Ecosystem Services Assessment, Trade-Off and Bundles in the Yellow River Basin, China

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Ecosystem services assessment, trade-off and bundles in the Yellow River Basin, China

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Abstract:

Understanding ecosystem services (ESs) and their interactions will help to formulate effective and sustainable land use management programs.This paper evaluates the water yield (WY), soil conservation (SC), carbon storage (CS) and habitat quality (HQ), taking the Yellow River Basin as the research object, by adopting the InVEST (Integrated Valuation of Ecosystem Services and Trade Offs) model. The Net Primary Productivity (NPP) was evaluated by CASA (Carnegie-Ames-Stanford approach) model, and the spatial distribution map of five ESs were drawn, the correlation and bivariate spatial correlation were used to analyze the trade-off synergy relationships between the five ESs and express them spatially. The results show that NPP and HQ, CS and WY are trade-offs relationship, and other ecosystem services are synergistic. The trade-off synergy shows obvious spatial heterogeneity. Driven by different factors, the leading ecological function services in the Yellow River Basin can be divided into three areas, and WY and SC service leading functional areas are mainly distributed in HQ and CS service leading functional areas and NPP service leading functional areas.The results of functional bundles are obviously affected by natural conditions such as land use/cover types and climate in the Yellow River Basin, which can provide the basis for the Yellow River Basin to regulate ESs and maximize benefits.

Keywords：Ecosystem service, Trade-off, Synergy, Ecosystem service bundles, Yellow River Basin

1. Introduction

ESs are the material basis and environmental conditions for the survival and development of human, which can be divided into three categories: supply services, regulation services, and social and cultural services. They are bridges to connect natural ecosystems and human well-being (MEA,2005a). The sustainable supply is of great significance to the sustainable development of districts, countries and even the whole world (Fu et al., 2014). In recent years, ESs have gradually received attention in sustainable development research, and their definitions, classifications, evaluations and driving mechanisms have been extensively studied (Costanza et al.,2017; Twenty et al., 2017). The research focus has gradually shifted from the structure and process of ecosystems to the relationship between human activities and ESs (Wu et al., 2019). Changes in environmental factors such as land-use change and climate change will affect multiple ecological processes such as the water cycle and carbon cycle, causing simultaneous changes in different ESs, and different services may be related to the same ecological process, which ultimately leads to complex connections between different ESs (Cord et al., 2017). The connections can be divided into three categories: trade-off, synergy, and irrelevance. The trade-off relationship indicates that the improvement of one service is accompanied by the decrease of another service; synergy indicates that two services are increased or decreased at the same time, while irrelevance indicates no significant connections between the temporal and spatial changes of the two services (Lyu et al., 2018). The trade-off relationship analysis is of great significance in the management and policy-making of ESs, and has gradually attracted the attention of researchers and has become a hot research topic in related fields (Lyu et al., 2018). Mouchet, et al. (2014) reviewed and quantitatively analyzed the main methods of exploring trade-off relationships in existing research. Deng, et al. (2016) summarized the main tools and processes applied in the analysis of trade-off relationships in land use management research. Howe, et al. (2014) conducted a comprehensive analysis of how social-ecological environmental factors cause the trade-off relationship between services. Richards et al. (2017) explored the trade-off relationship between ESs in tropical coastal

areas and future urban development, using the Pareto curve to analyze the trade-off and synergy relationship between habitat quality and various ecological indicators. Trodahl et al. (2017) studied the trade-off and synergy relationship between the water quality and agricultural productivity of the fertile bay of New Zealand based on the LUCI module. Tolessa et al. (2017) studied the impact of land use and land cover changes on ESs in the central highlands of Ethiopia from 1973 to 2015, and the results showed that the reduction of forest coverage will lead to a decrease in the value of ESs, which is mainly manifested in the ESssuch as nutrient circulation, raw material supply, and erosion control. Sun et al. (2019) used Yan'an City as the research area and applied partial correlation analysis and found that there is a trade-off relationship between food supply and soil conservation, water conservation and NPP, and there is a synergistic relationship between NPP and soil conservation and water conservation, there is a synergistic relationship between soil conservation and water conservation. Fu et al.(2016) studied ES trade-offs and regional integration methods and analyzed the relationship between land use change and ESs. Taking the Shiyang River Basin as an example, Wang Bei et al. used the InVEST model and correlation coefficient method to study the trade-offs and synergies relationship among five services, including water conservation, soil conservation, water purification, carbon storage, and biodiversity (Wang et al., 2018). Many studies have achieved some achievements in the trade-offs and synergy of ESs, but the researches on the regional differences and the driving factors in the trade-offs and synergy relationship of ESs are still very inefficient. For example, the existing studies mostly analyze natural environmental factors such as terrain and climate (Jiang et al., 2016), ignoring the influence of social and economic development conditions (Zoderer et al., 2016), even lacking comparative studies on the relative influence of different social-ecological factors (Rositano et., 2017), and lacking comprehensive analysis of driving forces and the identification of dominant driving forces, consequently limit the application of research on ES relationships in management practices.

Watershed is the best regional unit for studying ESs (Cheng et al.,2015), which has a variety of service types. Under the combined effect of social and ecological factors, ESs exhibit complex Spatio-temporal relationships. At the same time, the river basin is also one of the areas with the

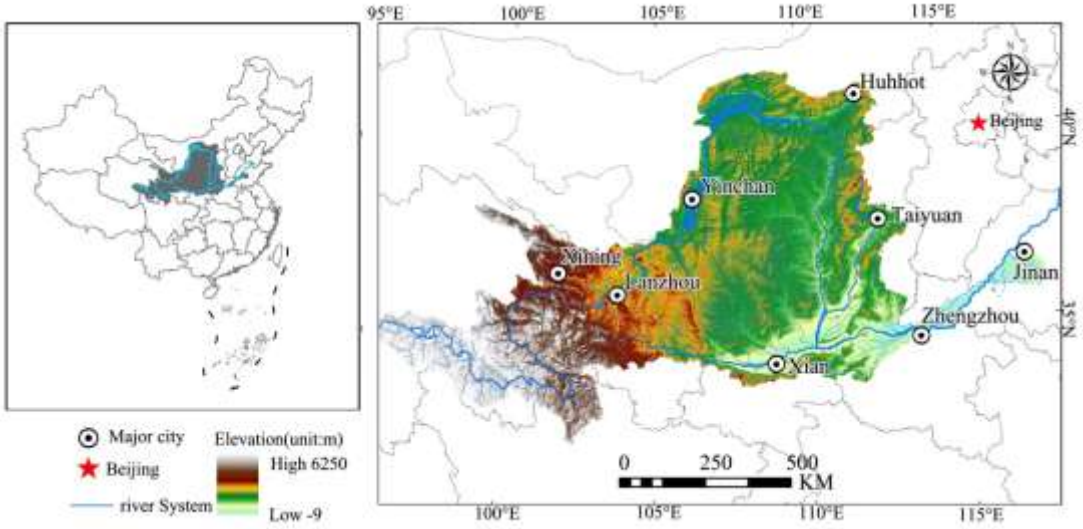
strongest disturbance to human activities. It is faced with water quality degradation, insufficient water supply, soil erosion, and degradation of habitat quality. How to coordinate economic development and environmental protection and alleviate conflicts between upstream and downstream stakeholders becomes the key to the sustainable development of the basin. ESs are an important link to connect the natural environment and human needs. By studying the trade-offs and synergy relationship of various ESs in the River basin, and clarifying its driving mechanism, it is helpful to formulate the "win-win" policy measures for the River basin development and ecological protection (Li et al., 2016; Liu et al., 2019). The Yellow River Basin is a vast area located in northwestern of China. It spans from the east to the west and has the characteristics of complex geomorphic units, diversified ecosystem types, and obvious regional climate differences. Its ecosystem environment is fragile and is one of the sensitive regions of global climate change (Chen et al.,). The Yellow River Basin constitutes an important ecological barrier in our country, is an ecological corridor connecting the Qinghai-Tibet Plateau, the Loess Plateau and the North China Plain, which has multiple geographical units such as the source of the Three Rivers, Qilian Mountains, Hetao Plain, and Huanghuaihai Plain. There are important areas with ecological functions such as water conservation, wind protection, sand fixation, and biological diversity protection, which play a very significant role in maintaining regional ecological security.

Based on this, this study takes the year 2018 as a cross-section to analyze the spatial trade-offs among the five ESs and their association with social ecosystems. First, it quantitatively calculates the spatial distribution pattern of WY, CS, SC, HQ, and NPP, calculates the correlation coefficient between ESs through correlation analysis and uses SOM to classify the spatial distribution of ESs clusters. Then the random forest model is used to explore the impact of social-ecological influencing factors on ESs, and the SOM method is used to classify the clusters of social-ecological factors. Finally, it distinguishes the relationship between ES clustering and social-ecological factor clustering through overlay analysis, to explore the response mechanism of ESs to the social-ecological system. It is expected to lay the foundation for the ecology and environmental protection of the basin.

