



Constraint relationship of ecosystem services in the Yangtze River Economic Belt, China

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Abstract

Understanding the relationship among ecosystem services (ESs) is essential to promote ESs management and sustainable development. The relationship between ESs is mutual and can be expressed in terms of trade-offs, synergy, and constraints. The paper selected the InVEST model to assess the water yield (WY), soil conservation (SC), food production (FP), net primary productivity (NPP), and habitat quality (HQ) of the Yangtze River Economic Belt (YREB) and used the constraint line method to analyze the relationship of paired ecological services at three scales: landscape, watershed, and land category. The following conclusions were drawn: (1) during the study period, the spatial changes of the five ecological services in the YREB did not change much, but the spatial distribution of the ecological services was different. (2) From 2000 to 2015, the constraint line of YREB paired ecological services had a high degree of fit. Under the three levels of landscape, watershed, and land category, the YREB has a variety of constraint types, including negative lines, logarithms, paraboloids, humped shapes, and rectangles. (3) At the three levels, the constraint lines between FP, NPP, WY, and SC and HQ were stable rectangular constraints; WY-SC was hump shaped, FP-NPP, FP-SC, FP-WY, NPP-WY, and NPP-SC changed with the scale, showing different spatial scale changes. (4) The paired ESs directly determined the ecological constraint curve but under the combined effect of other factors, which would affect or change the constraint line. We discussed the effects of weather, topography, and economy on the constraint relationship, and found that all have different degrees of influence.

Keywords Ecosystem service · InVEST · Constraints · Trade-offs · Synergy · Influence mechanism

Introduction

As a life system, the ecosystem is the basic premise and foundation for the activities of human society (Liu et al. 2017; Baral et al. 2016). While providing the necessary space and material conditions for human beings, the ecosystem also plays an important role in repairing and coordinating damaged natural environments (Shiple et al. 2020), such as regulating

the climate, conserving water sources, maintaining water and soil, reducing disasters, and protecting biodiversity (Sun et al. 2018). According to the definition of the Millennium Ecosystem Assessment (MA), ecosystem services (ESs) refer to the benefits people obtain from the environment, including goods and services that support human survival and improve well-being (Hao et al. 2017; Albert et al. 2016). Rapid population growth and swift advancement of the urbanization

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process have increased the development and utilization of nature (Zhang et al. 2020), which has caused serious problems such as global climate change, biodiversity destruction, and the decline in the quality of the ecological environment. Under the influence of natural and human factors, global ESs are rapidly declining (Li et al. 2020; Hao et al. 2017). Therefore, the International Community proposed the idea of “sustainable development” (He et al. 2019) to strengthen the understanding of the internal functional mechanism of the ecosystem and alleviate the contradiction between humans and ecosystems (Li et al. 2020; Milanović et al. 2020).

ES assessment refers to the assessment of supply services, regulatory services, cultural services, and support services (Zhao et al. 2018; Wu 2013) produced by ecosystems. Presently, the methods for assessing ESs include mathematical statistics and assessment models (Yuan and Wan 2019). Mathematical statistics directly reflect the size of ES functions through survey statistics, mainly using field sampling survey data, social media data and socioeconomic statistics to express the status of ecosystem functions (Yuan and Wan 2019; Fu et al. 2013); assessment models depend on methods such as InVEST to assess various service functions, such as ecosystem carbon storage, soil conservation, and biodiversity (Li et al. 2020; Hao et al. 2017). The research on ecosystem service relationships is based on the assessment of ESs and analyzes the correlation between paired ESs, thresholds, structures, and functions on both sides of the correlation curve, usually using trade-offs, synergy, or constraints (Milanović et al. 2020; Guan et al. 2019; Hao et al. 2019).

However, many scholars are devoted to the assessment of ES value, and there are few studies on the constraints of ESs. Although some ecologists have explored the potential ecological mechanisms and driving factors in the ecological environment, partial problems and challenges still exist in studies focusing on matching ecological constraints. (1) The ES constraint line characterizes the constraint effect between two service variables, but this relationship may not be directly determined by the role of the two ecological services and may also be affected by external factors such as climate and non-climate impacts (Hao et al. 2016). Therefore, research on the constraints of ESs should be combined with other relevant analysis methods to improve the understanding of the ecological constraints curve. (2) The constraint line method exhibits strong spatial-scale dependence (Huston 1999; Hao et al. 2016). The spatial heterogeneity of the geographical environment makes the paired constraint relationship likely to be affected by external factors to different degrees, resulting in differences in the paired ecological service constraint curve. When using constraint methods, the relationship of paired ESs should be analyzed at different research scales. (3) Abnormal points will inevitably appear in the large number of “scattered point clouds” that are used to draw ecological constraint curves. In the process of drawing these curves, the abnormal

points should be removed according to the actual situation for drawing the ecological constraint curve with the largest envelope. The constraint line has always been a powerful tool for optimizing crop production and has the potential to manage and optimize ecosystem services (Hao et al. 2016). The points on the constraint line represent the service value that the ecosystem can provide to the greatest extent under the constrained environment, thereby promoting its characteristics and the understanding of its potential influencing factors (Qiao et al. 2018; Sun et al. 2009). In the application process, we better understand the ecological constraint mechanism only by solving the problems of the constraint line during the study of ecological service relationships.

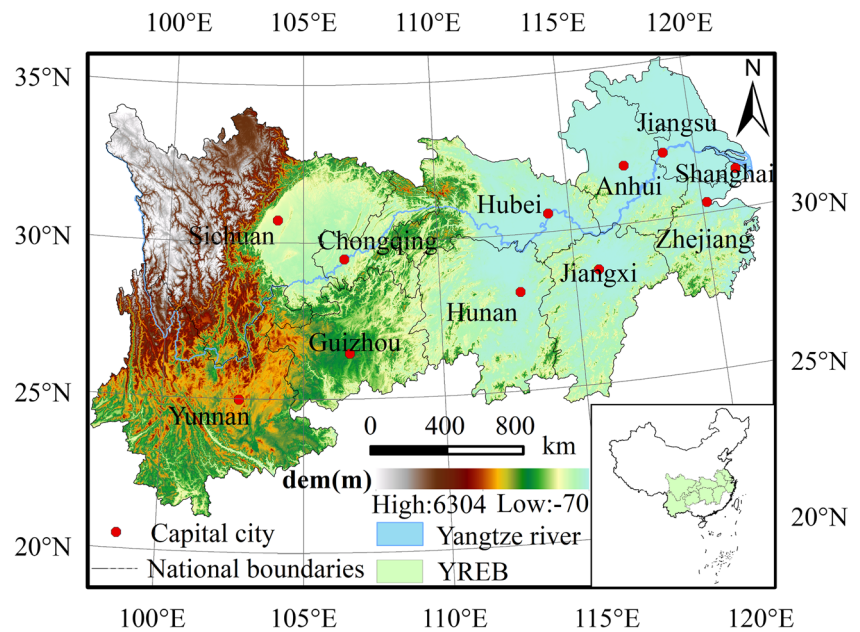
The development of the ecosystem environment in the Yangtze River Economic Belt (YREB) is great significance to China’s environmental protection and development, but there is still a lack of research on the ecosystem service mechanism in the region. Current research on ecosystem services in the YREB mainly focuses on ES mapping (Kong et al. 2018; Ouyang et al. 2016), analysis the changes of ESs (Fu et al. 2018; Zhai et al. 2019; Li et al. 2020), the exploration of ESs space-time trade-offs and synergies (Yang et al. 2018a, b; Xu et al. 2018; Liu et al. 2019), and related ecosystem service drivers (Deng et al. 2019; Shi et al. 2019); the ecological mechanism has not been explored from the perspective of the constraint relationship of ESs. With economic development, the YREB is facing increasingly serious environmental problems (Yin et al. 2016). Therefore, the article responds to the development policy of “enhanced protection without major development” proposed by the Chinese government from a new perspective of ecosystem service constraints, and explores the binding relationship and influence mechanism among ESs in the region. Hope to provide important reference significance for the coordinated development of ecology and economy in the YREB.

