shown in Table 1.

### Ecosystem service index and model system

Considering the ecological environment problems faced by SXP, eight targeted ESs are selected to construct the index and model system (Table 2, and Table S2 in Supplementary Information): (1) Supply service - The staggered geomorphic types form the unique terrain and climate suitable for various agriculture, forestry, animal husbandry and fishery, with product supply (PSS) having unique advantages and status in SXP. (2) Regulation service - SXP is located in the Loess Plateau with serious soil erosion, and Northern SXP is the key area for desertification monitoring and prevention in China, WCS, CSS and SFS are selected to evaluate water and soil conservation, and the status of desertification prevention and control. (3) Support service - SXP has abundant mineral resources, and the coal-steel industry has aggravated the land, vegetation and habitat destruction, CSS, EPS and HQS are selected to evaluate the quality and carbon sequestration capacity of terrestrial ecosystems. (4) Cultural service - SXP has profound cultural heritage and rich natural landscape, RCS is used to evaluate entertainment and cultural services.

| Data                | Dataset        | Resolution             | Period    | Source                                              |
|---------------------|----------------|------------------------|-----------|-----------------------------------------------------|
| Meteorology         | AT, P, TSR, PE | Raster; 1 km           | 2000–2020 | China Meteorological Science Data Center            |
|                     | WS             | Raster; 1 km           | 2000–2020 | National Climatic Data Center of the United States  |
| Land use/land cover | LUCC           | Raster; 100 m          | 2000–2020 | China Land Cover Dataset (CLCD) of Wuhan University |
| Vegetation          | NDVI           | Raster; 1 km           | 2000–2020 | Resource and Environment Science Data Center, CAS   |
| Topography          | DEM            | Raster; 90 m           | –         | National Aeronautics and Space Administration       |
| Soil                | Soil           | Vector;<br>1:1,000,000 | 2000      | Institute of Soil Science, CAS                      |

Table 1. Detailed information of the datasets.

| ESs | Evaluation index                         | Model/Method                                         | Principles                                                                                                                                | References |
|-----|------------------------------------------|------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|------------|
| PSS | Product supply capacity                  | GIS spatial analysis                                 | NDVI Ratio Method                                                                                                                         | 32         |
| WCS | Water conservation capacity              | InVEST model<br>Water Yield module                   | Balance equation of water quantity                                                                                                        | 33         |
| SCS | Soil conservation capacity               | InVEST model<br>Sediment Delivery Ratio module       | Modified soil loss equation                                                                                                               | 34         |
| CSS | Fixed carbon dioxide                     | InVEST model<br>Carbon module                        | The sum of average carbon density of above-ground carbon pool, below-ground carbon pool and soil carbon pool for different land use types | 35         |
| SFS | Sand consolidation capacity              | National Wind Erosion Survey Model of China (NWESMC) | Grass (forest) land module, sandy land module and farmland module based on different land use types                                       | 26         |
| EPS | Net primary productivity of plants (NPP) | CASAmoel                                             | Estimation of photosynthetically active radiation (APAR) and light energy utilization rate absorbed by vegetation                         | 36         |
| HQS | Habitat quality index                    | InVEST model<br>Habitat Quality module               | Consider the influence distance, weight and sensitivity of the threat factor                                                              | 37         |
| RCS | Recreation culture index                 | GIS spatial analysis                                 | Natural and cultural landscape grade combined with land use type                                                                          | 38         |

Table 2. Model and principle of ecosystem service assessment.

Multiple ES landscape index

The Multiple ES Landscape Index (MESLI) could assess the comprehensive capacity of multiple ES in different areas<sup>39</sup>. MESLI is described as the sum of standardized ES indicators, which is derived from the weighted average of eight standardized ES, including PSS, WCS, SCS, CSS, SFS, EPS, HQS and RCS<sup>40</sup>. The ES weight is obtained by principal component analysis, and the effectiveness and applicability are tested by Kaiser-Meyer-Olkin method (KMO)<sup>41</sup>. The KMO index was 0.477 (KMO < 0.5), which could not pass the principal component analysis test, indicating the nonstatistical primary and secondary difference of the above eight indicators, and the weights were all assigned as 1/8. The calculation formula is as follows:

$$MESLI = \frac{1}{8} \sum_{x=1}^8 \frac{I_x - \min I_x}{\max I_x - \min I_x} \tag{1}$$

Where *MESLI* represents the value of raster after standardization, with dimensionless index ranging from 0 to 1; *I<sub>x</sub>* is the actual raster value of the *x* (*x* = 1, ... 8) class ecosystem service index; *min<sub>I<sub>x</sub></sub>* and *max<sub>I<sub>x</sub></sub>* represent the minimum and maximum values of the *x* class index, respectively.

Hotspot analysis

Hotspot analysis is an effective method to explore the distribution of local spatial clustering, which could distinguish the agglomeration degree of variables’ spatial distribution by coldspot and hotspot. Hotspot analysis (Getis-Ord Gi\*) is a powerful spatial statistical technique used in geographic information systems (GIS), which can intuitively reflect the distribution of hot and cold spots in local spatial regions through identifying high-value or low-value clusters<sup>42</sup>. When the Z-score is greater than 0, the higher the Z-score, the closer the high-value clustering of the target object attributes (forming hotspots). Conversely, when the Z-score is less than 0, the lower the Z-score is, the tighter the low-value clustering of the target object attributes (forming coldspots). In this paper, based on the hotspot analysis in GIS, the coldspot is set to 0, the hotspot is set to 1, and the spatial distribution of ecosystem service hotspots is obtained by superposition.

Random forest model

ES are affected by multiple factors, such as climate change, surface factors and human social activities. The influencing factors on ecosystem service type were mainly selected from the perspective of topographic factors (slope, DEM), climatic factors (precipitation, temperature, evapotranspiration), surface factors (LUCC, NDVI) and social factors (population density, gross domestic product). The random forest analysis method was used to quantify the effect degree and contribution rate of different driving forces on ES. The random forest is a machine learning algorithm based on decision trees, consisting of independently constructed trees from the dataset guide samples<sup>19</sup>. The algorithm adopts the random and re-sampling method, forming multiple training set samples

proportionally from the original dataset in multiple extraction rounds, and constructing the corresponding decision tree for each training set sample. The final result is the average of all the decision tree results<sup>43</sup>.

The specific operation process is as follows: sampling was conducted by creating random points in the study area, and a basic analysis database was established using 10,000 sets of sample data. Data on each ecosystem service and its related influencing factors were extracted to multiple sampling points according to the corresponding year, which were divided into 20% test set and 80% training set. After the scores of the test dataset and the training dataset presented, the results will be cross-validated five times with  $R^2$  to prevent overfitting, and ultimately obtain the influence degree and contribution rate of each factor.

## Results

### Spatio-temporal characteristic of ES

#### Temporal change of ES

Among the eight ES evaluated in SXP from 2000 to 2020, the interannual changes of seven service indicators (PSS, WCS, SCS, CSS, EPS, HQS and RCS) showed an increasing trend, but the increasing rate was different (Fig. 2). Among them, the interannual fluctuation of soil conservation capacity exhibited significant variability and rapid increase, with the growth rate of  $11.57 \text{ t hm}^{-2} \text{ yr}^{-1}$  (Fig. 2c). Followed by NPP ( $5.31 \text{ gC m}^{-2} \text{ yr}^{-1}$ ), increasing from  $317.61 \text{ gC m}^{-2} \text{ yr}^{-1}$  in 2000 to  $432.99 \text{ gC m}^{-2} \text{ yr}^{-1}$  in 2020 (Fig. 2f). The product supply capacity increased at the rate of  $1.50 \text{ kg hm}^{-2} \text{ yr}^{-1}$ , especially with significant growth rate of  $27.22 \text{ kg hm}^{-2} \text{ yr}^{-1}$  from 2008 to 2014 (Fig. 2a). The interannual variation of water conservation showed fluctuating increasing trend, with the average growth rate of  $0.29 \text{ mm yr}^{-1}$  (Fig. 2b). The fixed carbon dioxide and recreation culture index exhibited significant linear increase (Fig. 2d and h), while the variation trend of habitat quality index was not significant, indicating the good overall habitat quality (Fig. 2g). In the past 21 years, the sand consolidation declined at the rate of  $0.203 \text{ t km}^{-2} \text{ yr}^{-1}$ , with the range of  $3.66\text{--}9.79 \text{ t km}^{-2} \text{ yr}^{-1}$ , and the total amount was  $5.74\text{--}15.35 \times 10^7 \text{ t}$ , decreased by  $9.61 \times 10^7 \text{ t}$  in 2020 compared to 2000 (Fig. 2e).