2. Study area

The Yellow River originates from the Yogu Zonlie Basin at the northern foot of the Bayan Har Mountain on the Qinghai-Tibet Plateau. It flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces, and injects into the Bohai Sea in Kenli County, Shandong Province. The main stream has a total length of 5464 kilometers and a drop of 4480 meters(Fig.1). The Yellow River Basin is located between 96° - 119° east longitude and 32° - 42° north latitude, with a length of about 1,900 kilometers from the east to the west and a width of about 1,100 kilometers from the north to the south. The area of the basin is 795,000 square kilometers (including the internal flow area of 42,000 square kilometers). Above Hekou Town, it is the upper reaches of the Yellow River, with a river course of 3,472 kilometers and a basin area of 428,000 square kilometers; from Hekou Town to Taohuayu, it is the middle reaches, with a river course of 1,206 kilometers and a basin area of 344,000 square kilometers; below Taohuayu, it is the lower reaches, with a river course of 786 kilometers and a basin area of only 23,000 square kilometers. In the Yellow River Basin, there is a vast area, numerous mountains, great differences in height between the east and the west, and great differences in landforms between regions. The climate of different regions in the basin differs significantly. In the Yellow River Basin, the sunlight is sufficient and the solar radiation is strong, and the sunshine conditions belong to sufficient areas across the country. The annual sunshine hours generally reach 2000-3300 hours. There are big seasonal differences in the Yellow River Basin. The annual precipitation in most areas of the basin is between 200 and 650 mm, and that of the upper reaches of the southern and lower reaches is more than 650 mm, especially the northern slope of the Qinling Mountains in the south, which is heavily affected by topography. Generally, it can reach 700-1000 mm, and it gradually increases from the northwest to the southeast. The precipitation is

129 unevenly distributed, and the ratio of rainfall between the north and the south is greater than 5.
130 According to the national water resources distribution, the Yellow River basin can be divided into
131 8 secondary basins and 29 tertiary basins.



132
133 **Fig.1** Range of Yellow River Basin and distribution of river system

134 # 3. Data and Methodology

135 ## 3.1 Data sources

136 In this study, we use multi-source data sets to evaluate ESs in space, including land use/cover
137 data sets, satellite image data sets, meteorological data sets, soil data sets, statistical data sets and
138 related auxiliary data sets. Detailed descriptions of data sources are shown in Table 1.

139 Tab.1 Summary of main data types and data sources

ES	Data requirement type	Unit	Data sources
WY	Precipitation	mm	Geographic Data Cloud of Chinese Academy of Sciences
	Potential evapotranspiration	mm	The Data Set of Global Potential Evapotranspiration and Global Drought Index
	Soil texture	int	HWSD Soil Database
	Available water content of plant	%	Generated from soil texture data

	Land use/cover type	int	Geographical national conditions monitoring cloud platform
	Catchment area/sub-catchment area distribution	int	DEM data generation
	Root depth of plant	mm	1:1 million soil database of China
	Evapotranspiration coefficient	—	Food and Agriculture Organization of the United Nations, 1998
CS	Land use / cover type	int	Geographical national conditions monitoring cloud platform
	Carbon density data of various land use types	t/hm^2	InVEST model, references
SC	DEM	m	Geospatial Data Cloud
	Rainfall erosivity	$MJ \cdot mm/(hm^2 \cdot h \cdot a)$	Calculation based on rainfall data
	Soil erodibility factor	$t \cdot hm^2/(MJ \cdot mm)$	Calculation based on soil texture data
	Land use /cover type	int	Geographical national conditions monitoring cloud platform
	Catchment area/sub-catchment area distribution map	int	DEM data generation
	Vegetation Management Factor	—	Calculation based on NDVI data
	Engineering measures factor	—	references
HQ	Land use/ cover type	int	Geographical national conditions monitoring cloud platform
	Major threats	—	InVEST model, references
	The weight of threat source factor	—	InVEST model, references
	Sensitivity of various land use types to stress factors	—	InVEST model, references
NPP	Land use /cover type	int	Geographical national conditions monitoring cloud platform
	NDVI	int	Earth resources observation and science center
	Meteorological data	int	Geographical national conditions monitoring cloud platform

3.2 ES quantification and mapping

Considering the characteristics of the ecological environment of the Yellow River Basin and the availability of data, combining the characteristics of natural geography and social economy, five more important ESs are selected from the ESs, namely NPP, WY, CS, SC and HQ.

3.2.1Net Primary Productivity (NPP)

NPP refers to the production capacity of green vegetation, which is an important parameter of the ecosystem carbon cycle and energy flow. This study evaluates the NPP of the Yellow River Basin by adopting the CASA model and ENVI remote sensing estimation module. This method has simple parameters and takes the impact of vegetation classification on the assessment results into account, due to the availability of the parameters and the simplicity of operation of the model that have been widely used in the estimation of NPP. The calculation formula of this method is:

$$\mathrm{NPP} = \mathrm{APAR} \times \varepsilon \quad (1)$$

$$APAR = SOL \times FPAR \times 0.5 \quad (2)$$

$$FPAR = \min[\frac{SR - SR_{min}}{SR_{max} - SR_{min}}, 0.95] \quad (3)$$

$$SR = [\frac{1+NDVI}{1-NDVI}] \quad (4)$$

$$\varepsilon = T_{\varepsilon 1} \times T_{\varepsilon 2} \times W_{\varepsilon} \times \varepsilon_{max} \quad (5)$$

In the formula, NPP, APAP, ε respectively represent the net primary productivity of vegetation ($gc \cdot m^{-2}$), the absorbed photosynthetically active radiation ($MJ \cdot m^{-2}$) and the actual light utilization rate ($g\ c \cdot MJ^{-1}$). SOL and FPAR are respectively the total solar radiation ($MJ \cdot m^{-2}$) and the absorption ratio of photosynthetically active radiation by vegetation; the constant 0.5 represents the solar radiation rate used by vegetation; SR_{min} is 1.08, and SR_{max} is related to vegetation types. NDVI represents vegetation coverage; $T_{\varepsilon 1}$、$T_{\varepsilon 2}$ and W_{ε} are the threat effects of

low temperature, high temperature, and moisture conditions on the light utilization efficiency. For specific algorithms, please refer to Piao et al. (2001), Zhu et al. (2005a, 2005b) and Mu et al.(2013).

3.2.1 Water yield (WY)

This study evaluates the water yield by adopting the InVEST model water production module, which is based on the Budyko water-heat coupling balance hypothesis and the annual average precipitation data, that is, the rainfall of each grid minus the actual evapotranspiration is the annual water production Y(x) of each grid unit x in the study area (Sharp et al., 2018), the calculation formula is:

$$Y_{xj} = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \quad (6)$$

$$\frac{AET_x}{P_x} = \frac{1+w_x R_x}{1+w_x R_{xj}+\frac{1}{R_x}} \quad (7)$$

$$w_x = Z \times \left(\frac{AWC_x}{P_x}\right) \quad (8)$$

$$R_x = \frac{k_x \times ET_{ox}}{P_x} \quad (9)$$

$$AWC_x = \mathrm{Min}(MSD_x, RD_x) \times PAWC_x \quad (10)$$

In the formula, Y_x is the average annual water production of grid x. Since the actual annual evapotranspiration cannot be directly measured and obtained, the curve pair AET_x/P_x can be used to approximate calculations. The R_x value is dimensionless and is the dryness index of grid x. It can be calculated by potential evapotranspiration and rainfall. w_x is an empirical parameter used to describe climate-soil properties, and can be calculated by the available water content of vegetation and annual rainfall. AWC_x is the available water content of vegetation, which is determined by soil texture and effective soil depth and is used to determine the total amount of water stored and provided by the soil for plant growth. Z is called the Zhang coefficient (Zhang et al., 2001), which

is an empirical constant, which represents the parameters of seasonal rainfall distribution and rainfall depth. For areas dominated by winter rainfall, the Z value is close to 10, while for humid areas where rainfall is evenly distributed and areas dominated by summer rainfall, the Z value is close to 1. According to the results of multiple simulations, the Z value is finally determined to be 3.6. ET_{0x} is the internal potential evapotranspiration in grid x, which reflects the evapotranspiration capacity determined by weather and climate conditions. Since the data of potential evapotranspiration are difficult to obtain, so they are usually calculated by the temperature method, the radiation method and the comprehensive method. InVEST model uses the Modified-Hargreaves method to calculate the potential evapotranspiration. k_x represents the evapotranspiration coefficient of vegetation or crops, and there are different evapotranspiration coefficients for different land use types. MSD_x (Max Soil Depthx) is the maximum soil depth. RD_x is the root depth. $PAWC$ is the available moisture content of plants. Please refer to (Yang et al., 2020) for the calculation of specific parameters.