Study area and data

Study area

The YREB encompasses nine provinces (Zhejiang, Jiangsu, Anhui, Hubei, Jiangxi, Hunan, Sichuan, Yunnan, Guizhou) and two municipalities (Shanghai, Chongqing), with a total area of approximately 2.05 million km², involving 21.3% of China's area and supporting 584 million people, half of the country's total population (Fig. 1). As it includes three urban agglomerations, the YREB consists of 124 prefectural cities, and the average urbanization rate exceeds 50.0%. Large infrastructure projects, rapid urbanization, and extensive economic activity contributed 44.76% of China's gross domestic product (GDP), making it the center of gravity and vitality of the economy.

Fig. 1 Location of the Yangtze River Economic Belt



Rapid growth in population and economic development in the YREB over the past 30 years has occurred at the cost of deteriorated ecosystems and the environment. These ecosystems include the terrestrial ecosystem in the upper reaches of the Yangtze River and the aquatic ecosystems in the middle and lower reaches of the Yangtze River. Statistics show that in 2015, 83.3% of the 60 major lakes in the Yangtze River Basin did not meet water quality standards (Xu et al. 2018). The forest coverage rate in the upper reaches of the Yangtze River has declined from 30 to 40% in the early 1950s to approximately 10% at present (Yangtze River Water Resources Commission (YRWRC) 2016); reclaiming lakes and land has reduced the area of lakes in the middle reaches of the Yangtze River from 17,198 km² in 1950 to below 6600 km² (Yang et al. 2016); in 2014, the total discharge of wastewater from the Yangtze River Basin was 33.88 billion tons (Zhou et al. 2020). In addition, due to the neglect of the integrity of the ecosystem, the habitats of fish and other organisms in the Yangtze River have been destroyed, and the number and types of aquatic organisms have continued to decrease (Yang et al. 2015a, b). Under such circumstances, studying the ecosystem service relationship in the YREB has important national and regional significance for protecting local ecological functions and ecosystem services.

Data

The land use/cover data of the YREB were derived from the remote sensing interpretation data of 2000, 2005, 2010, and 2015 downloaded from the Resource and Environment Data Cloud Platform (<http://www.resdc.cn/Default.aspx>), with a spatial resolution of 1000 m. Meteorological data such as temperature and precipitation were sourced from the

National Meteorological Center Platform (<http://www.cma.gov.cn/>). A digital elevation model (DEM) was obtained from the Shuttle Radar Topography Mission (SRTM) data of the US Space Shuttle Endeavour (<http://science.nasa.gov/missions/srtm/>). A 1:1 million soil spatial dataset was provided by the Cold and Arid Regions Sciences Data Center at Lanzhou (<http://westdc.westgis.ac.cn/>), and the data contain complete soil layering attributes, spatial information, etc. Other social statistics came from statistical yearbooks of various provinces and cities.

Since the InVEST model needs to run on a grid map in the grid format of a geographic information system, all data used were processed using ArcGIS 10.7, and the grid unit size was 1000 m × 1000 m. In addition, the spatial value extraction tool in ArcGIS 10.7 and origin8.0 were used to fit constraint lines.

Methods

Mapping ecosystem services

ESs are an indispensable basic condition for human well-being. And the Yangtze River links the ecosystem services of various regions in the YREB. The dense vegetation coverage and unique topographical conditions in the area have avoided a large amount of soil erosion (Wu et al. 2018); in addition, the YREB, as an important grain production base in China, has an annual grain output of more than 10 million tons to ensure that the safety of food production in China (Ruan et al. 2021); at the same time, as one of the important forest areas in China, it plays a vital role in the fields of organic matter fixation, carbon cycle and habitat quality protection (Liu et al. 2019). Therefore, we choose the most well-developed ecosystem service evaluation model, the InVEST, to evaluate several

important ecosystem services in YREB (water yield (WY), soil conservation (SC), food production (FP), net primary productivity (NPP), and habitat quality (HQ)). The following is the working principle of the evaluation module in the model.

(1) Water yield

The essence of the water yield (WY_{xj}) is the difference between the precipitation (P_x) of each grid unit and the actual evapotranspiration (AET_{xj}) in the study area. This value is based on the principle of water balance, comprehensively considering the influencing factors of terrain, hydrology, climate, land use type, soil condition, and vegetation available water to find the water supply for each grid cell (Sharp et al. 2015). The calculation formula is as follows:

$$WY_{xj} = P_x - AET_{xj} = \left(1 - \frac{AET_{xj}}{P_x}\right) \times P_x \tag{1}$$

The actual evapotranspiration AET_{xj} of the grid unit can be calculated by using the AET_{xj}/P_x of the land use/cover type vegetation evapotranspiration in the quantity balance formula.

$$\frac{AET_{xj}}{P_x} = \left(\frac{1 + w_x + R_{xj}}{1 + w_x + R_{xj} + 1/R_{xj}}\right) \tag{2}$$

$$w_x = Z \times \frac{AWC_x}{P_x} \tag{3}$$

$$R_x = \frac{K_{xj} \times ET_{ox}}{P_x} \tag{4}$$

where AET_x is the annual actual evapotranspiration of grid unit x , P_x is the annual precipitation of grid unit x , z is the ratio of actual evapotranspiration to precipitation, and w_x is the annual water volume required by vegetation. In the precipitation ratio, AWC is the water content of plants, ET_{ox} is the potential evapotranspiration in grid unit x , and K_{xj} is the vegetation coefficient, which represents the ratio of plant evapotranspiration to potential evapotranspiration at different developmental stages.

According to the temperature, precipitation, and radiation data obtained from the meteorological stations in the study area, spatial interpolation is performed, and the ET_o is calculated by the Modified-Hargreaves formula (Sharp et al. 2015). An appropriate Z coefficient was obtained from the seasonal precipitation distribution. Combined with the contents of sand, silt, clay and organic carbon in the soil data, the nonlinear fitting estimation model proposed by Zhou (Zhou et al. 2005) was used to estimate the AWC .

(2) Soil conservation

Without considering the influence of the sediment delivery ratio (SDR) in the watershed, the difference between the

potential soil loss (RKLS) and the actual soil loss (USLE) is the soil conservation SC at the pixel (Guan et al. 2019; Sharp et al. 2015). In fact, the sediment at the pixel moves downstream along with the slope, and the downstream plots will cause sedimentation of the alluvial sediments from the upstream plots, resulting in the actual soil loss of the watershed and the watershed reaching the outlet of the watershed (Guan et al. 2019). There is a difference in the amount of sediment transport (SE), and the difference is the amount of sediment (SR) in the watershed. Therefore, the soil conservation amount SC_i at pixel i should be the sum of the soil conservation amount of the pixel itself $RKLS_i - USLE_i$ and the pixel's upstream sediment deposition amount SR_i . The calculation formula of soil conservation is:

$$RKLS = R \times K \times LS \tag{5}$$

$$USLE = R \times K \times LS \times C \times P \tag{6}$$

$$SR = SE_{i-1} \times (1 - SDR_i) \tag{7}$$

$$SE = USLE_i + SE_{i-1} \times SDR_i \tag{8}$$

$$SC_i = RKLS_i - USLE_i + SR_i \tag{9}$$

where R is the rainfall-runoff erosivity ($MJ \cdot mm \cdot ha^{-2} \cdot h^{-1} \cdot a^{-1}$); K is the soil erodibility factor ($t \cdot ha \cdot MJ^{-1} \cdot mm^{-1}$); LS is the slope length and steepness factor; C is the vegetation cover factor; and P is the conservation practices factor (Jia et al. 2014).

R is the main factor that causes soil erosion and characterizes the erosion of precipitation on soil, which can be calculated using the Wischmeier and Smith (1965) formula of monthly average rainfall and annual average rainfall; the soil erodibility factor K is calculated by the sediment and organic matter ratio of soil spatial data. Watershed data were extracted using the DEM data under the ArcGIS hydrological analysis module. LS can be calculated automatically based on the DEM data of the depression. C refers to the condition of soil loss under different vegetation cover, which is the ratio of the amount of soil loss of land covered by vegetation to the amount of soil loss of bare surface. P is the amount of soil loss after taking relevant measures for land use and the amount of soil loss under the slope planting scenario. C and P show the inhibition of soil erosion, and the value is between 0 and 1.