#### Spatial distributions of ES

Figure 3 showed the spatial distribution of eight ES in SXP. The water conservation, fixed carbon dioxide, NPP and habitat quality index were high in the eastern and western mountainous areas (R-A: Loess Plateau hilly and gully ecological region, R-C: Yanshan Taihang Mountain ecological region, Fig. 1) and low in the central basin (R-B: Fenwei River Basin agro-ecological region), with annual average values of  $13.88 \text{ mm}$ ,  $176.59 \text{ t hm}^{-2} \text{ yr}^{-1}$ ,  $393.34 \text{ gC m}^{-2} \text{ yr}^{-1}$  and  $0.628$ , respectively (Fig. 3b, d and f, and 3g). The spatial distribution of product supply capacity was contrary (Fig. 3a), with high value areas concentrating in Datong, Xinding, Taiyuan, Linfen, Yuncheng Basin, as well as Changzhi and Jincheng Basin of the southeastern SXP, and Yuncheng Basin in south SXP showing the strongest PSC. The SCS in the eastern and southern regions was significantly higher than that in the western and northern regions (Fig. 3c), with the multi-year average of  $569.02 \text{ t hm}^{-2} \text{ yr}^{-1}$ . The highest SCS ( $725.65 \text{ t hm}^{-2} \text{ yr}^{-1}$ ) was found in Yanshan-Taihang Mountains (R-C), especially in forest covered areas. The SFS in northern SXP was relatively high (Fig. 3e), with an annual average of  $6.54 \text{ t km}^{-2} \text{ yr}^{-1}$ . The high recreation culture index were concentrated in nature reserves such as the northern Heng Mountain (SR-C1), western Lvliang Mountain (SR-A3), south-central Taiyue Mountain (SR-C3), southern Zhongtiao Mountain (SR-C5) and eastern Taihang Mountain (SR-C2) (Fig. 3h), while the recreation culture index in other areas was relatively low.

The spatial differences in the interannual variation of eight ES were significant from 2000 to 2020 (Fig. 4). The areas with increasing trends of product supply capacity, water conservation capacity, soil conservation capacity and NPP accounted for 76.77%, 91.62%, 82.27% and 95.35% of, respectively. The regions exhibiting significantly increased in water conservation capacity and NPP were distributed in the Loess Plateau agricultural and