3.2.2 Carbon Storage (CS)

This paper divides the carbon storage of the ecosystem into four basic carbon pools by using the InVEST model carbon storage module. They are respectively: the above-ground biological carbon (carbon in all living plant materials above the soil), the underground biological carbon (carbon presents in the living root system of plants), the soil carbon (organic carbon distributed in organic soil and mineral soil), and the dead organic carbon (carbon in litter, upside-down or standing dead trees). The carbon module of the model takes each land use type as the evaluation unit and multiplies the average density of the four carbon pools by the area of each evaluation unit to calculate the carbon storage of the study area. The calculation formula for the total carbon

density of each land-use type is as follows:

$$C_{tot}=C_{above}+C_{below}+C_{soil}+C_{dead} \quad (11)$$

In the formula: C_{tot} is the total carbon storage ($t \cdot hm^{-2}$). C_{above}、C_{below}、C_{soil}、C_{dead} are the above-ground biological carbon storage ($t \cdot hm^{-2}$), the underground biological carbon storage ($t \cdot hm^{-2}$), the soil carbon storage ($t \cdot hm^{-2}$), and the dead organic carbon storage ($t \cdot hm^{-2}$).

Based on the carbon density and land use data of various regions, the formula for calculating the carbon storage of the ecosystem in the basin is as follows:

$$C_{toti} = (C_{ai} + C_{bi} + C_{si} + C_{di}) \times A_i \quad (12)$$

Where: i is the average carbon density of each land use type. A_i is the area of the land-use type. Please mainly refer to related studies (Xie et al., 2004; Li et al., 2003; Chen et al., 2002; Chuai et al., 2013) for the carbon density data in the carbon pool table required for the model. According to regional similarity, the desirability of results, and other principles, it can generate a carbon pool table.

3.2.3 Soil Conservation (SC)

In this paper, the amount of soil conservation includes two parts: the amount of erosion reduction and the amount of sediment interception based on the calculating principle of the soil conservation module in the InVEST model. The former refers to the reduction of potential erosion land of each block, expressed as the potential erosion and actual erosion difference. The latter refers to the retention of sediment from the upslope by the block, which is expressed as the product of the amount of sediment and the efficiency of sediment retention. The model calculation formula is as follows:

$$SEDRET_x = RKLS_x - USLE_x + SEDR_x \quad (13)$$

$$RKLS_x = R_x \times K_x \times LS_x \quad (14)$$

$$USLE_x = R_x \times K_x \times LS_x \times P_x \times C_x \quad (15)$$

$$SEDR_x = SE_x \sum_{y=1}^{x-1} USLE_y \prod_{z=y+1}^{x-1} (1 - SE_z) \quad (16)$$

In the formula: $SEDRET_x$, $RKLS_x$, $USLEx$, $SEDRx$ and $USLEy$ are respectively the soil conservation amount of grid x, the potential soil erosion amount, the actual erosion amount after considering management and engineering measures, the sediment retention amount, and the actual erosion amount of the upslope grid y after considering management and engineering measures, which are all in units of t. R_x, K_x, LS_x, C_x, and P_x are the precipitation erodibility factor, soil erodibility factor, slope length factor, vegetation cover management factor, and soil and water conservation measures factor of grid x, respectively. Please refer to (Liu et al., 2018) for the calculation process of each factor.

3.2.4 Habitat Quality (HQ)

In the InVEST model, the Habitat Quality model evaluates the quality of the habitat. The model calculates the negative impact of threatening factors on the habitat, and obtains the degradation degree of the habitat, by establishing the connection between land use data and threat factors, and comprehensively considering factors such as the distance and intensity of threat factors. Then it calculates the quality of the habitat through the degradation degree and habitat suitability to reflect the biodiversity of the area (Bao et al., 2015). The calculation formula is:

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z}\right)\right)$$

In the formula: Q_{xj} *is* equal to the habitat quality index of grid x in land use j. Hj refers to the habitat suitability of habitat type j, with a value range of 0-1. D_{xj} refers to the habitat degradation

index. *R* is the number of threat factors. *k* is the half-saturation constant, which is generally 1/2 of the maximum value of habitat degradation. z is the normalized constant, which is usually set to 2.5 (Sharp et al., 2018).

The parameters that need to be input in this module mainly include land-use type maps, main habitat threat factors, weights of threat source factor and influence distances, and data such as the sensitivity degree of land use types to threat sources, etc. These research results are set after taking reference to the InVEST model manual (Sharp et al., 2014), the scholars' research results (Zhong et al., 2017; Liu et al., 2017; Zhang et al., 2020) and experts' suggestions.

3.3 Trade-offs, synergy, and bundle analysis among ESs

3.3.1 Correlation analysis

Correlation analysis can effectively reflect the direction and degree of the changing trend between two variables (Hou et al., 2017). The commonly used correlation coefficients are Pearson coefficient, Spearman coefficient, and Kendall coefficient. The Spearman rank correlation coefficient mainly performs the linear correlation analysis by using the rank size, and it doesn't require the distribution of the original variables. It is a non-parametric statistic method (Hu et al., 2015), and has lower requirements on the original data (Li et al., 2017). The overall distribution pattern or sample size is not required. As long as the observation values of the two variables are paired with each other, the coefficient can be used for calculation, and even the grade data converted from continuous variables can be analyzed. The scope of application is very wide (Ying er al., 2020).

$$P_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{E((X-\mu_X)(Y-\mu_Y))}{\sigma_X \sigma_Y} = \frac{E(XY)-E(X)E(Y)}{\sqrt{E(X^2)-E^2(X)}\sqrt{E(Y^2)-E^2(Y)}}$$

$$r_g = P_{rgX,rgY} = \frac{cov(rgX,rgY)}{\sigma_{rgX}\sigma_{rgY}}$$

In the formula, $P_{X,Y}$ is the Pearson correlation coefficient of variables X and Y. $\mathrm{cov}(X,Y)$ is the covariance of the two variables. σ_X and σ_Y are the standard deviation of the two variables. $P_{rgX,rgY}$ is the Spearman correlation coefficient, which is applied to the rank of the original variable.

Based on the correlation analysis function of the R language, this research explores the trade-offs and synergy among the five ESs of NPP, WY, CS, SC, and HQ The pie chart shows the correlation between the service function of ESs. Blue means positive correlation, red means negative correlation. The darker the color, the greater the correlation between the two variables. The meaning of the color of the upper triangular cell in the figure is the same as that of the lower triangular cell, but the degree of correlation is expressed by the filled area of the graph chart in the pie. The greater the correlation, the more the filled area. The positive correlation fills the pie chart clockwise from 12 o'clock, and the negative correlation fills the pie chart counterclockwise.

3.3.2 Global spatial autocorrelation

Moran's I index shows the similarity ratio of unit attribute values in the spatial adjacent areas. In this paper, it analyzed the spatial correlation between water yield and rainfall of each grid cell in the Yellow River Basin by GeoDA. The formula is in the following:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\,(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2\,(\sum_i\sum_j w_{ij})}$$

$$Z(G_i^*) = \frac{\sum_{j=1}^{n} w_{i,j}x_j - X\sum_{j=1}^{n} w_{i,j}}{s\sqrt{\frac{[n\sum_{j=1}^{n} w_{i,j}^2 - (\sum_{j=1}^{n} w_{i,j})^2]}{(n-1)}}}$$

$$X = \frac{1}{n}\sum_{j=1}^{n} x_i \ , \qquad S = \sqrt{\frac{1}{n}\sum_{j=1}^{N} x_j^2 - x^2}$$

In the formula: I is Moran's I index, n is spatial cells' number; x_i and x_j are respectively the observed values of i and j regions; w_{ij} is the spatial adjacency relationship of regions i and j; S2 is the variance of observed values. The Moran's I index is generally between - 1 and 1. [0,1] indicating that the geographical entities have a positive correlation, and [- 1,0] shows a negative correlation, and the value of 0 indicates there is no correlation.

3.3.3 Principal component analysis

Principal Component Analysis (PCA) is a method of mathematical transformation, which converts a given set of related variables into another set of unrelated variables which are arranged in descending order based on variance through linear transformation. In the mathematical transformation, the total variance of the variable is unchanged, so that in the first variable, there is the largest variance called the first principal component, and in the second variable, there is the second-largest variance and has no relation with the first variable, which is considered as the second principal component. By analogy, one variable has one principal component. The steps are as follows: 1) Standardization of multivariate data; 2) Determination of correlation between variables; 3) Determination of the number of principal components; 4) Obtaining of the principal components.