(3) Food production

The estimated value of crop yield is given in InVEST, which is derived from the existing data, percentage summary and simulated prediction results (Sharp et al. 2015; Ouyang et al. 2016). In the regression model of the module, the output of 12 major food crops was simulated by Mueller et al. on a global scale. The crop production regression model can provide the output of a given fertilizer input and then evaluate the output of food crops. Therefore, running this model, the user

must provide an additional table corresponding to the crop’s nitrogen, phosphate, and potassium application rates for each crop. The paper used the model provided by the UN Food and Agriculture Organization to generate simulated and observed crop yields and nutritional value tables and estimated three main food crops (Ouyang et al. 2016; Fu et al. 2018) in YREB: rice, corn and wheat.

(4) Net primary productivity

NPP refers to the remaining part of the total amount of organic matter produced by photosynthesis in plants per unit time and area after deduction of autotrophic respiration and is the energy that producers can use for growth, development and reproduction (Liu et al. 2019; Hao et al. 2019). NPP reflects the efficiency of plant fixation and conversion of photosynthetic products and the material basis for the survival and reproduction of other biological members in the ecosystem. It is a key parameter that characterizes the terrestrial ecological process and an important manifestation of the earth’s ability to support or is commonly used to evaluate land, which shows indicators of sustainable development of the ecosystem. The NPP data used in this article come from the data calculated by the Resource and Environment Data Cloud Platform (<http://www.resdc.cn/Default.aspx>) based on the light energy utilization model (GLM_PEM).

(5) Habitat quality

HQ is actually the potential capacity that ecosystems can provide for the survival and reproduction of biological species, which is measured in terms of the intensity of threats from the outside world and the magnitude of threats to the ecosystem (Sun et al. 2009; Sharp et al. 2015). In general, under the conditions of healthy and stable ecosystem types, the threat intensity is relatively small, and the habitat quality is also high. The assessment of habitat quality at a larger spatial scale usually considers the changes in land use/covering, quantifies the impact of human influence factors on habitat patches, and comprehensively considers the influence range weight and influence distance of various influence factors (Elliff and Kikuchi 2017). The calculation formula is as follows:

$$Q_{xj} = H_j \left(1 - \frac{D_{xj}^Z}{D_{xi}^Z + K^Z} \right) \tag{10}$$

$$D_{xj} = \sum_{r=1}^R \sum_{y=1}^{Y_y} \left(\frac{\omega_r}{\sum_{r=1}^R \omega_r} \right) r_y i_{rxy} \beta_x S_{jr} \tag{11}$$

where Q_{xj} is the habitat quality of grid x in land use type j ; H_j is the habitat adaptability of land use type j ; D_{xj} is the habitat stress level of grid unit x in land use type j ; k is the half

saturation constant, usually taken half of the maximum value of D_{xj} ; Z is a constant; R is the number of stress factors; y is all the grid cells of the stress factor r ; Y_r is the total number of grid cells occupied by the stress factor r . Comprehensively considering the special geographical environment of YREB, combined with relevant research (Zhong and Wang 2017; Zhang et al. 2014), this paper determines the maximum impact distance, weight, and impact mode of the following six ecological stress factors (Table 1): paddy field (st), dry land (hd), urban land (cs), rural residential area (nc), road traffic (qt), bare land (ld).

Types and quantification methods of ecosystem service constraints

(1) Types of constraints

The constraint relationship among ESs refers to the constraint effect of one ES (limit variable) on another ES (response variable). However, in addition to the constraints among the two services, many factors exist that affect ESs, including climate, land cover, soil, terrain, etc. (Bennett et al. 2009; Hao et al. 2019). This makes it difficult to directly observe and measure the relationship among ESs, so the constraint line method is usually used to characterize the distribution characteristics between two variables (Wang et al. 2016; Zhao et al. 2017). The concept of the constraint line was originally derived from the concept of the boundary line proposed by Webb (Hao et al. 2016). This method can better characterize the limiting effect of the limiting variable on the response variable under the mechanism of various influencing factors (Guo et al. 1998; He et al. 2019). The constraint line is a good representation of the potential distribution range of one ES under the constraint of another ES, and the scattered points under the constraint line mean that between ESs were affected by other variables and cannot directly reflect the relationship between the limiting variable and the response variable (Hao et al. 2017). There may be multiple constraints in ESs, and the Appendix in the article describes several possible types.

Table 1 The maximum influence distance and influence weight of the hazard source

Threat	Max_Dist	Weight	Decay
Paddy field	1	0.3	Exponential
Dry land	1	0.3	Exponential
Urban land	10	1	Exponential
Rural residential area	5	0.6	Exponential
Road traffic	4	0.4	Linear
Bare land	3	0.1	Exponential

(2) Method of extracting constraint lines

Changes in the constraint relationship of ESs are caused by the interaction and restriction of many environmental factors. The contribution intensity of various factors in different time periods will change, which will lead to changes in ecosystem constraints at different times and scales. Therefore, it is very necessary to explore the constraints of ecosystem services from multiple scales (Landscape, watershed and land category level). The points between ESs are extracted into a two-dimensional scattered point cloud, and the corresponding constraint lines are obtained by extracting boundary points and fitting. With the increase in research on ESs, the method of drawing constraint lines has gradually developed and matured. Presently, there are four main drawing methods for drawing constraint lines: the parameter method, scatter cloud grid method, quantile regression method and quantile segmentation method (Hao et al. 2016; Guan et al. 2019; Zheng et al. 2014). Among them, the quantile segmentation method has a more statistical basis than other methods, so this paper used the quantile segmentation method to extract the ES constraint line. The essence is to combine the logical slicing method with the quantile regression method, divide the limiting variables as the x axis of the scatter plot into 100 groups according to their value range, and select more than 99% of the quantiles in each group as the boundary points. Finally, fit the extracted boundary points to obtain the constraint line between ESs (Guan et al. 2019; Hao et al. 2019).

Results

Spatiotemporal pattern of ecosystem services in the YREB

Based on the InVEST model, the five ESs of WY, SC, FP, NPP, and HQ in the YREB were assessed (Fig. 2). Generally, the spatial distribution of the five services in the ecosystem of the YREB was heterogeneous. The areas with high WY values were mainly distributed in the lower reaches of the YREB, which was closely related to the amount of precipitation. The middle and lower reaches of the Yangtze River are located in the eastern coastal region of China and could receive more water vapor from the ocean, resulting in more rainfall. The high-value areas of CS were mainly distributed in the southwest and central areas of the study area. The surface vegetation covered in this area is mostly forestland, which plays an important role in soil conservation. FP was mainly distributed in grain production bases such as the Sichuan Basin and the middle and lower reaches of the Yangtze River. These areas are flat and fertile and are momentous grain production bases in China. The high-value areas of NPP were mainly distributed in the eastern and southwestern

margins of the study area. The main land use/cover type in these areas is forestland, and a small part is farmland; the low values of NPP were mainly distributed in the northwest of the study area where the vegetation is sparse in the Ministry area. The high-value areas of HQ were mainly distributed in the middle and lower reaches of the YREB. The value of HQ was mainly affected by threat factors such as highways, construction land, unused land, etc. The closer to the threat source, the lower the HQ, and vice versa, the greater. The spatial distribution patterns of CS, WY, and HQ were basically similar, and the spatial distribution patterns of high and low values of NPP and SC were basically opposite; the high value areas of CS, HQ, and NPP were basically distributed in the low value area of SC; FP only had a distribution on the utilization status of cultivated land but not on other noncultivated land.

The temporal distribution exhibited large differences in the space of WY, and other ecological services did not change much. The WY in the lower reaches of the Yangtze River in 2010 and 2015 was significantly higher than that in 2000 and 2005. The main reason for the formation was that the precipitation in the lower reaches of the Yangtze River in 2010 and 2015 was significantly more than normal, and the 2010 precipitation in this area was higher than that in 2015. Therefore, a large amount of precipitation contributes to a higher WY.