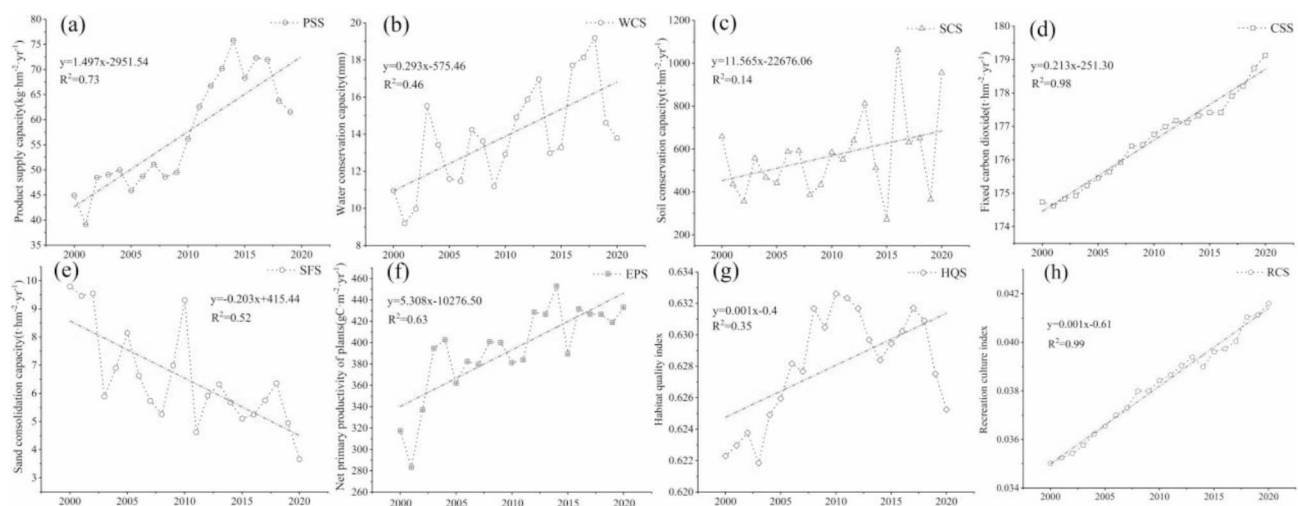


**Fig. 2.** Interannual variations of ES. (a) PSS, (b) WCS, (c) SCS, (d) CSS, (e) SFS, (f) EPS, (g) HQS, (h) RCS.

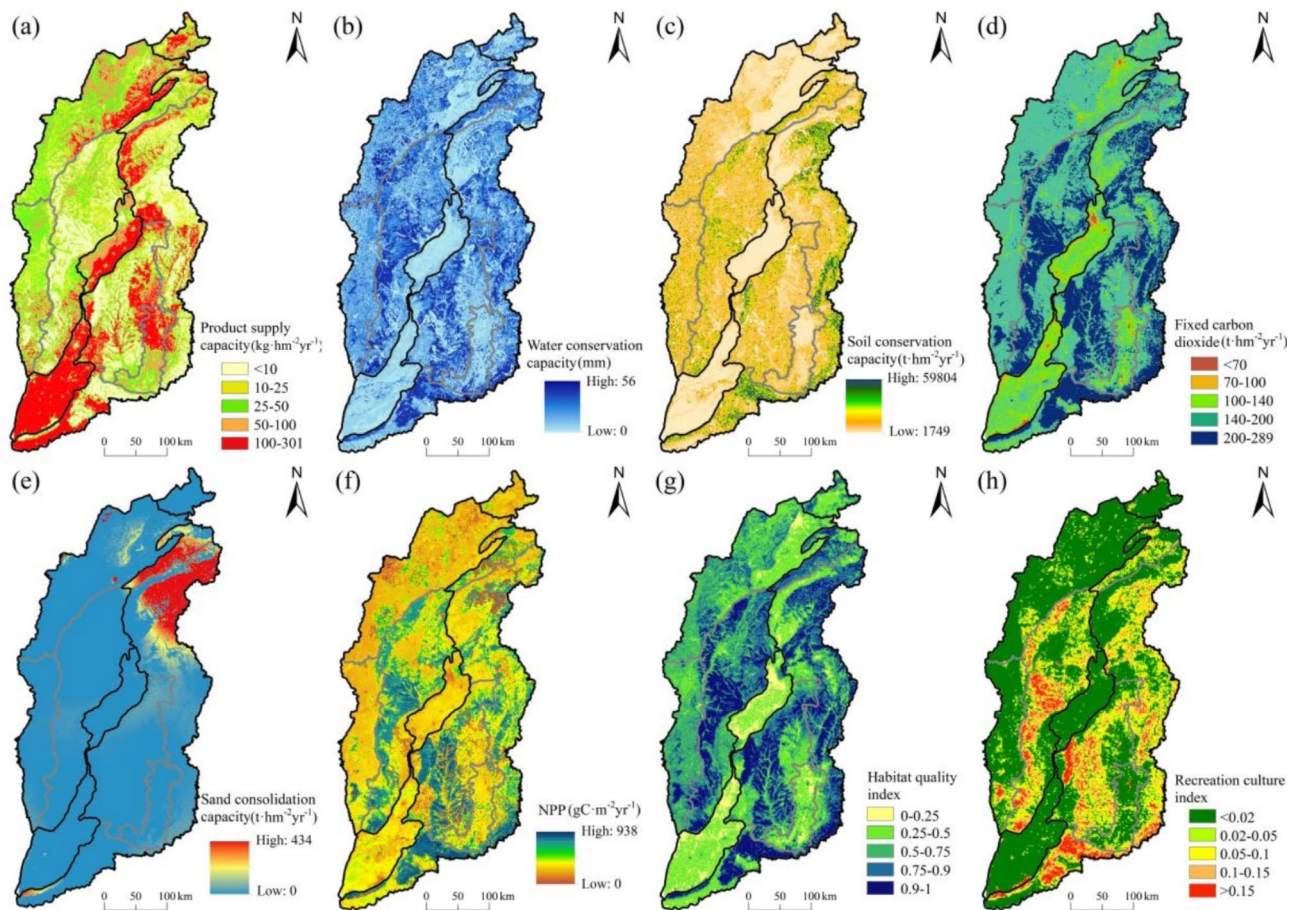


**Fig. 3.** Spatial pattern of ES. (a) PSS, (b) WCS, (c) SCS, (d) CSS, (e) SFS, (f) EPS, (g) HQS, (h) RCS. The (b) WCS, (c) SCS, (d) CSS and (g) HQS were simulated through the Water Yield module, Sediment Delivery Ratio module, Carbon module and Habitat Quality module of the InVEST 3.8.7×86 model (<https://naturalcapitalproject.stanford.edu/software/invest>), respectively. The (f) EPS was simulated by CASA model with ENVI 5.1 software (<https://envi.geoscene.cn/>). The final mapping was completed in the ArcGIS 10.8 software (<http://arc.cnglyh.com/>). The (a) PSS and (h) RCS were calculated based on the formula in ArcGIS 10.8 software (<http://arc.cnglyh.com/>). The (e) SFS was simulated based on the National Wind Erosion Survey Model of China (NWESMC) model with ENVI 5.1 software (<https://envi.geoscene.cn/>), and the graph was completed in the ArcGIS 10.8 software (<http://arc.cnglyh.com/>). The resolutions of all the maps were 1 km×1 km.

grassland ecological region (R-A, Fig. 4b and f), indicating the remarkable effectiveness of ecological engineering measures since 2000. The soil conservation capacity increased significantly in the mountainous areas of Lvliang Mountain, Taiyue Mountain, Heng Mountain and Wutai Mountain (12.04%), but decreased significantly in the southern Taihang and Zhongtiao Mountains (Fig. 4c). The regions with significantly increased product supply capacity were mainly concentrated in Datong, Xinding, Linfen and Yuncheng basins, while decreased in Taiyuan and Changzhi basins (Fig. 4a). In recent 21 years, fixed carbon dioxide, sand consolidation capacity, habitat quality index and recreation culture index showed decreasing trend. The sand consolidation capacity in 81.36% of the area showed the decreasing trend, distributing in Hengshan Mountain, Wutai Mountain and the surrounding mountain areas, while only increased in the northwest SXP mountain area (Fig. 4e). The fixed carbon dioxide, habitat quality index and recreation culture index all showed increasing trend in mountainous areas and decreasing trend in valley and basin areas (Fig. 4d and g, and h), showing that the ecological environment governance measures, such as the grain for green project and the natural forest protection project, in mountainous areas have achieved initial results, the plant communities productivity was gradually enhanced, and the ecosystem quality was continuously improved. However, the urban expansion and human economic development caused multiple ecosystem service degradation in the river valley and basin areas.

### Comprehensive capability analysis of multiple ES

#### *Spatial and temporal changes of MESLI*

The annual average MESLI in SXP from 2000 to 2020 was 0.259, increasing at a rate of  $0.0006 \text{ yr}^{-1}$  (Fig. 5). The increase rate of MESLI in R-A region ( $0.0011 \text{ yr}^{-1}$ ) was higher than that in R-C region ( $0.0004 \text{ yr}^{-1}$ ) and R-B region ( $0.0002 \text{ yr}^{-1}$ ). The integrated capacity of terrestrial ecosystems to provide multiple services has

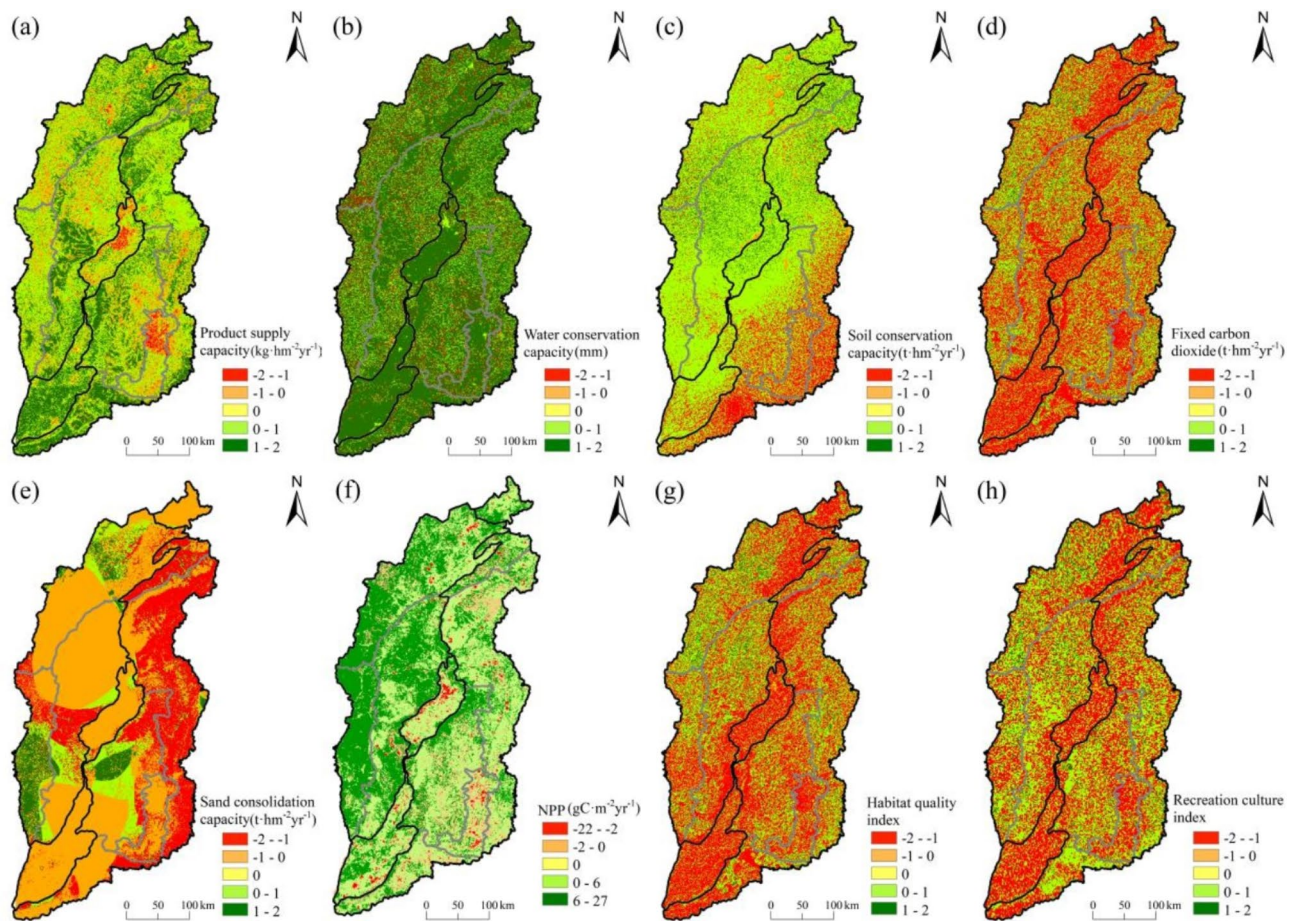


**Fig. 4.** Spatial change characteristics of ES. (a) PSS, (b) WCS, (c) SCS, (d) CSS, (e) SFS, (f) EPS, (g) HQS, (h) RCS. The mapping was completed in the ArcGIS 10.8 software version (<http://arcnglyh.com/>). The resolutions of all the maps were 1 km×1 km.

improved. The MESLI changes in SXP are characterized by fluctuation rising period, rapid decline period and recovery period. During the rising period from 2000 to 2012, the improvement of comprehensive service capacity was mainly related to the protection and restoration of forests and grasslands in the eastern and western mountainous and hilly areas of SXP since 2000. The MESLI peaked in 2013 and has declined since then. During this period, due to the acceleration of human socio-economic development and urban expansion, the economic body dominated by coal-steel industry has apparently conflicted with ecological sustainable development, highlighting the mutual constraints between urban expansion, economic development and ES. The ecosystem entered the recovery period after 2016, thanks to the government's vigorous promotion of ecological civilization construction and comprehensive measures for enhance ecological quality, and the increased precipitation also provided good natural environmental conditions for vegetation recovery.