3.3.4 SOM method

The SOM is an unsupervised neural network method based on competitive learning (Kohonen et al., 1989). It is composed of an input layer and an output layer (also called a competition layer). The input layer is used to receive input training samples, and the neurons in the output layer are generally arranged in a two-dimensional array, and each neuron in the two layers is bidirectionally connected. The SOM classifies the set of input patterns by finding the

optimal weight vector, that is, the best matching neuron. The steps of the SOM algorithm are: initializing each weight vector, that is, assigning small random numbers to each weight vector in the output layer and normalize it; finding the winning neuron of the input data; adjusting the weight vector in the winning neighborhood; repeatedly searching for the input data of the winning neuron and subsequent steps until the iteration termination condition is met.

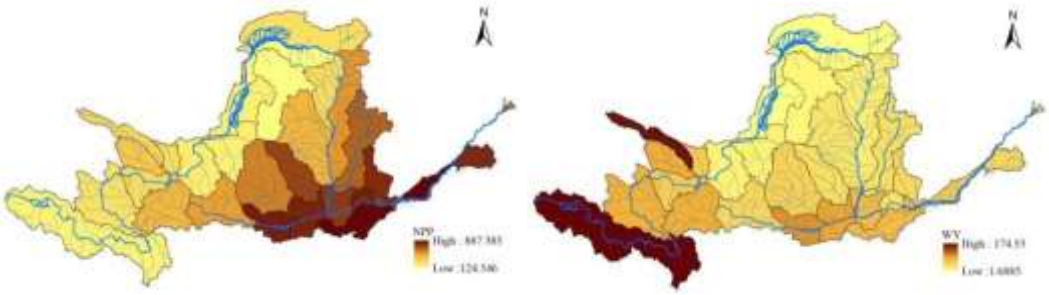
4. Results and Analysis

4.1 ESs and their spatial distribution characteristics

In 2018, the five ESs of NPP, WY, CS, SC and HQ in the Yellow River Basin were 336.99gc·m^{-2}，451.695×$10^{8}m^{3}$，15.4685×106^{6}t，78.4265×10^{8}t and 0.684, respectively. The five ESs functions studied in this study are calculated and displayed on the map. They are unevenly distributed (Fig. 2). The areas with high NPP values are distributed mainly in the lower reaches in the Yellow River, including the Weihe-Guanzhong Basin, Fenhe River Basin, as well as the area below Huayuankou. The low-value areas are mainly distributed in the middle reaches of the Yellow River Basin, including the Lanzhou to Hekouzhen watershed etc, showing a zonal pattern of high in the east and low in the west. WY shows the highest water production in the upper reaches of the Yellow River, such as areas of Longyangxia and above. This area has more ice and snow melt water replenishment, higher vegetation coverage, and low evapotranspiration. It is the main source of runoff in the Yellow River Basin, and the main stream has a large runoff. The basin from Lanzhou to Hekou Town is the low-value area of WY. The evaporation in this area is strong, and the precipitation is relatively low. The overall performance of CS is that the upper reaches of the Yellow River Basin, the Luohe River Basin, the Fenhe River Basin and the Qinling Mountains are high-value areas of CS. The above-mentioned areas have good vegetation conditions and

strong carbon sequestration capacity. The low-value areas are mainly distributed in the Loess Plateau, especially the Mu Us sandy area in the north of the Loess Plateau and the Badain Jaran Desert in the north of the Helan Mountain and in the west of the Yellow River. The basins with higher SC are mainly distributed in the upper reaches of the Yellow River Basin and the central area of the Loess Plateau, especially the upper reaches of the Yellow River, while the SC from Lanzhou to Hekou Town, the Hetao Plain and the lower reaches of the Yellow River is relatively low. The high HQ areas are mainly distributed in the upper river basins and the Taihang Mountains. The main land cover in this area is woodland and grassland. Human activities are infrequent and the level of biodiversity is high. The lower areas are mainly distributed in the Guanzhong Basin, Weihe Valley and the lower Yellow River plain area. This area is a concentrated distribution area of cultivated land and construction land in the Yellow River Basin, highly disturbed by human activities.

From the spatial distribution of the five ESs, some show relatively similar spaces, such as HQ and CS, while others show opposite spatial characteristics, such as WY and CS. In short, the five ESs are agglomerated and related in space, rather than randomly distributed with each other.



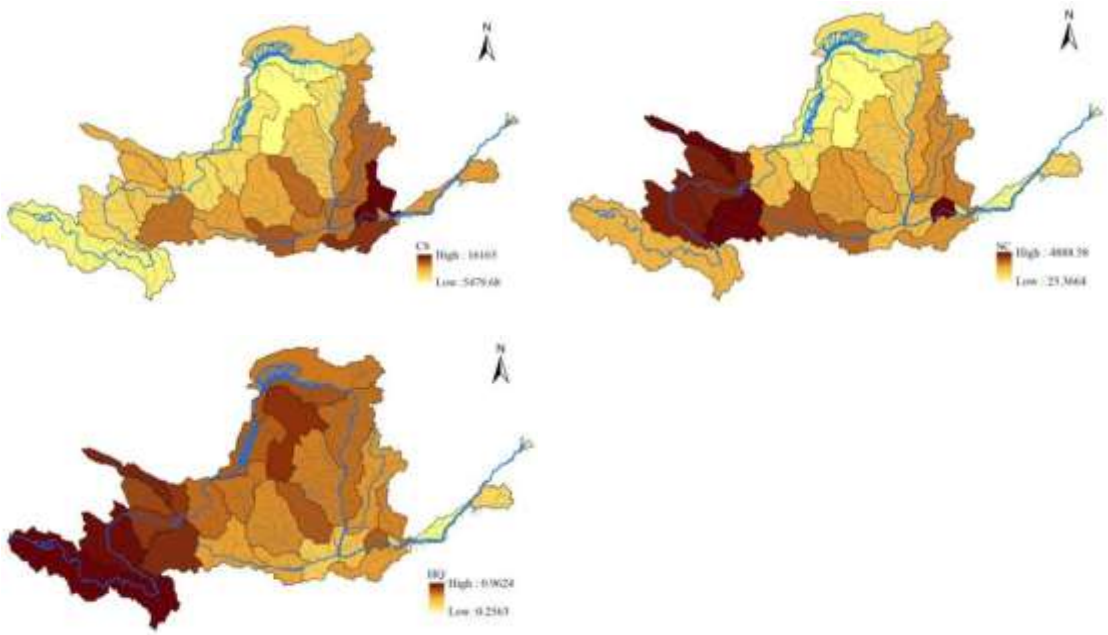


Fig. 2 Spatial distribution map of ESs in the Yellow River Basin

4.2 Trade-off and synergy of ESs in the Yellow River Basin

The correlation between various ESs is shown in the pie chart (Fig. 3). Except for the negative correlation between NPP and HQ, and CS and WY, the correlation coefficients are -0.0139 and -0.0179 respectively, and the other 8 combinations are all positively correlated. The positive correlation between NPP and CS is the strongest (r=0.2515), followed by CS and HQ (r=0.1907). The results show that NPP has a synergistic relationship with CS, SC, and WY, and a trade-off relationship with HQ. There is a synergistic relationship between CS and SC and HQ, and a trade-off relationship with WY. The relationships between SC and HQ, SC and WY are all synergistic. So is the relationship between HQ and WY.

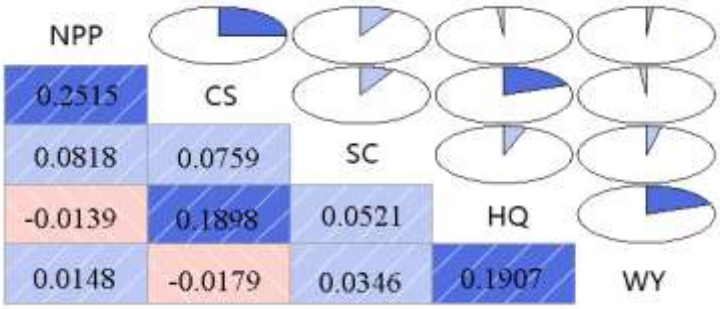


Fig.3 Corrgram of ES pairs in the Yellow River Basin (The values in the lower-left of each graph are the correlation coefficients of each ES pair in the whole Yellow River Basin)

In terms of space(Fig. 4), WY and NPP in the basin are mainly synergistic. The synergy relationship is particularly prominent in the "Hetao Plain-Ningxia Plain-Lanzhou-Sanmenxia" area. The rainfall and vegetation coverage is low in the Hetao Plain, Ningxia Hui Autonomous Region and Lanzhou. In this area, the WY and NPP are relatively low. From Shaanxi to Sanmenxia, there is abundant rainfall, high WY, and abundant water and heat conditions, which contributes to the increase of vegetation coverage. The NPP is relatively high. In the Bayan Har Mountains in the upper reaches of the Yellow River Basin and in Yan'an, Shaanxi and other places in the middle reaches of the Yellow River Basin, WY and NPP are in a trade-off relationship. The upstream rainfall is rich and there are permanent glaciers and snowfields, where there is a high WY. At the same time, there are a large number of grasslands in this area, but the light is insufficient and the temperature is relatively low, so the NPP is low. While there are woodlands in Yan'an, Shanxi and other areas with sufficient sunlight, so the NPP is high. Woodlands can consume a lot of water resources, resulting in low WY in this area, and WY and NPP are in a trade-off relationship.