Constraint relationship

The YREB has a large area and a large climate difference, covering a variety of soil types and topographical features, which also makes the impact on the determination of the relationship between ESs less due to local factors. In addition, the relationship among ESs often changes due to changes in scale. Therefore, this research used the pixel size as the sampling unit to study the ES relationship and analyzed the scale effect from three different spatial scales: landscape, watershed, and category. The landscape level refers to the entire study area; the watershed level refers to the upper, middle, and lower watershed areas according to the stage division of the Yangtze River Basin; at the category level, six land uses/covers of cultivated land, forestland, grassland, water area, construction land and unused land are selected as the first-level classification criteria.

Constraint relationship at landscape level

As shown in Fig. 3, at the landscape level, all the constraint lines exhibited a high degree of fit. The constraint lines were better to include all points below the line, which also pictured that the quantile segmentation method could better extract the fitting curve. Ten pairs of service relationships and four types of constraint lines were generated by paired ecosystem services of the YREB. The service constraint curve of HQ and

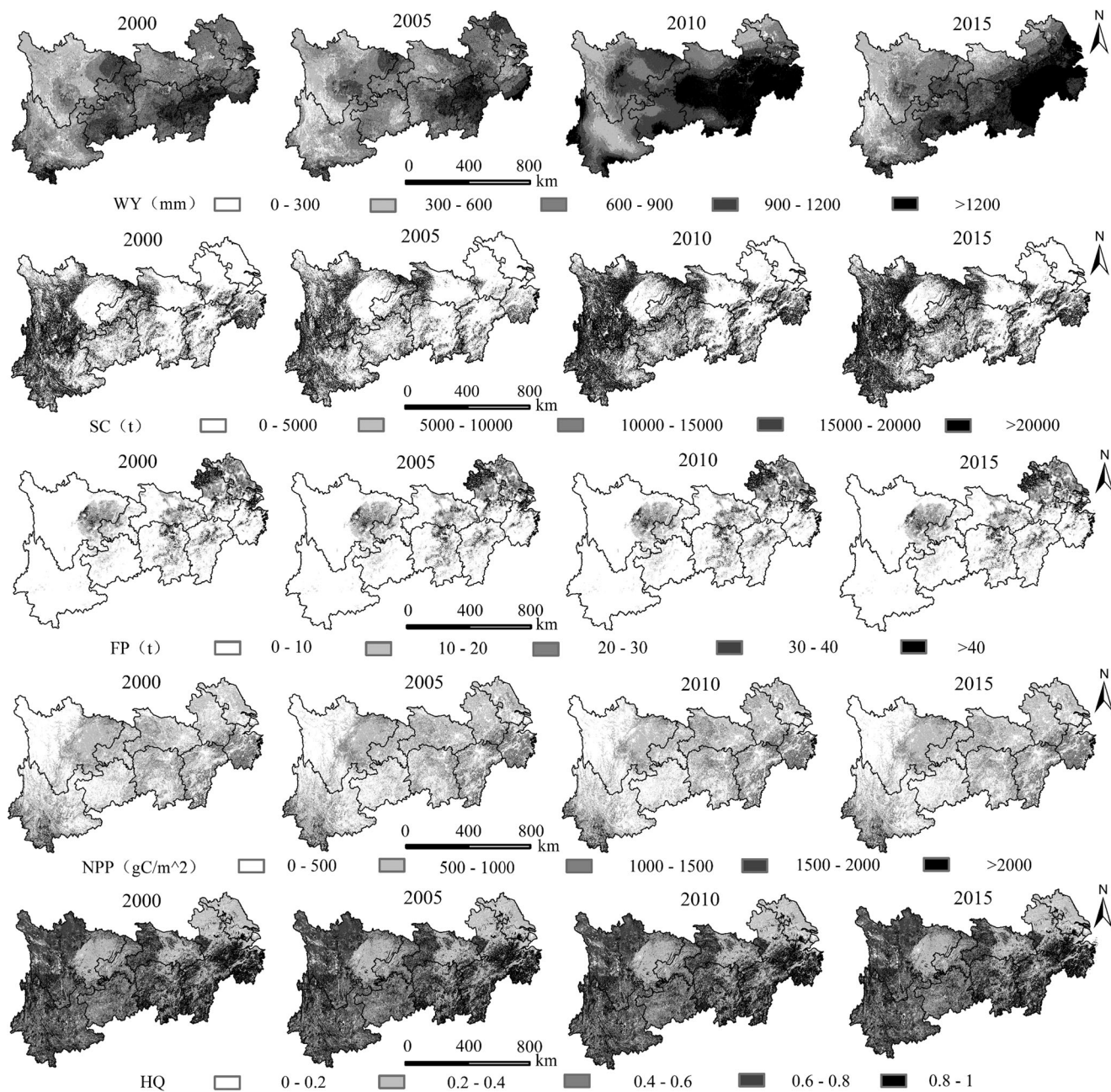


Fig. 2 Spatial distribution of ecosystem services in the Yangtze River Economic Belt from 2000 to 2015

FP, NPP, WY, SC and the x and y axes form a rectangle. It can be seen from the figure that the FP, NPP, WY, and SC increase and have no impact on HQ; when services reached the best advantage (at right angles), the FP, NPP, WY, and SC impact of the change on HQ was huge and irreversible change. Both NPP and SC showed a logarithmic negative constraint with the increase of FP, but there was a difference in the decreasing trend of the two. After NPP increased to a certain value with FP, NPP tended to stabilize, while SC decreased as small as 0. The constraint relationship of NPP-SC and WY-SC was hump-shaped. The constraint threshold of this kind of relationship directly affected the constraint relationship of

the ecological service. The constraint threshold of NPP and SC reaches the maximum at approximately 600, while WY and SC the threshold reaches the highest point at approximately 500. FP-WY and NPP-WY are parabolic curves. This type also determines that the WY was the largest only when the WY tended to 0.

Constraint relationship at watershed level

At the watershed, the number of ESs in the upper, middle, and lower reaches of the five ESs that are paired with each other is the same as that on the landscape, but the types are differ. The FP-