MESLI in SXP exhibited significant spatial heterogeneity (Fig. 6a and b). In the 2000s, SXP was dominated by the high MESLI areas, accounting for 45.98%. The comprehensive ES tended to deteriorate in the 2010s, and the proportion of low MESLI area increased to 42.56%. From the spatial variation characteristics of MESLI from 2000s to 2010s (Fig. 6c), 63.12% of the regions showed increasing trend in MESLI, mainly distributed in R-A. The areas with decreasing trend in MESLI (36.88%) were concentrated in the central Fen River Valley (SR-B1) and southeastern Taihang Mountain and Taiyue Mountain inter-mountain basin hilly (SR-C4).

#### Hotspot analysis of ES

Figure 7 illustrated the spatial distribution of ES hotspots in 2000, 2010 and 2020. The ESs hotspots (1–7 class) account for 57.41–64.59% in SXP. Among them, the 1–2 class hotspots account for the largest proportion, ranging from 30.98 to 38.85%, mainly distributed in Datong Basin, Xinding Basin, Fenhe Valley (SR-B1), and Taiyue Mountain and Taihang Mountain intermountain basin (SR-C4) from north to south in the central SXP. The 5–7 class hotspots account for 12.87–14.72%, located in the eastern Taihang Mountains (R-C2), the western Lvliang Mountains (SR-A3) and the southern Zhongtiao Mountains (SR-C5). In the past 21 years, the comprehensive ecosystem service ability of SXP has been improved. The 5–7 class hotspots in Lvliang Mountain have obviously expanded. ES in the central Taiyuan Basin and the south-eastern Taiyue and Taihang Mountain intermountain

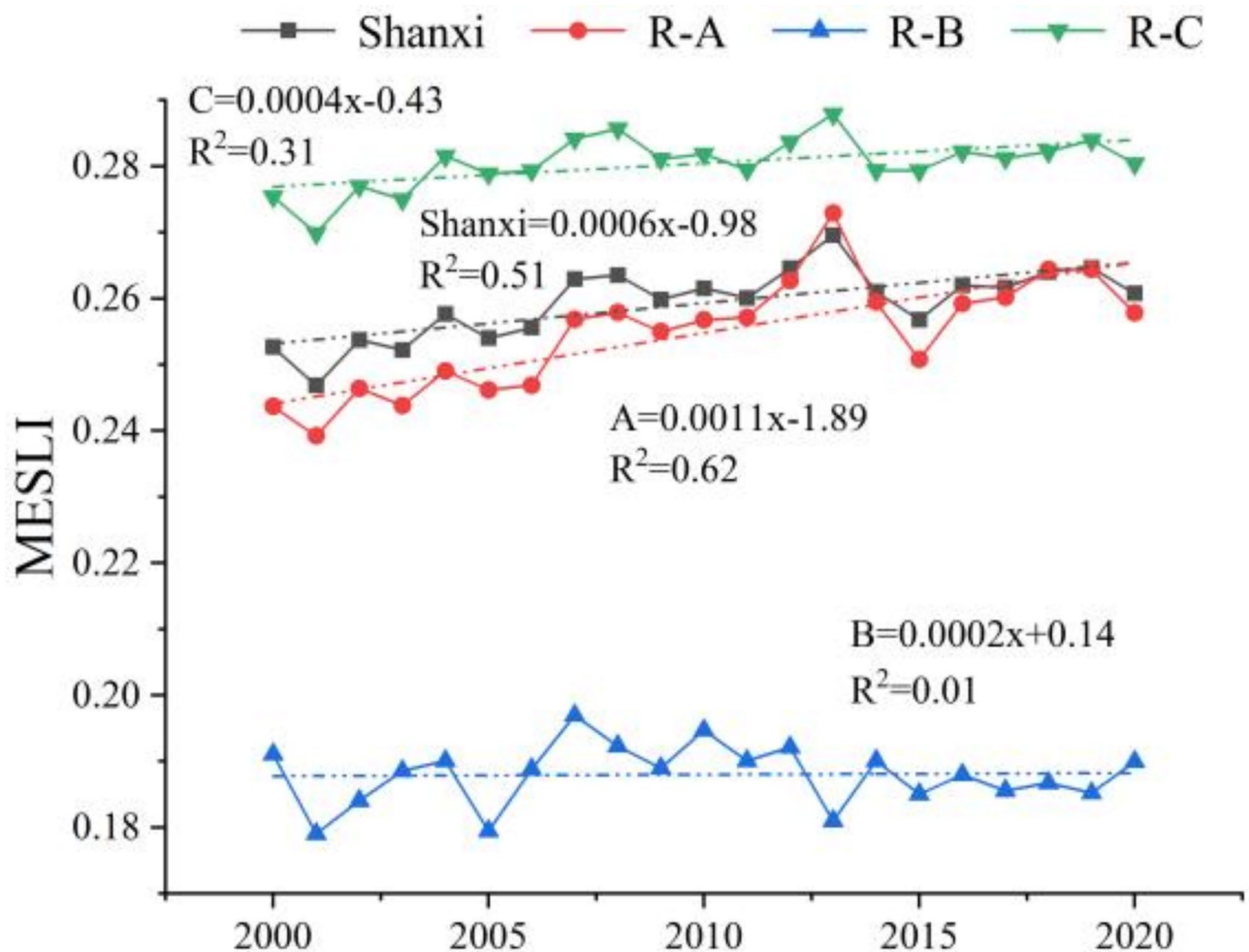


Fig. 5. Interannual changes of MESLI in SXP.

basin (SR-C4) have deteriorated sharply, especially about 89% of the southeastern basin has changed from the 1 class hotspot in 2000 to the coldspot in 2020, which is in urgent need for remediation.

#### Driving factors analysis of ES

The contribution rates of climate, surface and human social activities to different ES from 2000 to 2020 were shown in Table 3; Fig. 8. LUCC was the dominant influencing factor of PSS, with the contribution rate of 68.29%. Farmland, forest land, grassland and water areas provided direct supply of agricultural, forestry, animal husbandry and fishery products, respectively.

Climate was the key driving force for regulating services. WCS was dominated by climate factors, and the contribution rate of Tem, Pre and Evp was 60.24%; NDVI followed, with a contribution rate of 30.71%. The forest land and grassland with good hydrothermal conditions and high vegetation coverage have strong water storage and moisture conservation capacity, which can regulate runoff and conserve water resources. Slope and Pre have the greatest impact on SCS, with contribution rates of 32.24% and 26.26%, respectively. The increase of slope and rainfall erosivity lead to increased water-induced runoff, resulting in elevated soil erosion potential. In addition, the influence of NDVI on SCS was strengthened in recent 21 years. Ecological engineering is usually implemented in mountainous areas with large slopes, where vegetation roots help to enhance soil stability, effectively inhibit soil desertification and erosion, and thus reduce actual erosion. As the direct source of soil wind erosion, wind speed controlled the SFS change, with the contribution rate of 68.54%. The contribution rate of LUCC to SFS was 12.91%, and showed an increasing trend, indicating the strengthened impact of human social activities on SFS. The contribution rates of Tem and Pre to the EPS change were 22.50% and 15.93%, respectively. In addition to hydrothermal conditions, the impact of topographic factor on EPS cannot be ignored, and the contribution rate of DEM was 20.68%. Simultaneously, the contribution rate of Pop to EPS exhibited gradual upward trend, indicating the enhanced human activities interference.