WY and SC are in a synergistic relationship. The Hetao Plain, Ningxia Plain and

Tianshui-Weinan in the middle reaches of the Yellow River Basin show a synergistic relationship. In the Hetao Plain and Ningxia Plain, there is low rainfall, low vegetation coverage, so WY and SC are low. In the Tianshui-Weinan area, there is abundant rainfall, high vegetation coverage, high water production capacity and soil conservation function, while in Huangshui, Taohe and other places, vegetation coverage is high, the consumption of water leads to a decrease in WY, an increase in SC, and below Xiaolangdi in the lower reaches of the Yellow River basin, most of the lands are for construction, and the WY is relatively high. On the contrary, because the area is densely populated, human activities are strong, and vegetation coverage is low, resulting in the decrease of SC, which makes a trade-off relationship between WY and SC.

WY and CS show a trade-off relationship throughout the entire region. The two are in a synergistic relationship in a small amount areas of the upper reaches of the Yellow River Basin, the middle reaches of Inner Mongolia, and the Ningxia Hui Autonomous Region. The low precipitation and low vegetation coverage in this area result in low CS and WY. The trade-off relationship is mainly distributed in the upper and middle reaches. In the upper reaches of the Bayan Har Mountains and Zhaling Lake, low-coverage grasslands are mostly distributed, with relatively low CS and high WY. In the middle reaches, such as in Yan'an, Fenhe and Shanxi, there are a large number of woodlands. The higher evapotranspiration and stronger interception capacity of woodland makes the WY of the land smaller. At the same time, the higher carbon density of woodland make the higher CS in this area.

WY and HQ show a trade-off relationship. The trade-off relationship and the synergy relationship are interspersed and distributed throughout the basin, and there is no obvious dividing line. The upstream Maqu and the middle Qinling area have high vegetation coverage, strong

406 rainfall, and low-intensity human interference. Therefore, the WY is high and the Q index of
407 habitat quality is high. The Hetao Plain, Ningxia Plain and Guanzhong Plain are located in arid
408 and semi-arid areas with insufficient water and heat conditions, low vegetation coverage, poor
409 water production capacity and habitats, and the two show a synergy relationship. The distribution
410 trade-off relationship is around the synergy relationship, which is mainly distributed in the Mu Us
411 sandy land and below the Xiaolangdi Huayuankou in the lower reaches of the Yellow River. The
412 land-use types are unused land and construction land, with less infiltration and large runoff,
413 resulting in higher WY and vegetation. The coverage is low, the downstream population is dense,
414 and human activities are strong, destroying the connectivity of the habitat, resulting in poor HQ.
415 To the west of Lanzhou, the west of Taihang Mountains, they are mostly distributed in
416 high-coverage grassland and woodland due to the high vegetation coverage, which consumes and
417 intercepts a large number of water resources, resulting in a decrease in WY. However, due to its
418 high vegetation coverage, sparse population, and low destructive degree, so HQ is better. WY and
419 HQ are in a trade-off relationship in the above regions.

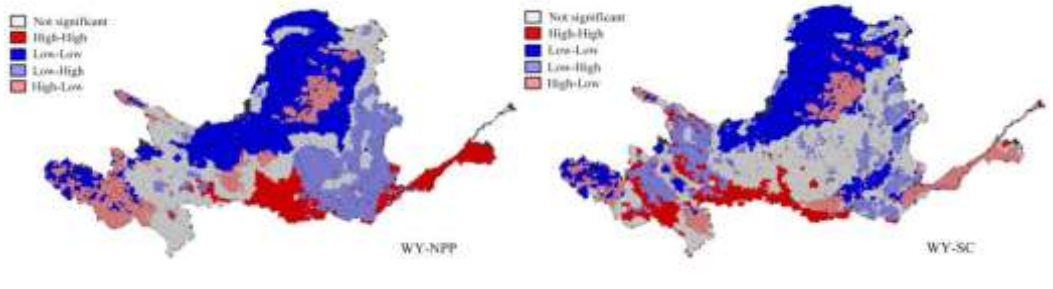
420 NPP and SC are mainly synergistic in the whole region, mainly distributed in the central
421 Qinghai-Tibet Plateau, the northern and southern areas of the Loess Plateau and the lower reaches
422 of the Yellow River Basin. Because of the strong regional dependence of NPP, it will increase with
423 the increase of regional vegetation coverage. The change of coverage changes the resistance to
424 rainfall erosion and indirectly affects the soil retention, so the two maintain consistent changes to a
425 large extent. NPP and CS are also mainly synergistic. From the angle of spatial distribution, the
426 two are synergistic in most areas of the entire basin, and they are distributed throughout the upper
427 and middle reaches of the Yellow River. Obviously, areas with higher vegetation coverage have

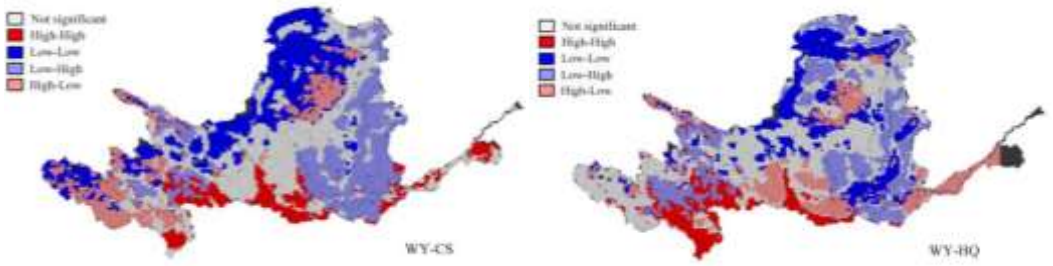
higher NPP and CS. Compared with the Guanzhong Plain and Taihang Mountains, the upper Bayan Har Mountains, there is lower vegetation coverage in the northern and central parts of the Loess Plateau, so NPP and CS are lower.

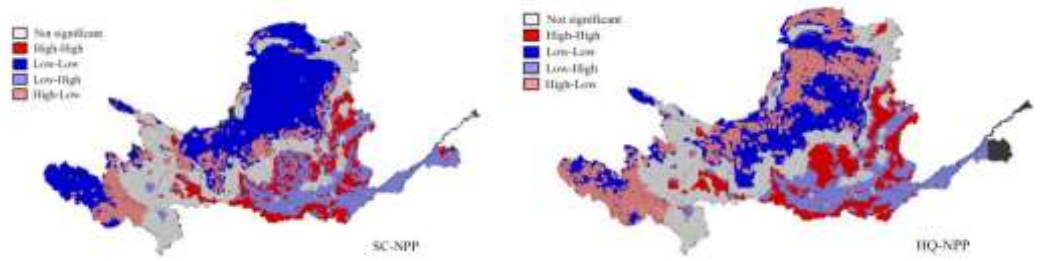
NPP and HQ are in a synergistic relationship, most of which are distributed in the central Loess Plateau, Yan'an and Shanxi. The central part of the Loess Plateau is dominated by Mu Us's sandy land. The land types are sandy and bare land where the vegetation coverage is low, so NPP and HQ are low. In Yan'an and Shanxi, there is high vegetation coverage, good water and heat conditions, so NPP and HQ are high. However, in the Qinghai-Tibet Plateau and the Loess Plateau, the source area of the Yellow River, there is a trade-off between one and the other. Due to the low degree of human activities in these areas which are far away from threat sources such as cultivated land and construction land, so HQ is high. But NPP is low in these areas due to insufficient light, low temperature and photosynthesis.