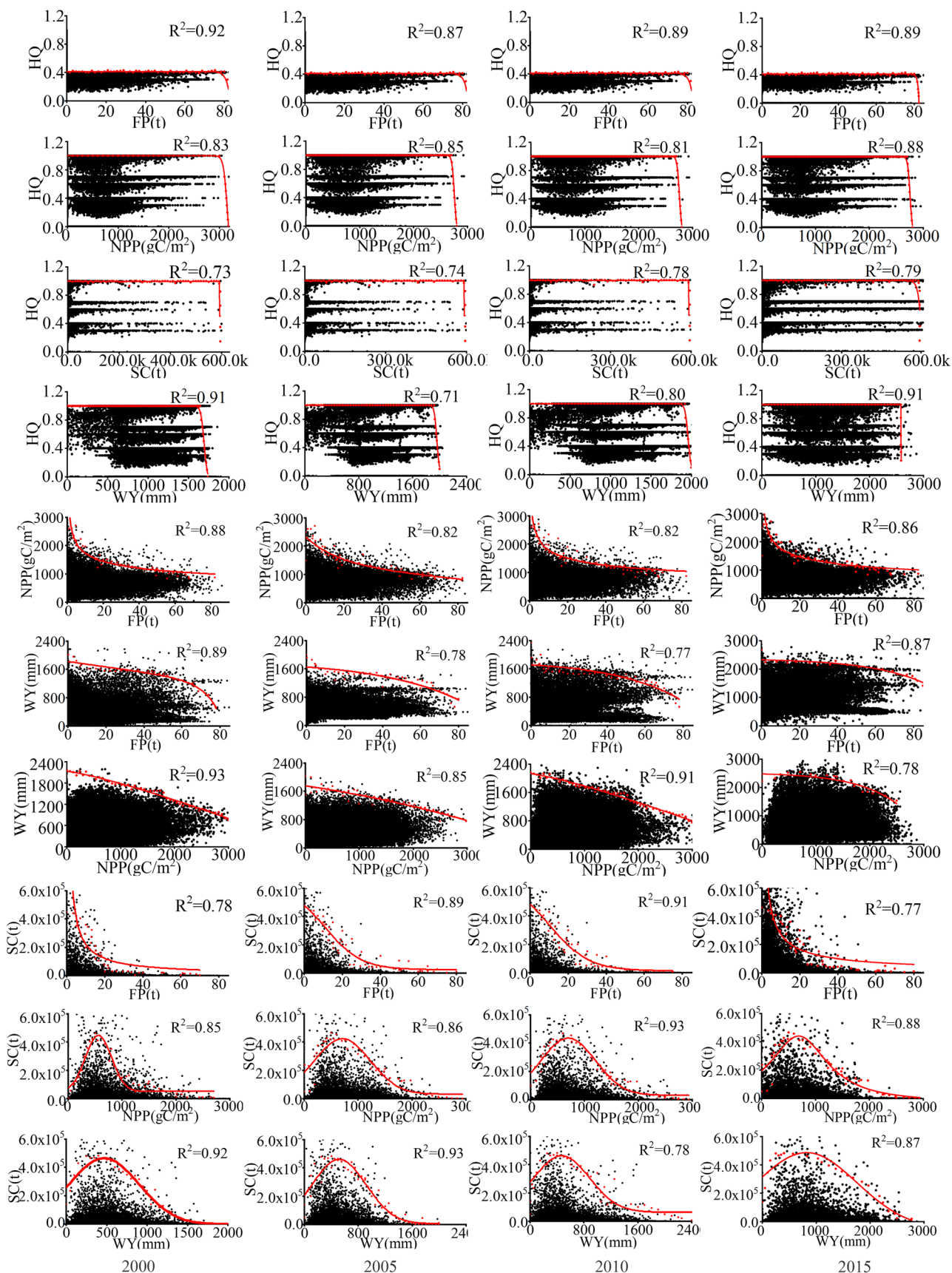


Fig. 3 Constraint relationship between ecosystem services under landscape level from 2000 to 2015

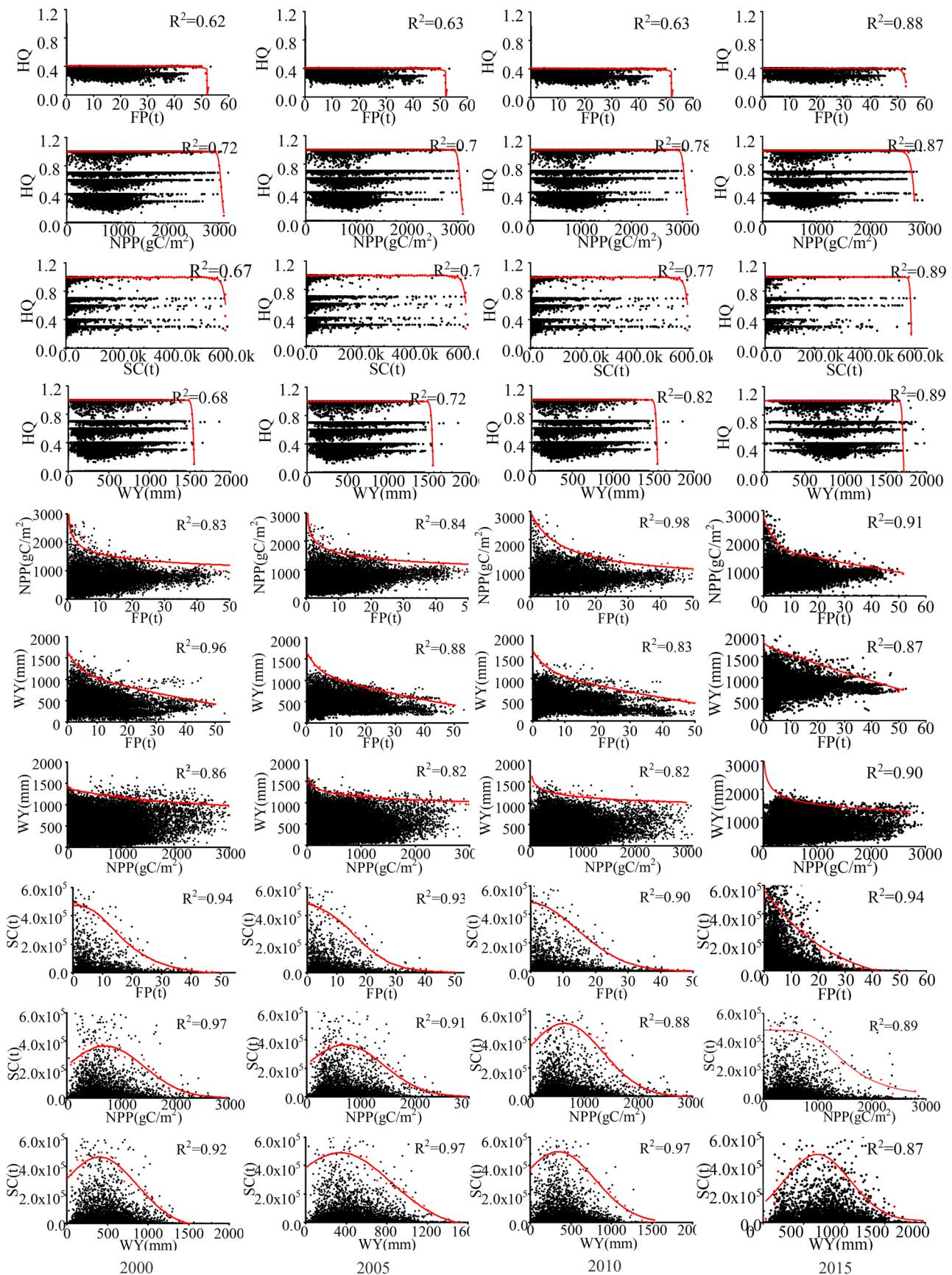


Fig. 4 Constraint relationship between upstream scale ecosystem services from 2000 to 2015