The underlying surface condition dominated the changes in support and cultural services. LUCC and NDVI were the main factors affecting HQS, with contribution rates of 32.99% and 18.00% respectively, indicating that surface cover changes determined the habitat quality. NDVI was the key driving force affecting CSS and RCS, contributing 43.72% and 48.51% respectively. For CSS, fixed carbon dioxide mainly depends on the green

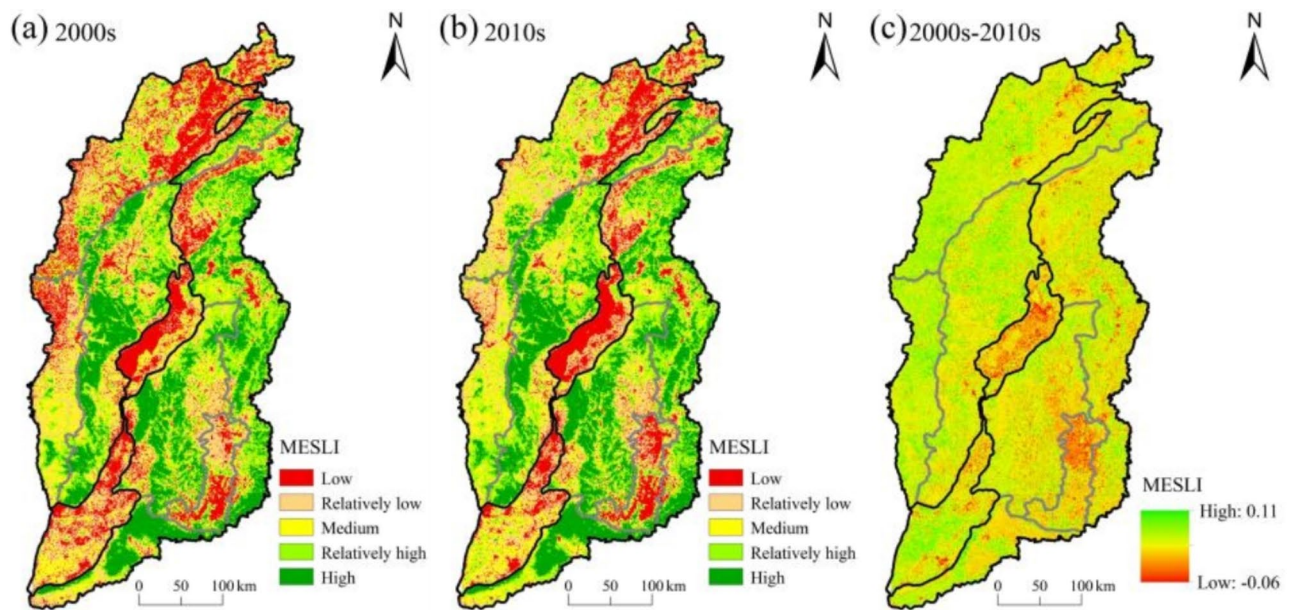


**Fig. 6.** Classification pattern and variation characteristics of MESLI. (a) Classification pattern of MESLI in the 2000s; (b) Classification pattern of MESLI in the 2020s; (c) Variation characteristics of MESLI in the 2000–2020 s. The mapping was completed in the ArcGIS 10.8 software (<http://arc.cnghy.com/>). The resolutions of all the maps were 1 km×1 km.

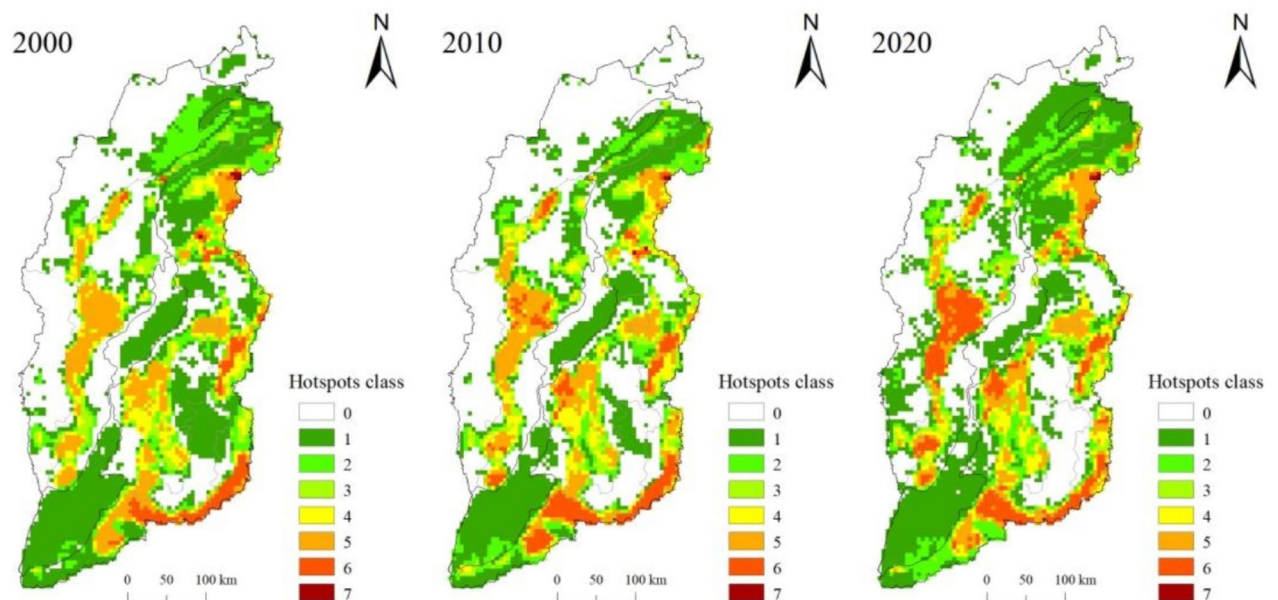


**Fig. 7.** Spatial distribution of ecosystem service hotspots in 2000, 2010 and 2020. The mapping was completed in the ArcGIS 10.8 software version (<http://arc.cnghy.com/>). The resolutions of all the maps were 1 km×1 km.

plants photosynthesis, and the vegetation coverage directly affects the carbon storage level. Low human activity intensity, diverse biodiversity, luxuriant vegetation and robust plant photosynthesis enhance carbon storage capacity. Natural landscapes play the dominant role for RCS. In mountainous areas with high NDVI, SXP develops natural recreation (forest parks, ecological parks) in accordance with local conditions, and improves RCS services under the protection of natural environment and reasonable control and reconstruction.

| Index | Tem   | Pre   | NDVI  | LUCC  | DEM   | Slope | Pop   | GDP   | Evp   | Wind speed |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------------|
| PSS   | 15.97 | 9.24  | –     | 68.29 | 4.25  | –     | 2.24  | –     | –     | –          |
| WCS   | 21.69 | 20.12 | 30.71 | 9.06  | –     | –     | –     | –     | 18.43 | –          |
| SCS   | –     | 26.26 | 19.79 | 2.87  | 18.85 | 32.24 | –     | –     | –     | –          |
| CSS   | 12.38 | 11.68 | 43.72 | 4.92  | –     | –     | 12.89 | 14.41 | –     | –          |
| SFS   | 5.08  | 6.45  | 7.02  | 12.91 | –     | –     | –     | –     | –     | 68.54      |
| EPS   | 22.50 | 15.93 | –     | 12.89 | 20.68 | 13.56 | 14.44 | –     | –     | –          |
| HQS   | 9.72  | 8.13  | 18.00 | 32.99 | 12.72 | 7.04  | 11.41 | –     | –     | –          |
| RCS   | –     | –     | 48.51 | 18.70 | –     | –     | 13.52 | 19.54 | –     | –          |

**Table 3.** Contribution rates of different influencing factors on ES in SXP (%). Note: Tem, Pre and Evp are short for temperature, precipitation and evaporation; NDVI is normalized difference vegetation index; LUCC is land use and cover change; DEM is digital elevation model; Pop is population density; GDP is gross domestic product.