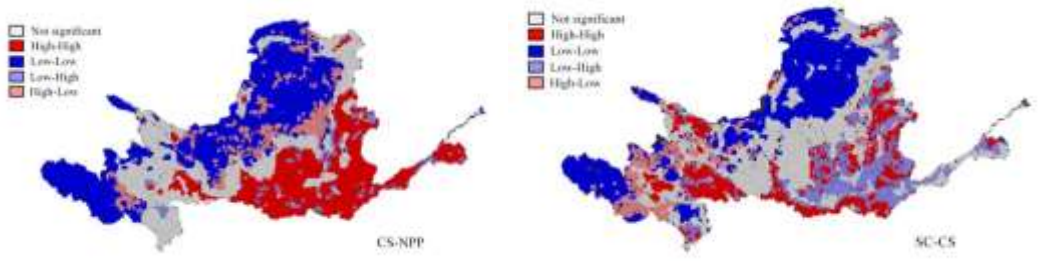
SC and CS mainly show a synergistic relationship. They are obviously scattered in the middle reaches of the Loess Plateau and Qinling Mountains. The Loess Plateau is mainly concentrated in the Ningxia Hui Autonomous Region and the Mu Us Sandy Land. Due to its lower vegetation coverage and less rainfall, both SC and CS are low in this area. There are many woodlands in the Qinling Mountains, with high vegetation coverage and high carbon density, so SC and CS are high. CS and HQ are mainly synergistic relationship. In the Hetao Plain and the Mu Us Sandy Land, CS and HQ are low due to low vegetation coverage and poor climate conditions. In the Qinling Mountains, Yan'an and Taihang Mountains where woodland is the main land type, the high carbon density, good original vegetation, and low level of damage caused the CS and HQ to change simultaneously. However, in the lower reaches of the Yellow River and the Weihe Valley in the

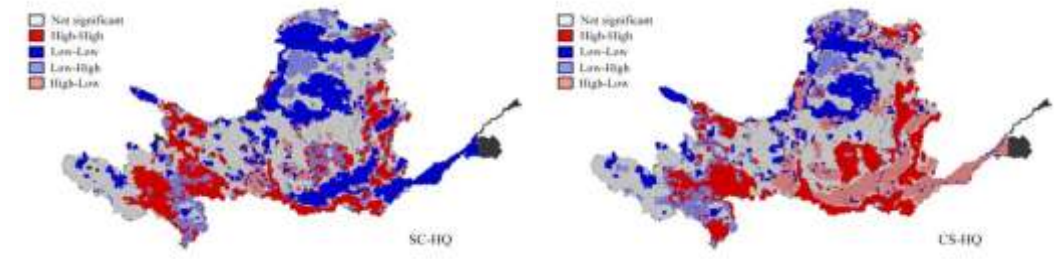
Guanzhong Plain, the land types are mainly woodland, cultivated land and construction land. The flat terrain, frequent human activities, and dense road crossings lead to habitat fragmentation and poor connectivity, resulting in poor HQ. So the two are in a trade-off relationship in these areas.











458 **Fig.4** Schematic diagram of the coordination relationship

459 space of the ESs of the Yellow River Basin

460 ## 4.3 ES bundles

461 The researchers identify the Yellow River Basin ES bundles by using the SOM model. First,
462 they perform a principal component analysis of ESs. The results show that the first two principal
463 components can explain 73% of the total variance of the variables, with WY and HQ having a
464 higher positive load on the first principal component (PC1) , NPP and CS having a higher positive
465 load on the second component (PC2), and the load difference of SC on the two principal
466 components is relatively small. From the principal component analysis graph, it can be seen that
467 NPP and CS are relatively close, HQ and WY are relatively close, while NPP and WY tend to be
468 perpendicular, and SC and other ecological services are at a certain distance. Therefore, it is
469 recommended to divide the five ESs into three clusters based on the results of principal
470 component analysis.

471 SOM clustering algorithm has been widely used in the field of environmental science
472 (Václavík et al., 2013). This algorithm can effectively consider the topological relationship
473 between the input data and is of great significance for the division of ES bundles (Cord et al.,
474 2017). The spatial distribution clustering of ESs mainly divided based on the relative similarity of
475 the various services provided by different geographic regions (Renard et al., 2015). Therefore,
476 clustering can directly reflect the spatial differences in the supply level of specific ESs in different
477 regions. According to the spatial distribution and correlation of the five ESs, the Yellow River
478 Basin can be divided into three regions as shown in Fig. 5: The results of the bundles are similar to
479 the upper, middle, and lower basins of the Yellow River Basin, and bundles 1 and2 is basically

480 bounded by the transition bundles between the Loess Plateau and the Qinghai-Tibet Plateau. On
481 the basis of the ecological function bundles, it obtains the ESs of each ecological function in the
482 district and performs normalization processing by adopting the district statistics means, aiming to
483 analyze each district within the ES structure, and then identifies the active ES function of each
484 district (Fig. 5). According to the result of the division:

485 4.3.1 Bundle 1: the dominate functional area of WY and SC

486 It mainly includes three-level river basins such as Maqu to the source of the river, Maqu to
487 Longyang Gorge, Longyang Gorge to Lanzhou, Daxia River and Tao River, Weihe River and
488 above Baoji Gorge, Huangshui River, and Datong River Basin. The regional area accounts for
489 39.35% of the total area of the Yellow River Basin. WY and SC are significantly higher than that
490 in the other two regions. In this region, there is a plateau mountain climate, affected by the
491 large-scale climate of the Qinghai-Tibet Plateau, with concentrated precipitation, many lakes,
492 grasslands, and swamps, low water consumption and low evapotranspiration. At the same time,
493 vegetation coverage is relatively high, so the conservation services of soil are strong, indicating
494 that the core functions of ESs in this area are WY and SC.

495 4.3.2 Bundle 2: the dominate functional area of HQ and CS

496 It mainly includes three-level river basins such as the Qingshui River and the Kushui River
497 Basin, Xiaheyan to Shizuishan, Shizuishan to the north bank of Hekou Town, Shizuishan to the
498 south bank of Hekou Town, internal flow area, the right bank above Wubao, and the right bank
499 below Wubao. The regional areas account for 35.18% of the total area of the Yellow River Basin.
500 This area is an important functional area for habitat maintenance and carbon storage. There are
501 many types of land use/cover, which mostly are grassland and woodland. However, bare land and

sandy land are also distributed in the central area. Due to the large area and the distribution of vegetation types, having high carbon density such as woodland and grassland, the CS is higher. At the same time, due to there is a lower degree of accessibility by human activities in these areas which are also far away from threat sources such as cultivated land and construction land, so HQ is higher than that of in downstream areas. However, the WY service is low and evapotranspiration capacity is strong in the area. It has the largest annual evaporation in the region in this area, which can exceed 2500 mm at most. The insufficient precipitation in the middle reaches leads to the lack and uneven distribution of water resources. In addition, the service function of NPP is also extremely lower than that of other areas. Because this area is located in the hinterland of the inland, it forms a natural landscape with a dominant arid and semi-arid ecosystem. The vegetation structure is simple relatively and the productivity is low in this area which is an extremely poor biomass area in the terrestrial ecosystem of the Yellow River Basin.

4.3.3 Bundle 3: the dominate functional area of NPP

It distributes in the Fenhe River Basin, the Weihe River from Baoji to Xianyang and below. The regional area accounts for 25.47% of the total area of the Yellow River Basin. Comparing with various ESs, it is found that the NPP service in this area has obvious advantages, so it is the dominant functional area of NPP service. The terrain is relatively flat in these areas, and the mainstream of the Yellow River and many tributaries pass through them. It is a temperate monsoon climate with sufficient water and heat conditions, which is beneficial to vegetation growth and restoration. The woodland coverage is higher in the Qinling Mountains, so the NPP is higher. However, other services are low in this area, especially HQ. Due to the concentrated distribution of arable land and construction land in this area, the habitat is fragmented, the

connectivity is reduced, and the distance to the threat factor is relatively small, resulting in low HQ. The population below Xiaolangdi Huayuankou is dense, the land for economic construction is concentrated, the vegetation coverage is extremely low, so the SC is small.