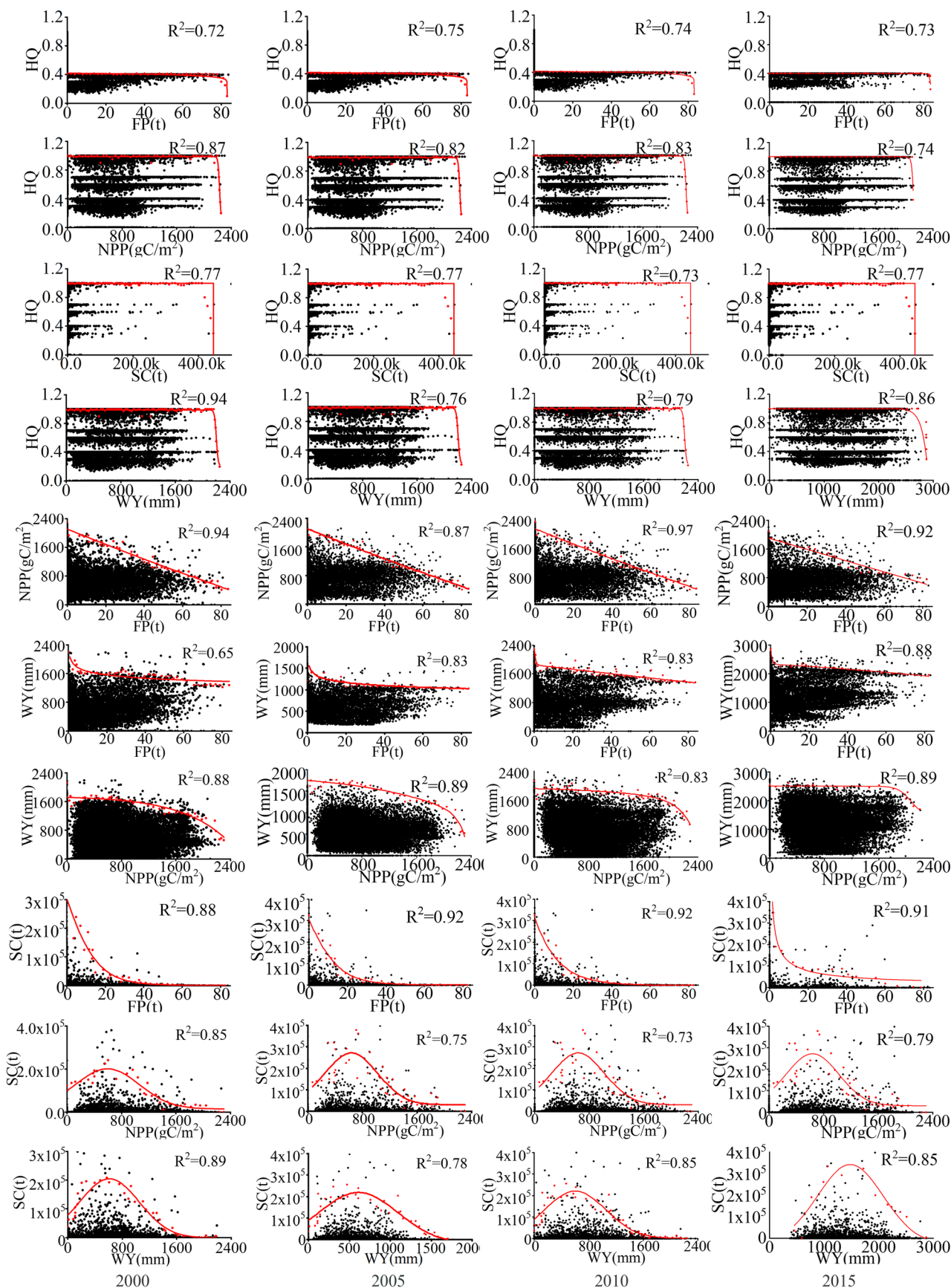


Fig. 5 Constraint relationship between midstream scale ecosystem services from 2000 to 2015

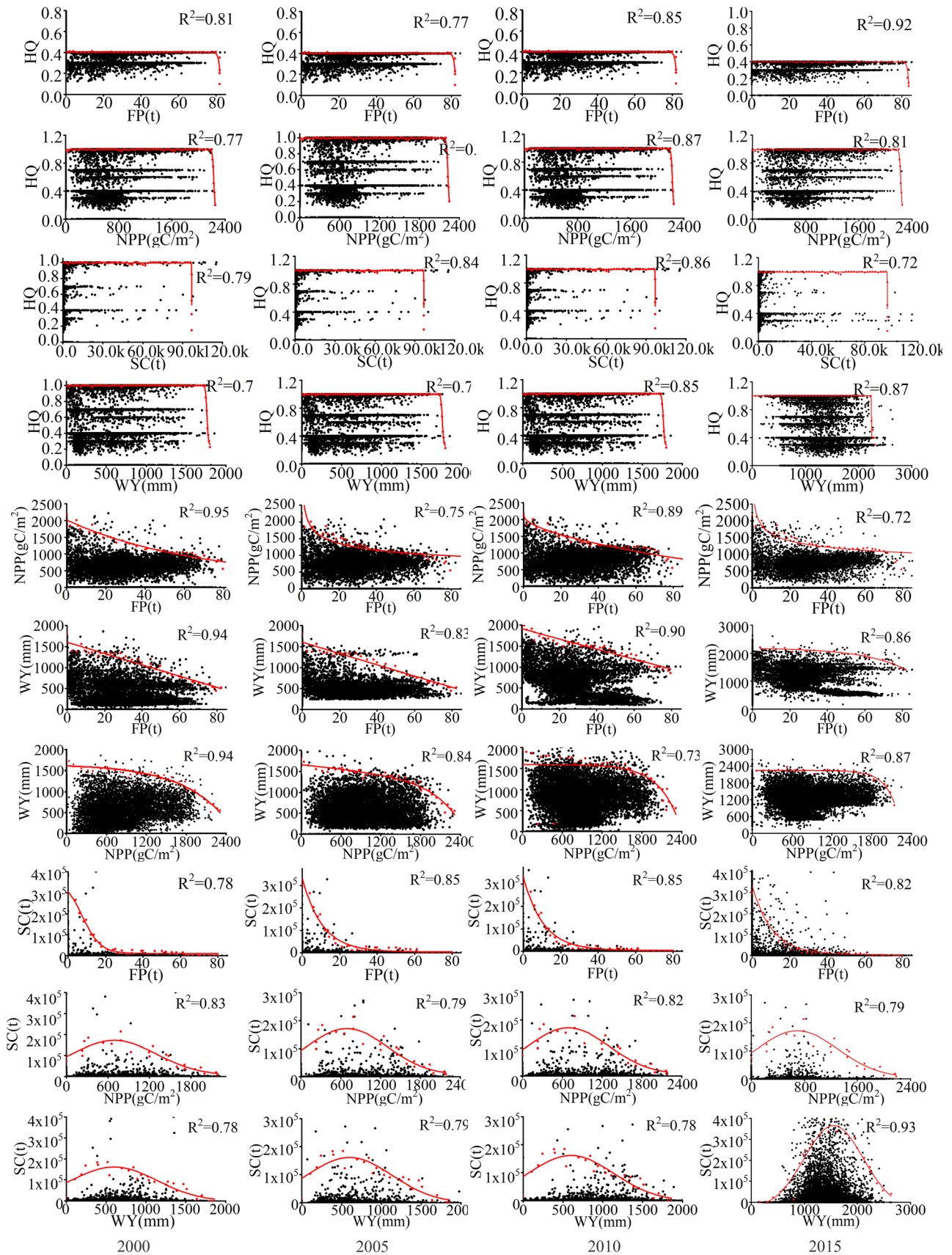


Fig. 6 Constraint relationship between downstream scale ecosystem services from 2000 to 2015

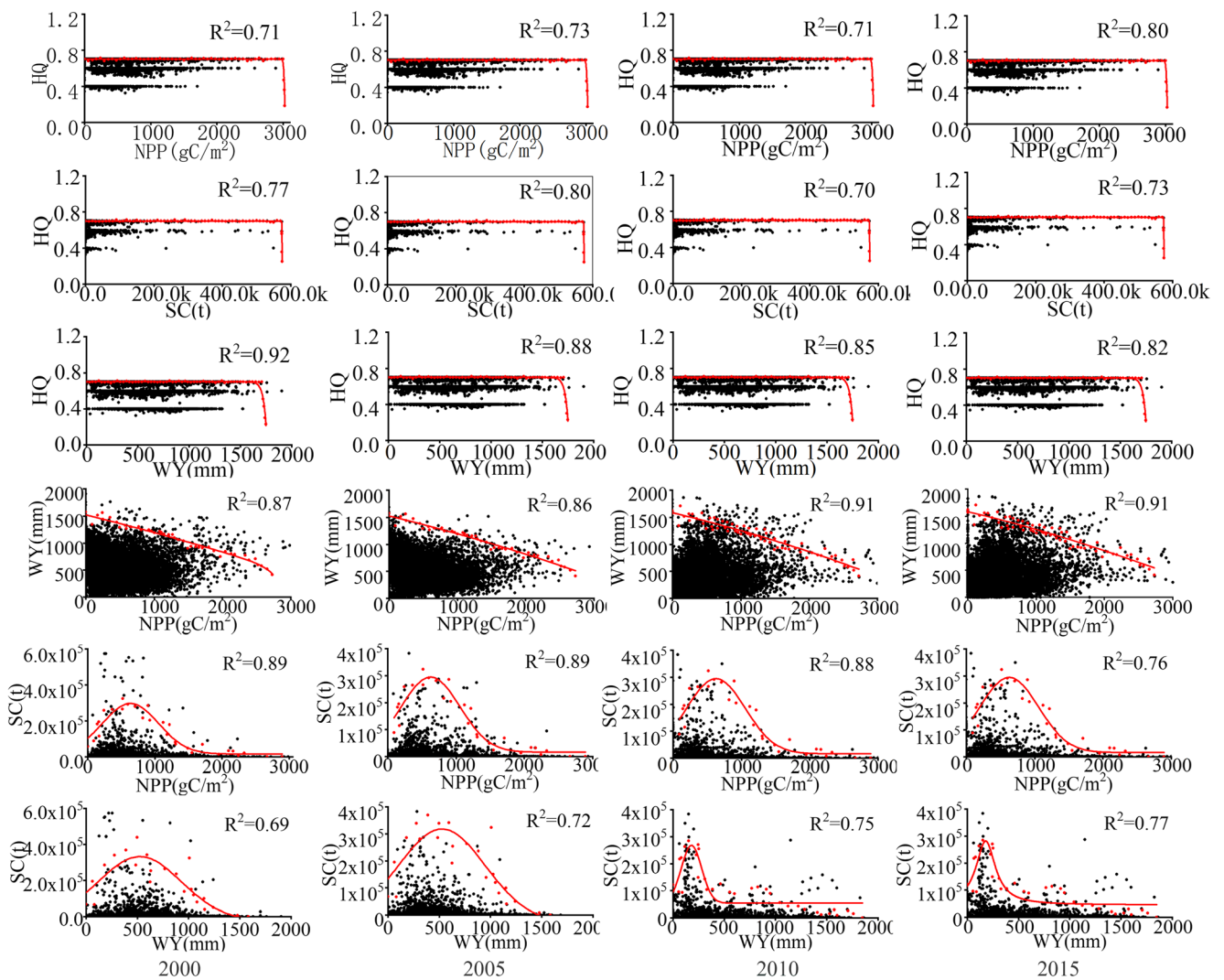


Fig. 7 Constraint relationship between cultivated land ecosystem services from 2000 to 2015