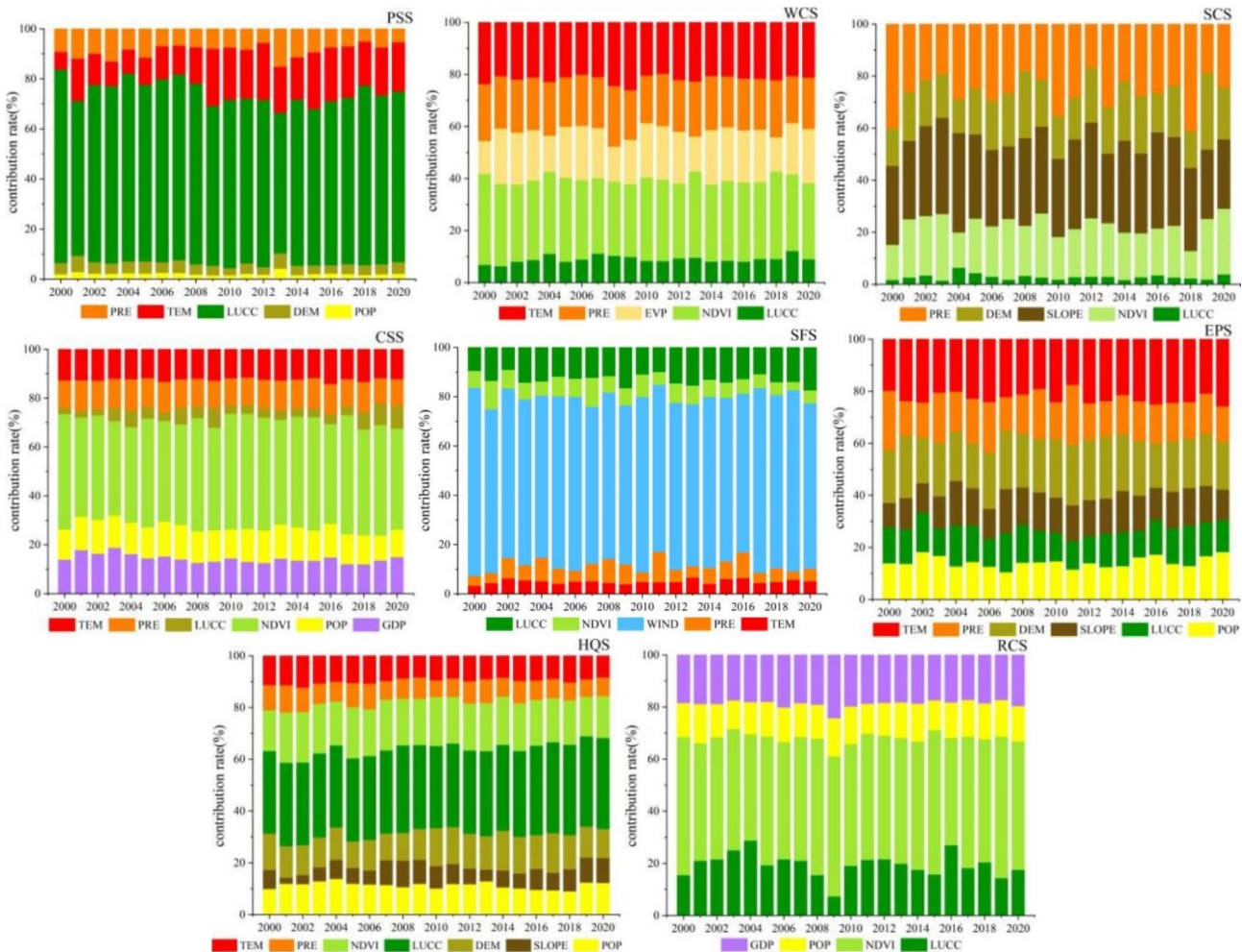


**Fig. 8.** Interannual variation of contribution rate of different factors to ES.

**Discussion**  
**Differences in driving forces of ES in ecological regions**

There are differences in the impact intensity of various natural-human driving factors on the distributions and changes of ES, and the diversity response of ES to influencing factors is also different. Land use played the dominant role on the PSS distribution and variation, which is consistent with the results of Wang et al. in the Ulansuhai Basin and Geng et al. in the Yellow River basin<sup>44,45</sup>. However, the PSS provided by different land use types differed significantly. The highest product supply is farmland (> 100 kg hm<sup>-2</sup> yr<sup>-1</sup>), and precipitation in the range of 500–550 mm and temperature > 13 °C are extremely favorable for yield increase. Therefore, the product

supply capacity is very high in the R-B (farmland > 71.33%) and the southeastern SR-C4 (farmland > 58.32%). Liu et al. reported that water and soil conservation were mainly affected by climate in the Yellow River Basin, which was basically consistent with the results of this study<sup>46</sup>. WCS is greatly affected by NDVI and climate factors, and the water retention capacity increases under the conditions of abundant precipitation (550–600 mm), low potential evapotranspiration and good vegetation coverage (0.75–0.9). Since the topography and soil properties seldom change significantly in the long term, artificial intervention to improve vegetation coverage is the main way to regulate water conservation, which is particularly prominent in western (SR-A2) and northwest SXP (SR-A1), and a series of ecological projects, such as Green for Grain Program and shelter forests, should be implemented continuously. For SCS, the conditions with large slope (> 15 °C) and abundant precipitation (> 600 mm) are prone to induce potential erosion, and the vegetation coverage determines the regional soil conservation capacity. Wind speed directly affects wind erosion, thereby determining the sand consolidation capacity. Soil wind erosion increases significantly when the cumulative wind speed exceeds 2500 m s<sup>-1</sup>. Since 2000, the vegetation coverage increase under artificial intervention in northern SXP has improved soil and surface conditions, and enhanced sand consolidation capacity. NDVI has great influence on CSS and HQS. The areas with high vegetation coverage (0.75–0.9) have rich biodiversity, which is conducive to improving carbon storage and habitat quality. The hydrothermal conditions are crucial for the vegetation growth and development, with higher EPS under conditions of temperature > 11 °C and precipitation > 550 mm. In addition, areas with an altitude of > 2000 m have low human interference, CSS, HQS, EPS and RCS are strong. The leading factors confirmed that the implementation of ecological engineering on the Loess Plateau had significant promoting effect on the carbon storage and habitat of the terrestrial ecosystem<sup>47</sup>. In the areas with increased human activity intensity, land use patterns have changed significantly, and the habitat quality has been severely damaged by the development and occupation of ecological land. Therefore, in order to maintain the ecological security of the R-B, it is urgent to improve the integrity and connectivity of farmland patches, and ensure the diffusion and exchange of biological species. The RCS is affected by NDVI and GDP. Regions with high vegetation coverage (0.75–0.9) are conducive to the construction and development of natural tourism, while high economic levels (> 8 billion yuan) affect the accessibility of regional transportation and the completeness of public infrastructure. SXP should integrate natural resources, build public landscape facilities and strengthen pollution prevention and control policies to promote RCS.

### Differences and adaptive countermeasures of ESs comprehensive capacity in ecological regions

To maintain the overall ecological security, the comprehensive capacity of ES provided by different regions should be fully considered, and differentiated optimization measures can be adopted to gradually enhance the benefits of different ES. The comprehensive capacity of ES in SXP is relatively low, and the ecosystem of the Fenwei River Basin agro-ecological region (R-B) is fragile. The low MESLI area increased by 7.79% in 2020 compared to 2000, and the coldspots increased by 91.05% in the Fenhe River Basin of the central R-B. While pursuing economic development and product output (relatively strong supply services), forest and grassland ecosystems are seriously damaged, and regional support and regulation services are extremely poor. Based on the current situation of R-B mainly consisting of farmland and construction land (> 88%), it is positioned as the supply & cultural service region. On the premise of protecting high-quality farmland, the intensive use of land should be strengthened in central and southern SXP, and the urban expansion must be prohibited to occupy high-quality farmland in Taiyuan, Linfen and Yuncheng basin, so as to consolidate the dominant position of product supply service to the greatest extent. At the same time, it is necessary to strengthen the green ecological planning of the Fen River Valley and improve the underlying surface status (such as the construction of wetland park, ecological park and park city). While giving full play to the advantages of culture service and supply service, the tradeoff relationship between recreation and regulation/support services in urban areas should be reduced to promote regional sustainable development.

The comprehensive service capacity in the Loess Plateau agricultural and grassland ecological region (R-A) has been significantly improved. Compared to 2000, the low MESLI area decreased by 56.57% in 2020. The hotspots increased significantly, showing that the northern SXP mountains and hills (SR-A1) and the western SXP loess hills and gullies (SR-A2) increased by 56.45% and 108.18%, respectively. At present, the MESLI in R-A is still lower than the average value, thereby designating it as the ecological conservation service region. The Northern SXP mountains and hills (SR-A1) should continue to strengthen sand fixation service, enhance ecological intensive management, and establish different forms of buffer zones by adopting the combination of natural and artificial interventions in accordance with local conditions, so as to bolster the ecosystem stability in northwestern SXP. The western SXP loess hills and gullies (SR-A2) should continue to strictly implement the natural forest protection and the Green for Grain Project to increase vegetation coverage. WCS, CSS and EPS are continuously improved by slope protection and gully protection engineering, so as to strengthen the ecological security barrier function of loess gully area.

The Yanshan-Taihang Mountains (R-C) have strong comprehensive ecosystem service capacity and are positioned as the multifunctional composite service area. The advantageous resources in the upper reaches of Yongding River, Taihang Mountain, Taiyue Mountain and Zhongtiao Mountain (SR-C1, C2, C3 and C5) should be fully utilized to promote the ecotourism development, facilitate the coordinated development of regional regulation, support and culture service, and realize the positive interaction between social economic development and ecological protection. The MESLI in the Taihang-Taiyue mountains intermountain basins (SR-C4) decreased significantly (the low MESLI area increased by 52.13%), and the coldspots increased by 7.45 times. Therefore, given the prevailing agricultural development context, it is imperative to integrate land resources, incorporate advanced agricultural science and technology, actively promote scientific land management

practices, and gradually reinstate the regional product supply capacity, so as to control continuously decreasing PSS situation in SR-C4.