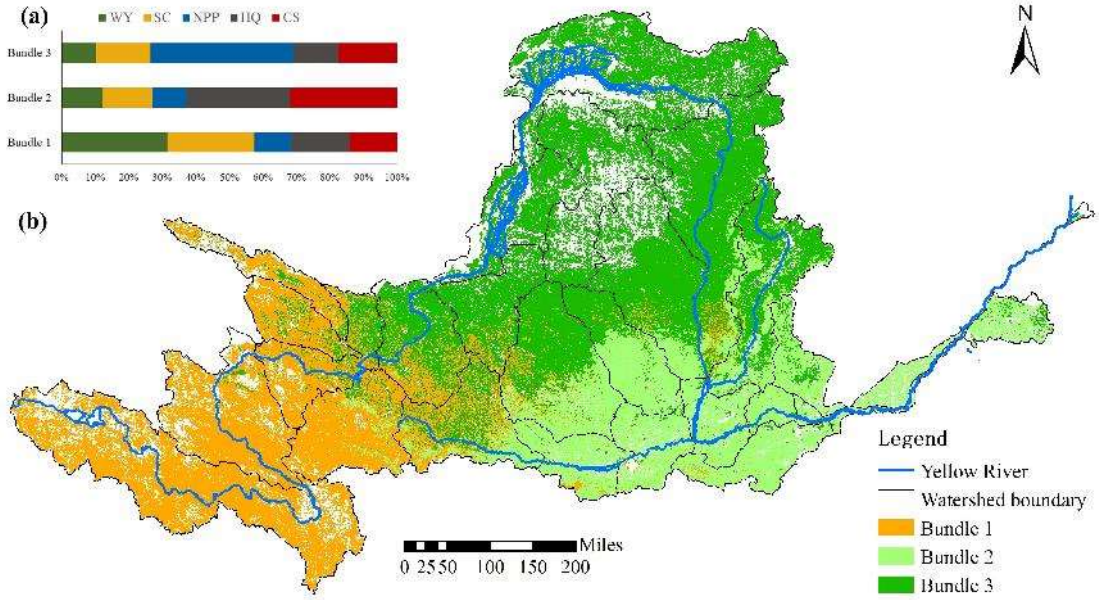


Fig.5 The spatial distributions of the three ES bundles in Yellow River Basin a.the proportion of the standardized value of each ES bundle b. the ES bundles map

5. Discussion

Reasonably regulating the time-space trade-offs between multiple services and clarifying their socio-economic-ecological environment driving mechanism is of great significance to the sustainable management of the ecosystem and the formulation of land use planning (Tammi et al., 2017). This paper systematically analyzes the spatial associations of the five important ESs in the Yellow River Basin and their social-ecological driving mechanism. First, it analyzes the spatial distribution of the five ESs quantitatively; then compares and analyzes trade-off and synergy among ESs and their spatial distribution.

5.1 The trade-off and synergy relationship of ESs

Identifying the interrelationships between ESs is essential for understanding services and guiding decision-making (Jiang et al., 2018). However, the interactions between ESs are not all linear. Therefore, the interaction between them can be understood only by evaluating multiple ESs. (Howe et al., 2014). The spatial distribution patterns of the five ESs in the Yellow River Basin are related, and the results are similar to and different from related studies. Supply services and other services usually have a trade-off relationship, especially between agricultural production, water production services and regulation services such as carbon fixation, pollutant retention, and soil conservation (Zhou et al., 2017). The results of this study show that there is a trade-off relationship between WY and CS, but the relationships between water production and SC, HQ and NPP are synergistic. Bennett et al. (2009) believe that the nonlinear relationship between ESs is under the basis of the following two mechanisms: one is driven by common influencing factors; another is the interactions between multiple ESs. Driven by common factors such as rainfall and terrain, there is a synergistic relationship between WY and SC. The increase of NPP can inhibit WY by increasing canopy interception (Wang et al., 2020). HQ, SC and CS are in a spatially synergistic relationship, that is to say, a complete habitat with low interference can offer a superior environment for various organic substances, thereby promoting some adjustment service functions (Peng et al., 2013).

This conclusion affirms the support function of HQ, and HQ is in a trade-off relationship with NPP. There are high altitude and low temperature in the places with high HQ, which is not conducive to the photosynthesis of vegetation. In downstream areas with high NPP, frequent human activities lead to lower habitat quality. There is a trade-off relationship between CS and NPP. Although both of these are carbon-related services and share a similar carbon cycle, CS

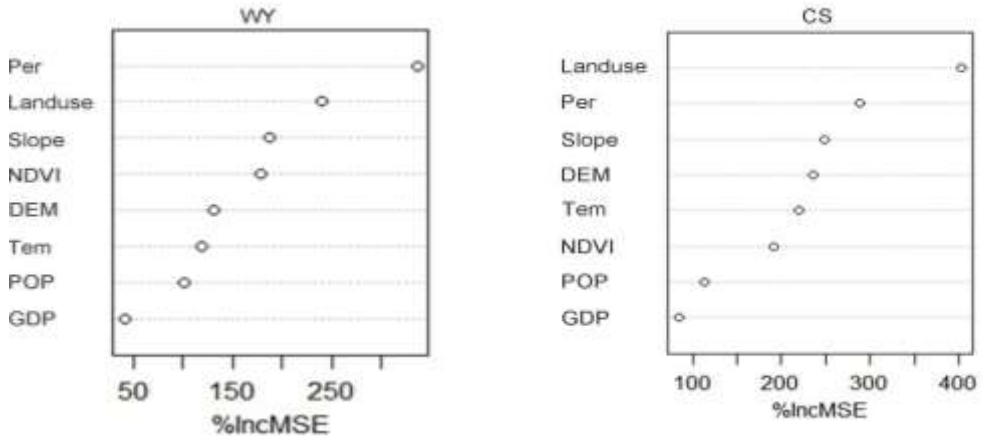
represents the stock of carbon and NPP represents the rate of carbon sequestration. There is an opposite relationship between the two. This result is supported by the findings of Zhang et al. (2010). In the Yellow River Basin, there is a wide range of east-west and north-south spans. It is a transitional bundles between the east and the west in our country. The transition has an impact on the barrier and differentiation of the region, resulting in differences in topography, landforms, and climate, which will affect the ecosystem and will promote the difference in ES relationships. The Yellow River Basin spans the Qinghai-Tibet Plateau, the Inner Mongolia Plateau, the Loess Plateau and the Huanghuaihai Plain from the west to the east. The height difference between the east and the west is huge, and the climate of different regions is obviously different. The Yellow River Basin is mainly in the southern temperate bundles, middle temperate bundles and plateau climate bundles. These differences make the vegetation, soil, animals and plants in the Yellow River Basin show significant latitude zonality differences, longitude differentiation, and natural rules such as vertical zonality and slope differentiation, which promote the high complexity and diversity of ESs in the Yellow River Basin, and more importantly, promote the spatial heterogeneity.

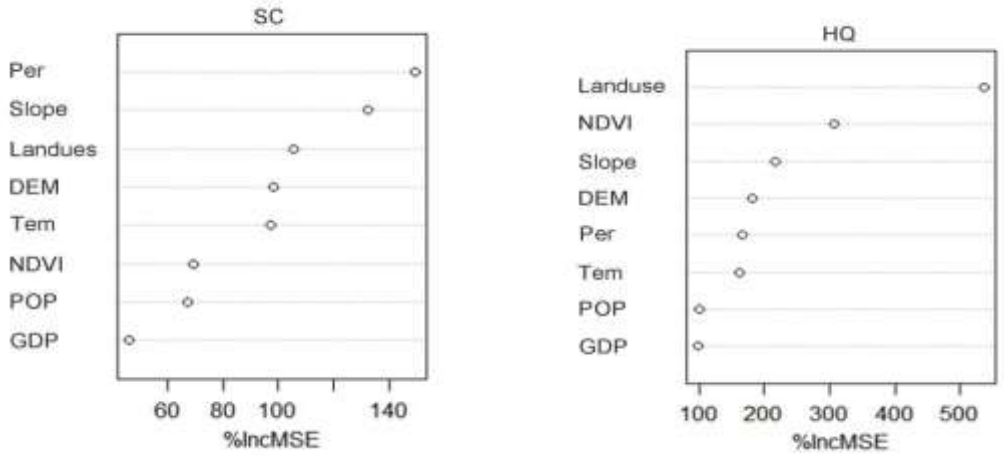
5.2 Factors affecting the spatial distribution of ESs

It performs statistical modeling on the social-ecological environmental factors of the five ESs in the Yellow River Basin in 2018 by using the random forest regression model. The fitting degrees are all above 0.90, indicating that the model can well fit the spatial distribution differences of ESs. The relative weights of the eight environmental factors on the spatial distribution of the five ESs are shown in Fig. 6: WY is affected by climatic factors more, especially precipitation, which has consistence with the results of previous studies (Yang et al., 2019). WY is the result of