NPP, FP-WY, and NPP-WY had a scale change effect, and other paired ecosystem service relationships had not changed the type of relationship with changes in the watershed scale, which showed the constraint relationship was stable (Figs. 4, 5, 6).

At the upstream scale (Fig. 4), the service constraint curves of HQ and FP, NPP, WY, SC, and the x and y axes formed a rectangle, and the paired services of FP, NPP, WY, SC, and HQ achieved the best at right angles. FP-NPP, FP-SC, FP-WY, and NPP-WY were logarithmic, but there are differences in the restraint strength among them. The constraints of the FP on the NPP, SC, and WY were gradually weakened, and the rate of change was gradually reduced. When the FP variable was very small, the maximum value of the three services could be obtained. NPP-SC and WY-SC were hump-shaped. NPP and SC did not have a restrictive effect on SC before reaching the threshold (612, 508), but after the value, the restrictive effect on SC increased sharply.

At the midstream scale (Fig. 5), the types of constraint lines for HQ and FP, NPP, WY, and SC were consistent with the upstream

results, and the best service was achieved at right angles. FP-NPP was a straight line with a slope less than 0, and the restrictive effect of FP on NPP increased proportionally. The constraint lines of FP-SC and FP-WY were logarithmic reduction curves, but the intensities of the two constraints were different. The NPP-SC and WY-SC constraint curves were also consistent with the upstream hump shape, and the constraint thresholds were also very similar. The logarithmic NPP-WY in the upstream region shows a parabolic shape with increasing restraint.

At the downstream scale level (Fig. 6), the constraint relationship between HQ and FP, NPP, WY, and SC was similar to the mid-upstream result: there were right-angle points that make the service value reach the optimal constraint relationship type; the constraint types of FP-NPP, FP-SC were the same as FP-WY on the middle and upstream scales, but they also differ in the strength of constraints. FP-WY was a straight line with a slope less than 0; NPP-SC and WY-SC were hump-shaped; NPP-WY was parabolic.

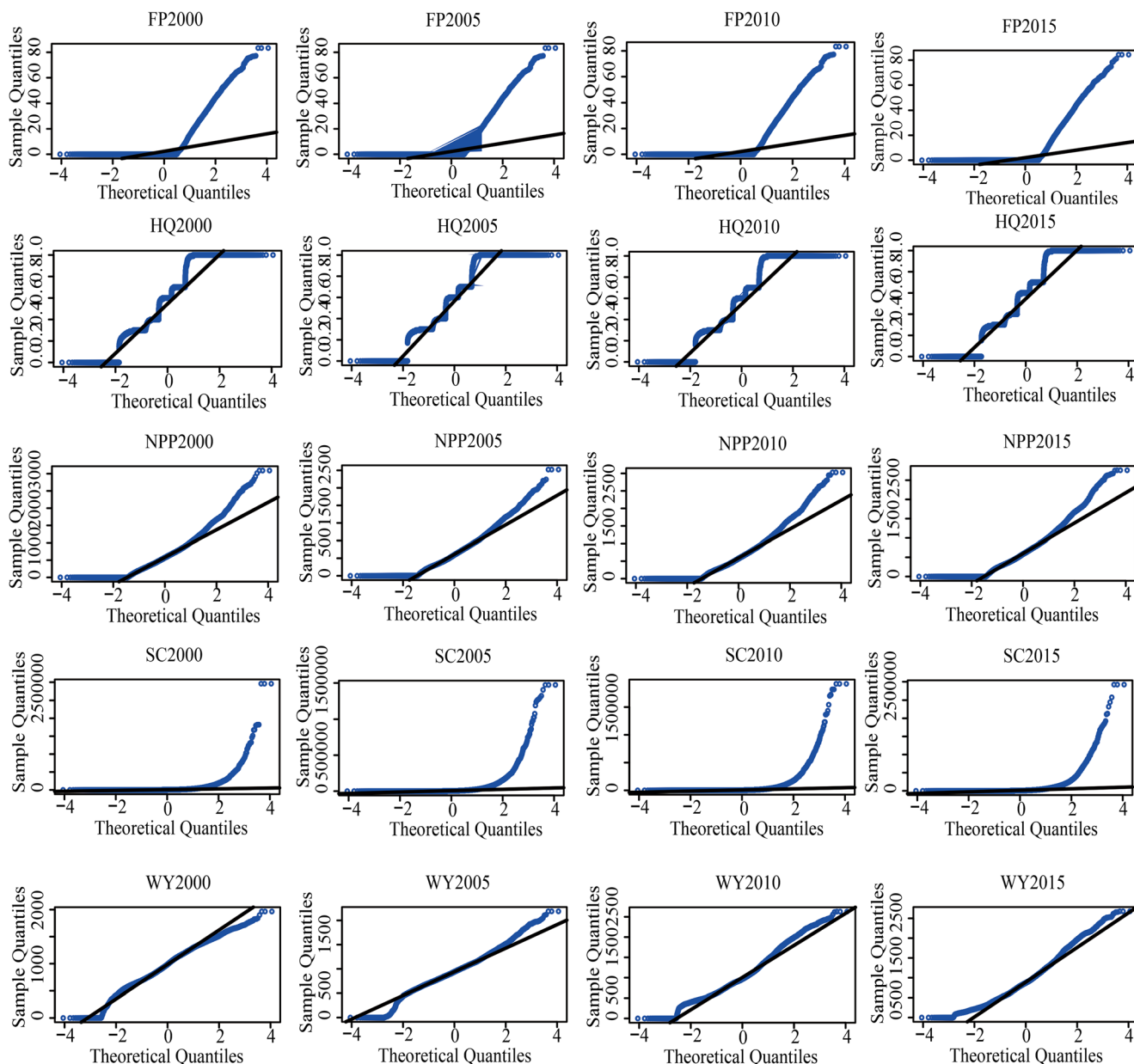


Fig. 8 Dynamic relationship of ecosystem services in the Yangtze River Economic Belt from 2000 to 2015

Constraint relationship at land category level

This paper depicts the ES constraint relationship pairings of six land use types. Each type may have a different number of constraint relationships, and the details please refer to the Appendix. The constraints of cultivated land are shown in the figure below.

The type of constraint line of the cultivated land was similar to the results at the landscape level and the watershed level (Fig. 7). The FP, NPP, WY, SC, and HQ constraint lines were all rectangular in the two-dimensional diagram. FP-NPP was a straight line with a slope less than 0; FP-SC was a logarithmic curve; FP-WY and NPP-WY were uniformly represented by a

parabolic decrease curve; NPP-SC and WY-SC were hump-shaped, but the shape of NPP-SC was not complete enough, strictly belonging to the half-humped camel type.

At forestland, the four ESs of WY, SC, NPP, and HQ formed a pair of 6 service constraint relationships and 3 types of constraint lines. The constraint lines of NPP, SC, WY, and HQ were rectangular, NPP-SC and WY-SC were hump-shaped, and NPP-WY was parabolic.

The 6 pairs of service relationships generated under the grassland were rectangular, hump-shaped, and negative lines. NPP, SC, WY, and HQ were rectangular; NPP-SC and WY-SC were hump-shaped; NPP-WY was a negative line.