## Conclusions

Based on the environmental characteristics of SXP, an evaluation index and model system of eight ES, including PSS, WCS, SCS, CSS, SFS, EPS, HQS and RCS, were constructed. By analyzing the spatiotemporal evolution of ES from 2000 to 2020, the ecosystem health status was explored. The contribution rate of different factors to ES was quantified from the natural and human perspectives, so as to provide more accurate measures to ensure the effectiveness of regional governance in SXP. The results indicate that: the comprehensive capacity of ES gradually increased in SXP. The support and regulation service capabilities of the Loess Plateau in western SXP have been improved, especially in the mountainous and loess hilly areas of northern and western SXP. The PSS is only enhanced in the southern Fenwei Basin, while the other services and the comprehensive service capacity are still extremely poor. The Yanshan-Taihang Mountains ES is strong as a whole, but the SCS, EPS and PSS capabilities are reduced, especially in the intermountain basins. LUCC is the dominant factor affecting supply service, climate factors occupy the dominant position in regulate service, and underlying surface condition is the key factors in support service change. The Loess Plateau in western SXP is the ecological conservation service region, ecological protection policies and engineering measures should be strictly implemented to strengthen the ecological security barrier function of the loess gully area. The Fenwei Basin is the supply & cultural service region. Under the premise of ensuring the supply capacity, green ecological planning is carried out, and ecological construction such as wetland park is implemented to improve the current underlying surface situation. The Yanshan-taihang Mountain is the multi-functional service region that needs to make use of resource advantages to enhance eco-cultural tourism services according to local conditions, so as to realize the positive interaction between ecological protection and economic development. The study process has global applicability and provides a classic paradigm for constructing ecological security barrier and ecological sustainability research in resource-based regions.

## Data availability

Data will be available upon request. Part of the data set generated during this study is available in the attachment, and other data sets are available from the corresponding authors. E-mail: wangsheng@sxnu.edu.cn.

Received: 8 February 2024; Accepted: 17 September 2024

Published online: 27 September 2024

## References

- Villamagna, A. M., Angermeier, P. L. & Bennett, E. M. Capacity, pressure, demand, and flow: a conceptual framework for analyzing ecosystem service provision and delivery. *Ecol. Complex.* **15**, 114–121. <https://doi.org/10.1016/j.ecocom.2013.07.004> (2013).
- Millennium Ecosystem Assessment. *Ecosystems and Human Well-Being: Biodiversity Synthesis* (Island, 2005).
- Bennett, E. M., Peterson, G. D. & Gordon, L. J. Understanding relationships among multiple ecosystem services. *Ecol. Lett.* **12**, 1394–1404. <https://doi.org/10.1111/j.1461-0248.2009.01387.x> (2009).
- Xu, J. Y., Chen, J. X. & Liu, Y. X. Partitioned responses of ecosystem services and their tradeoffs to human activities in the Belt and Road region. *J. Clean. Prod.* **276**, 123205. <https://doi.org/10.1016/j.jclepro.2020.123205> (2020).
- Xia, H., Yuan, S. & Prishchepov, A. V. Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: implications for spatial planning and management. *Resour. Conserv. Recy.* **189**, 106767. <https://doi.org/10.1016/j.resconrec.2022.106767> (2023).
- Baskent, E. Z. Characterizing and assessing key ecosystem services in a representative forest ecosystem in Turkey. *Ecol. Inf.* **74**, 101993. <https://doi.org/10.1016/j.ecoinf.2023.101993> (2023).
- Whitney, K. M. A stakeholder-engaged approach to anticipating forest disturbance impacts in the Colorado River basin under climate change. *J. Water Res. Plan. Man.* **149**. <https://doi.org/10.1061/jwrmd5.wreng-5905> (2023).
- Tuo, D. F. Evaluation of grassland ecosystem services in northern China. *Acta Ecol. Sin.* **44** (02), 455–462. <https://doi.org/10.20103/j.stxb.202302260341> (2024).
- Costanza, R. et al. The value of the world's ecosystem services and natural capital. *Nature* **387**, 253–260. <https://doi.org/10.1038/387253a0> (1997).
- Aneseyee, A. B., Elias, E., Soromessa, T. & Feyisa, G. L. Land use/land cover change effect on soil erosion and sediment delivery in the Winike watershed, Omo Gibe basin, Ethiopia. *Sci. Total Environ.* **728**, 138776. <https://doi.org/10.1016/j.scitotenv.2020.138776> (2020).
- Li, W. et al. Impact of land use change on watershed water conservation and water quality purification service: a case study of Wujiang River basin. *Acta Ecol. Sin.* **43**, 8375–8389. <https://doi.org/10.20103/j.stxb.202208052236> (2023).
- Liu, C. J., Men, B. H., Shen, Y. D. & Pang, J. F. Soil conservation and water purification services and their trade-offs and synergies in Luanhe River basin. *Acta Ecol. Sin.* **43**, 5740–5752. <https://doi.org/10.5846/stxb202207101963> (2023).
- Zhang, Q. et al. Dynamic responses of ecological vulnerability to land cover shifts over the Yellow River basin, China. *Ecol. Indic.* **144**, 109554. <https://doi.org/10.1016/j.ecolind.2022.109554> (2022).
- Fang, Z. et al. Impacts of land use/land cover changes on ecosystem services in ecologically fragile regions. *Sci. Total Environ.* **831**, 154967. <https://doi.org/10.1016/j.scitotenv.2022.154967> (2022).
- Hossain, M. S., Dearing, J. A., Rahman, M. M. & Salehin, M. Recent changes in ecosystem services and human well-being in the Bangladesh coastal zone. *Reg. Environ. Chang.* **16**, 429–443. <https://doi.org/10.1007/s10113-014-0748-z> (2016).
- Sun, X., Yang, P., Tao, Y. & Bian, H. Y. Improving ecosystem services supply provides insights for sustainable landscape planning: a case study in Beijing, China. *Sci. Total Environ.* **802**, 149849. <https://doi.org/10.1016/j.scitotenv.2021.149849> (2021).
- Shen, J. S. et al. Exploring the heterogeneity and nonlinearity of trade-offs and synergies among ecosystem services bundles in the Beijing-Tianjin-Hebei urban agglomeration. *Ecosyst. Ser.* **43**, 101103. <https://doi.org/10.1016/j.ecoser.2020.101103> (2020).
- Steur, G., Verburg, R. W., Wassen, M. J. & Verweij, P. A. Shedding light on relationships between plant diversity and tropical forest ecosystem services across spatial scales and plot sizes. *Ecosyst. Ser.* **43**, 101107. <https://doi.org/10.1016/j.ecoser.2020.101107> (2020).
- An, Y. M., Zhao, W. W., Li, C. J. & Ferreira, C. S. Temporal changes on soil conservation services in large basins across the world. *Catena* **209**, 105793. <https://doi.org/10.1016/j.catena.2021.105793> (2022).