583 comprehensive consideration of the balance of harvest (precipitation) and support (actual
584 evapotranspiration) during the regional water cycle. Therefore, WY is not only greatly affected by
585 rainfall, but also affected by the actual evapotranspiration in the region. The actual
586 evapotranspiration is not only affected by weather factors (temperature, wind speed, relative
587 humidity and sunshine hours, etc.), it is also affected directly by the land use/cover of the
588 underlying surface. The land use impact on actual evapotranspiration is mainly through changing
589 the underlying surface conditions, thereby affecting WY (Lang et al., 2018). SC is mainly affected
590 by rainfall, because precipitation is one of the leading factors that cause soil erosion. The increase
591 in precipitation leads to intensified soil erosion, which leads to a decrease in soil conservation (Liu
592 et al., 2018). The results show that slope is also one of the important factors affecting SC, because
593 there is a less human disturbance, higher vegetation coverage, lower actual erosion, and larger soil
594 conservation in the steep slope area (EI et al., 2013). In the plain area of the lower Yellow River,
595 despite the heavy rainfall, flat terrain, and small vegetation coverage, the actual erosion amount is
596 also large, so the SC is small, and other factors have no obvious impact on the SC. Land use type
597 is the most important factor affecting CS. From the perspective of the spatial distribution of CS,
598 the upper reaches of the Yellow River Basin, Luohe River Basin, Fenhe River Basin and Qinling
599 Mountains are the high-value areas of CS, which are mainly woodland and high-coverage
600 grassland, with good vegetation conditions and strong carbon sequestration capacity. The
601 low-value of CS areas are mainly distributed in the Loess Plateau, especially the Mu Us sandy
602 area in the north of the Loess Plateau and the Badain Jaran Desert in the north of the Helan
603 Mountain and in the west of the Yellow River, which is mainly sandy and other unused lands. At
604 the same time, the influence of temperature on CS is more important than other factors. This

conclusion is consistent with the results of Zhao et al. (2018), because the vegetation is easier to recover in areas with high temperatures. The spatial distribution of HQ is absolutely affected by the types of land use. The HQ of the Yellow River Basin as a whole presents the spatial characteristics of high in the west and low in the east, mainly because the upstream is dominated by woodland and grassland, while the cultivated land is concentrated in the downstream area. This is consistent with the researches in other regions at home and abroad. (Ma et al., 2019; Brumm et al., 2019; Yang et al., 2017). At the same time, natural features such as topography, climate, and NDVI are stable endogenous driving factors relatively, which determine the HQ spatial distribution, while social economic activities considered as manageable external driving factors often lead to the degradation of HQ (Yan et al., 2018). The influence of NDVI on NPP is much higher than other factors. The spatial distribution of NPP and NDVI tends to be consistent. Due to the sensitivity of NDVI to ground vegetation chlorophyll changes and high temporal and spatial resolution, it can sensitively reflect the dynamic changes of NPP (Jiang et al., 2011).





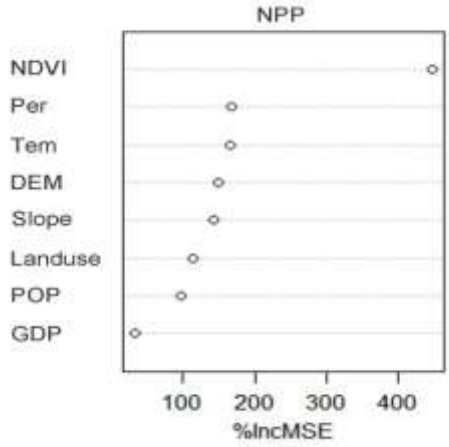


Fig. 6 Impact factors and degree of impact of various ESs(Per:precipitation, Tem:temperature, POP:population density, GDP:gross domestic product)

5.3 Land use management implications

Because the spatial heterogeneity of ESs determines different ES combinations, zoning can quickly identify areas with similar ecosystem clusters determined by similar social environment and other factors, so that policies can better formulate sustainable development strategies for different regions (Hamann et al., 2015). At the same time, ESs are affected by land-use ways and patterns, but most studies show that land-use types have the greatest impact on ESs (Paterson et al., 2012). Therefore, policy makers must understand how to construct land-use structures in a more

reasonable way to promote regional sustainable development. Based on the bundles results of the Yellow River Basin, they put forward several suggestions for the future urbanization and land planning in different areas. In bundle 1, multiple ESs are superimposed here, with irreplaceable ecological functions. In future, it should be strictly managed as a key protected ecological function area, delineate the ecological protection red line, and strictly enforce the ecological access system. It is strictly forbidden to carry out various development activities that do not conform to the main function positioning in the area designated as the ecological protection red line. It is necessary to promote ecological protection, restoration and construction projects with grassland restoration as the main body, focusing on the Three Rivers, Qilian Mountains, and the upper reaches of the Yellow River in Gannan, so as to improve the authenticity and integrity of the ecosystem. In terms of implementation measures, the researchers adhere to the principle of ecological priority and organic integration of production and ecology. Grassland pastures such as Gannan Plateau should carry out ecological restoration, strictly implement grass-determining livestock, control livestock carrying capacity, fundamentally curb overloading and overgrazing, and remove part of the ecological system and carrying capacity to wild animals, and establish and improve a natural reserve system with national parks as the main body. Management measures such as the prohibition of grazing, rest grazing, reduction of grazing, and rotation of grazing should be taken to accelerate the restoration of degraded grasslands. Measures such as reseeding of native grass seeds and soil bioremediation should be adopted to accelerate the restoration and reconstruction of severely degraded grasslands, strengthen the protection of biodiversity, ensure the connectivity of habitat, and improve environmental carrying capacity and water conservation capacity. In bundle 2, it encompasses the entire Loess Plateau. In this area, there is not only low rainfall and uneven

distribution, but also heavy rainstorms, coupled with the loose structure of loess, so it is easy to form soil erosion. From 1950, our country began to adopt measures such as slope management, joint management of slope and gully, comprehensive consolidation of small watersheds, and returning farmland to forests and grasslands to control serious soil erosion problems in this area. In general, the currently implemented soil erosion control measures and projects in the Loess Plateau have achieved significant ecological benefits, and the overall regional ESs have developed in a healthy direction; however, the overall fragile characteristics of the Loess Plateau's ecological environment have not been changed. Therefore, people should not only consider reducing soil erosion and increasing the area of arable land for the management of this area, more importantly, they should also improve landscape varieties and the living environment, optimize the economic and industrial structure, and boost regional social and economic growth. Guided by the concept of landscape, forests, fields, lakes and grasses as a living community, people should practice the idea of “reinforcing the ditch and protecting the plateau in plateau areas, returning farmland to forests and grasses on slopes, blocking trenches for land preparation, and fixing sand and restoring shrubs and grasses in sandy areas”. A comprehensive protection system for the plateau and ditch head with water systems and roads as the framework of fields, roads, forests, villages, shelter forests, etc. on the plateau and ditch should be formed to prevent the development of erosion ditch on the plateau. A ditch slope protection system that focuses on vegetation restoration, and combines engineering measures with forest, grass, and plant measures on the sloped surface is formed to reduce the water erosion of the ditch slope. The Saying Gully Scouring Forest has formed a gully protection system combining trench engineering and forest, grass and vegetation measures to prevent gravitational erosion such as collapses, landslides, and gully bank expansion.

In bundle 3, it is a densely populated area with concentrated construction land. The disorderly and intensive urbanization process and agricultural development in this area are the main reasons for the loss of other important ESs. This is consistent with the results of other areas (Cumming et al., 2014; Seto et al., 2012; Foley et al., 2011). The expansion of cities has led to the reduction of the service functions of CS, HQ, and SC. The ESs in urban concentrated areas are mainly reflected in green infrastructure. Therefore, in urban core areas, it establishes the green belts to eliminate the side effects of increased impervious surfaces, taking into account the low contribution rate of unused land to ESs. Therefore, priority is given to unused land in site selection for new urbanization.

6. Conclusion

This study evaluated the five ESs of the Yellow River Basin in 2018, including WY, CS, SC, HQ, and NPP, and made a spatial expression with the three-level basin as a unit, and then quantitatively analyzed the trade-offs and synergies among the five ESs. It delineated the dominant ecological service function bundles of the Yellow River Basin based on the SOM method. The main conclusions are as follows:

The spatial distribution of the 5 ESs not only shows spatial heterogeneity, but also reflects certain regional laws. The upper reaches of the basin show higher ES, especially WY, SC and HQ are significantly higher than that of in the middle reaches and lower reaches of the Yellow River basin, however ESs is generally lower in the middle reaches.

NPP has a synergistic relationship with CS, SC, and WY, and a trade-off relationship with HQ. CS has a synergistic relationship with SC and HQ, and a trade-off relationship with WY. The trade-off synergy relationship shows obvious spatial heterogeneity in space. The vegetation, soil,

animals and plants in the Yellow River Basin all show significant latitude zonality differences, longitude differentiation, and natural laws such as vertical zonality and slope differentiation, which promotes the high complexity and diversity of ESs in the Yellow River Basin, more importantly, promotes the heterogeneity of space.

According to the spatial distribution and related relationships of the five ESs, the dominant ecological function services in the Yellow River Basin can be divided into 3 bundles. Bundle 1 is the dominant function area for WY and SC services, Bundle 2 is the dominant function area for HQ and CS services, and Bundle 3 is the NPP service dominate function area.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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