20. Hu, B. A., Kang, F. F., Han, H. R., Cheng, X. Q. & Li, Z. Z. Exploring drivers of ecosystem services variation from a geospatial perspective: insights from China's Shanxi Province. *Ecol. Indic.* **131**, 108188. <https://doi.org/10.1016/j.ecolind.2021.108188> (2021).
21. Pan, N. H. et al. Spatial differentiation and driving mechanisms in ecosystem service value of arid region: a case study in the middle and lower reaches of Shule River Basin, NW China. *J. Clean. Prod.* **319**, 128718. <https://doi.org/10.1016/j.jclepro.2021.128718> (2021).
22. Stupariu, M. S., Cushman, S. A., Plesoianu, A. I., Stupariu, I. P. & Fürst, C. Machine learning in landscape ecological analysis: a review of recent approaches. *Landsc. Ecol.* **37** (5), 1227–1250. <https://doi.org/10.1007/s10980-021-01366-9> (2021).
23. Omer, A., Ma, Z. G., Yuan, X., Zheng, Z. Y. & Saleem, F. A hydrological perspective on drought risk-assessment in the Yellow River Basin under future anthropogenic activities. *J. Environ. Manag.* **289**, 112429. <https://doi.org/10.1016/j.jenvman.2021.112429> (2021).
24. Yang, Y., Yang, F. Y. & Cai, Z. X. Evolutionary characteristics and driving factors of the resources and environmental carrying capacity of the urban agglomeration in the Yellow River basin: a case study of the Cuanzhong Plain urban agglomeration. *Acta Sci. Circumst.* **42** (2), 476–485. <https://doi.org/10.13671/j.hjkxxb.2021.0283> (2022).
25. Deng, Y. J. et al. Assessing the effects of the Green for Grain Program on ecosystem carbon storage service by linking the InVEST and FLUS models: a case study of Zichang county in hilly and gully region of Loess Plateau. *J. Nat. Resour.* **35**, 826–844. <https://doi.org/10.31497/zrzyxb.20200407> (2020).
26. Hao, X. J., Zhang, H., Xu, X. M., Wang, L. & Cui, Y. Evolution and simulation of land use/land cover pattern in northern Shanxi Province. *Acta Ecol. Sin.* **40**, 257–265. <https://doi.org/10.5846/stxb201812032636> (2020).
27. Ning, T., Guo, X. Y., Rong, Y. J., Du, S. X. & Li, C. Evaluation of soil conservation function importance of ecosystems in Shanxi Province based on RUSLE model. *Bull. Soil. Water Conserv.* **39**, 205–210. <https://doi.org/10.13961/j.cnki.stbctb.2019.06.030> (2019).
28. Zhu, C. C. et al. Changes of windbreak and sand fixation services and the driving factors in the desert steppe, Inner Mongolia. *Acta Ecol. Sin.* **41**, 4606–4617. <https://doi.org/10.5846/stxb201905231065> (2021).
29. Ren, H. et al. Impact of land use change on habitat in the Qihe River basin of Taihang Mountains. *Prog. Geogr.* **37**, 1693–1704. <https://doi.org/10.18306/dlkxjz.2018.12.011> (2018).
30. Lin, F. et al. Spatial and temporal changes of ecosystem service value in Fenhe River basin from 1980 to 2020. *Bull. Soil. Water Conserv.* **42**, 322–329. <https://doi.org/10.13961/j.cnki.stbctb.2022.02.043> (2020).
31. Costanza, R. et al. Twenty years of ecosystem services: how far have we come and how far do we still need to go? *Ecosyst. Serv.* **28**, 1–16. <https://doi.org/10.1016/j.ecoser.2017.09.008> (2017).
32. Liu, L., Liu, C. F., Wang, C. & Li, P. P. Supply and demand matching of ecosystem services in loess hilly region: a case study of Lanzhou. *Acta Geogr. Sin.* **74**, 1921–1937. <https://doi.org/10.11821/dlxb201909016> (2019).
33. Hu, W. M., Li, G. & Li, Z. N. Spatial and temporal evolution characteristics of the water conservation function and its driving factors in regional lake wetlands: two types of homogeneous lakes as examples. *Ecol. Indic.* **130**, 108069. <https://doi.org/10.1016/j.ecolind.2021.108069> (2021).
34. Liu, M. Z., Zhang, H. J., Ren, H. Y. & Pei, H. W. Spatiotemporal variations of the soil conservation in the agro-pastoral ecotone of northern China under Grain for Green Program. *Res. Soil. Water Conserv.* **28**, 172–178. <https://doi.org/10.13869/j.cnki.rswc.2021.05.020> (2021).
35. Yu, B. L. et al. Benefits of soil wind erosion control of the Beijing-Tianjin Sand Source Control Project in Inner Mongolia. *Arid Zone Res.* **33**, 1278–1286. <https://doi.org/10.13866/j.azr.2016.06.19> (2016).
36. Dai, L. D., Zhang, Y. L., Ding, R. J. & Yan, Y. G. Spatiotemporal distribution and influencing factors of the net primary productivity in the Datun Mine in Western Beijing. *Sustainability* **14**, 15567. <https://doi.org/10.3390/SU142315567> (2022).
37. Yang, Z. P. et al. Effects of land use change on habitat based on InVEST model in northeast China. *Ecol. Sci.* **37**, 139–147. (2018). <https://doi.org/10.14108/j.cnki.1008-8873.2018.06.018> (2018).
38. Zhou, R., Wang, X. J., Su, H. L. & Lou, Y. L. Identification and security pattern of ecological land in Pingdingshan newly developed area. *Acta Ecol. Sin.* **35**, 2003–2012. <https://doi.org/10.5846/stxb201305241169> (2015).
39. Manning, P. et al. Publisher correction: redefining ecosystem multifunctionality. *Nat. Ecol. Evol.* **2**, 1515. <https://doi.org/10.1038/s41559-018-0660-x> (2018).
40. Shen, J. S. et al. Exploring the heterogeneity and nonlinearity of trade-offs and synergies among ecosystem services bundles in the Beijing-Tianjin-Hebei urban agglomeration. *Ecosyst. Serv.* **43**, 101103. <https://doi.org/10.1016/j.ecoser.2020.101103> (2020).
41. Li, Q., Li, W. J., Wang, S. & Wang, J. F. Assessing heterogeneity of trade-offs/synergies and values among ecosystem services in Beijing-Tianjin-Hebei urban agglomeration. *Ecol. Indic.* **140**, 109026. <https://doi.org/10.1016/j.ecolind.2022.109026> (2022).
42. Chang, J. Y. et al. Spatiotemporal distribution of ecosystem services and analysis of cold and hot spots in Beijing-Tianjin sandstorm source region. *J. Soil. Water Conserv.* **38** (3), 1–11. <https://doi.org/10.13870/j.cnki.stbctb.2024.03.002> (2024).
43. Yang, J. S. *Study on Grassland Ecosystem Service and its trade-off and Synergy in the Yellow River Basin* (Gansu Agricultural University, 2022). <https://doi.org/10.27025/d.cnki.ggsnu.2021.000048>
44. Wang, L. et al. The analysis of change of ecosystem services and driving factors in Ulansuhai basin. *Ecol. Economy* **39**(02), 173–180. <http://doi.org/1671-440702-173-08> (2023). (2023).
45. Geng, W. L. et al. Analyzing spatio-temporal changes and trade-offs/synergies among ecosystem services in the Yellow River basin, China. *Ecol. Indic.* **138**. <https://doi.org/10.1016/j.ecolind.2022.108825> (2024).
46. Liu, Q., Qiao, J. J., Li, M. J. & Huang, M. J. Spatiotemporal heterogeneity of ecosystem service interactions and their drivers at different spatial scales in the Yellow River basin. *Sci. Total Environ.* **908**, 168486. <https://doi.org/10.1016/j.scitotenv.2023.168486> (2023).
47. Wang, N. F., Chen, X. P., Zhang, Z. L. & Pang, J. X. Spatiotemporal dynamics and driving factors of county-level carbon storage in the Loess Plateau: a case study in Qingcheng County, China. *Ecol. Indic.* **144**, 109460. <https://doi.org/10.1016/j.ecolind.2022.109460> (2022).

## Acknowledgements

This research was funded by the National Key Research and Development Program of China (2023YFF1305304), National Natural Science Foundation of China (42401042, 41801007), Second Tibetan Plateau Scientific Expedition and Research Program (2019QZKK0201), Science Technology Project of Hebei Academy of Sciences (2024PF11), Basic Research Program of Shanxi Province (202203021211258, 202103021223248), Shanxi Philosophy and Social Science Planning Project (2022YJ039, 2023YJ045), Science and Technology Strategy Research Project of Shanxi Province (202304031401073), Shanxi Postgraduate Education and Teaching Reform Project (2021YJG154, 2022YJG137), Shanxi Universities Teaching Reform and Innovation Project (J2021284, J20220457).

## Author contributions

All authors contributed to the research conception and design. J. Wang provided the conceptualization, investigation, project administration, validation, writing-review & editing and supervision. Y. Li provided the data

curation, formal analysis, methodology, software, writing-original draft preparation. S. Wang provided the conceptualization, formal analysis, methodology, resources, supervision, visualization. Q. Li provided the formal analysis, investigation, writing-original draft preparation. R. Wang provided the resources, writing-review & editing. R. Zhang provided the formal analysis, methodology. X. Ge provided the data curation, writing-review & editing. All authors have read and agreed to the published version of the manuscript.

## Declarations

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-73419-3>.

**Correspondence** and requests for materials should be addressed to S.W.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024