Table 2 The trade-offs and synergy coefficients between ecosystem services in the Yangtze River Economic Belt

Pair ecosystem services	2000	2005	2010	2015
FP_HQ	-0.468**	-0.467**	-0.464**	-0.425**
FP_NPP	0.026**	0.077**	0.057**	0.062**
FP_SC	-0.458**	-0.450**	-0.444**	-0.401**
FP_WY	0.035**	0.095**	0.038**	0.151**
NPP_HQ	0.131**	0.102**	0.128**	0.114**
NPP_SC	0.099**	0.042**	0.024**	0.096**
NPP_WY	0.315**	0.273**	0.292**	0.159**
SC_HQ	0.422**	0.411**	0.411**	0.437**
WY_HQ	0.058**	0.016*	0.097**	-0.208**
WY_SC	0.097**	0.011	-0.013	-0.237**

** Correlation is significant at the 0.05 level (2-tailed); * Correlation is significant at the 0.01 level (2-tailed)

Under the water area, NPP, SC, and WY had the best relationship with HQ in terms of service value; NPP-SC and NPP-WY were negative lines; WY-SC was hump-shaped.

Construction land and unused land were the dangerous sources for assessing the Habitat Quality Index. In these two types, the value is 0. Therefore, without considering the habitat quality index, there were three pairs of service relationships at the two types. At the construction land, NPP-SC and WY-SC are hump-shaped, and the threshold reaches the maximum value at approximately 500, while NPP-WY presents a parabolic constraint relationship. At unused land, the three pairs of service relationship types are diverse. NPP-SC is a logarithmic type with increasing constraints, NPP-WY was a linear type with a slope of less than 0, and the maximum value of the constraint was 1300, while WY- SC was hump-shaped.

In the land category, ecosystem services had a large change in the constraint relationship, which changed more obviously with scale. Therefore, it also showed that the land use type was one of the important reasons that affected the change in the constraint relationship.

Discussion

Analysis of the relationship among the ecosystem services of the YREB

From the related research results of ES relationships, it can be found that paired ESs may exhibit trade-off, synergy, and constraint relationships. In order to fully understand the interaction between the ESs of the YREB, we would discuss and analyze several relationships.

According to the landscape horizontal constraint relationship curve (Fig. 3), the constraints of the five ESs in the YREB from 2000 to 2015 are mainly rectangular, parabolic, logarithmic, and hump-shaped distributions. The paired ecosystem service constraint relationship curve shows different trends according to the constraint line type. Observed the threshold of the constraint relationship of the paired ESs and found that the threshold point indicates that the direction of the constraint relationship of the ESs has changed and changed over time. The reason may be that many factors affect the relationship of paired the ESs, resulting in a difference in the constraint threshold. At the landscape (Fig. 3), watershed level (Figs. 4, 5, 6), and land category levels (Figs. A2–A5), except for the stable relationship of FP-HQ, NPP-HQ, WY-HQ, and SC-HQ, the remaining paired service relationships, including rectangle, parabola, logarithm, camel and straight. The changes in the constraint relationship at different levels indicate that the influencing factors at different research scales are different.

Currently, correlation analysis is the most commonly used mathematical analysis method for studying ES trade-offs and synergies (Guan et al. 2019; Gregory et al. 2020). If the correlation coefficient obtained is positive, the two ESs are considered to have a synergistic relationship; if the correlation coefficient obtained is negative, there is a trade-off relationship between the two services, including Spearman’s rank correlation coefficient and Pearson correlation coefficient analysis (Yang et al. 2015a, b, 2018a, b; Sharma et al. 2015). Since this study uses pixels as the sampling unit, the number of scattered points is large and does not follow the normal distribution (second quadrant and fourth quadrant in Fig. 8). In statistics, rank correlation, also known as rank correlation, can be used to describe the degree and direction of correlation between two variables for data that do not obey the normal distribution, so the Spearman correlation index is used to describe the relationship among service relationships. According to SPSS19.0 analysis, the Spearman correlation coefficient between ESs at the landscape level from 2000 to 2015 (Table 1) showed that paired ecosystem services at the landscape level have both negative and positive correlations ($p < 0.01$). The correlation between FP and HQ was between -0.564 and -0.700, which had a medium negative correlation and had a strong trade-off; NPP and SC had a small correlation coefficient, and between -0.094 and -0.014, there was a weak trade-off; SC and HQ’s weighing effect in 2015 was stronger than that in 2000–2010. If there was a synergistic effect between FP and NPP, NPP and HQ, the correlation coefficient was between 0.01 and 0.02. For NPP and WY, WY, and HQ, WY and SC, there were trade-offs and synergistic conversions during the research period (Table 2).

Comparing the relationship among constraints, trade-offs, and synergies, it is found that the correlation coefficient describes the trade-offs and synergies between ecosystem services from the perspective of the mean variable, but it cannot

Table 3 Types of statistics of landscape level and watershed level constraint lines

Scale level	Time	FP_HQ	FP_NPP	FP_SC	FP_WY	NPP_HQ	NPP_SC	NPP_WY	SC_HQ	WY_HQ	WY_SC
Landscape level	2000	1	2	2	5	1	3	5	1	1	3
	2005	1	2	2	5	1	3	5	1	1	3
	2010	1	2	2	5	1	3	5	1	1	3
	2015	1	2	2	5	1	3	5	1	1	3
Upstream scale	2000	1	2	2	2	1	3	2	1	1	3
	2005	1	2	2	2	1	3	2	1	1	3
	2010	1	2	2	2	1	3	2	1	1	3
	2015	1	2	2	2	1	3	2	1	1	3
Midstream scale	2000	1	4	2	2	1	3	5	1	1	3
	2005	1	4	2	2	1	3	5	1	1	3
	2010	1	4	2	2	1	3	5	1	1	3
	2015	1	2	2	2	1	3	5	1	1	3
Downstream scale	2000	1	2	2	4	1	3	5	1	1	3
	2005	1	2	2	4	1	3	5	1	1	3
	2010	1	2	2	4	1	3	5	1	1	3
	2015	1	2	2	5	1	3	5	1	1	3

Types of constraints represented by 1~5: 1: rectangle; 2: logarithmic; 3: hump-shaped; 4: negative linear; 5: parabolic

Table 4 Statistics of the types of horizontal constraint lines for land use

Land type	Time	FP_HQ	FP_NPP	FP_SC	FP_WY	NPP_HQ	NPP_SC	NPP_WY	SC_HQ	WY_HQ	WY_SC
Arable land	2000	1	2	2	5	1	3	5	1	1	3
	2005	1	4	2	5	1	3	5	1	1	3
	2010	1	2	2	2	1	3	5	1	1	3
	2015	1	2	2	5	1	3	5	1	1	3
Woodland	2000	-	-	-	-	1	3	5	1	1	3
	2005	-	-	-	-	1	3	5	1	1	3
	2010	-	-	-	-	1	3	5	1	1	3
	2015	-	-	-	-	1	3	5	1	1	3
Grass	2000	-	-	-	-	1	3	4	1	1	3
	2005	-	-	-	-	1	3	4	1	1	3
	2010	-	-	-	-	1	3	4	1	1	3
	2015	-	-	-	-	1	3	4	1	1	3
Waters	2000	-	-	-	-	1	3	4	1	1	3
	2005	-	-	-	-	1	3	4	1	1	3
	2010	-	-	-	-	1	3	4	1	1	3
	2015	-	-	-	-	1	3	4	1	1	3
Construction land	2000	-	-	-	-	-	3	5	-	-	3
	2005	-	-	-	-	-	3	5	-	-	3
	2010	-	-	-	-	-	3	5	-	-	3
	2015	-	-	-	-	-	3	4	-	-	3
Unused land	2000	-	-	-	-	-	2	4	-	-	3
	2005	-	-	-	-	-	2	4	-	-	3
	2010	-	-	-	-	-	2	4	-	-	3
	2015	-	-	-	-	-	2	4	-	-	3

Types of constraints represented by 1~5: 1: rectangle; 2: logarithmic; 3: hump-shaped; 4: negative linear; 5: parabolic; -: none

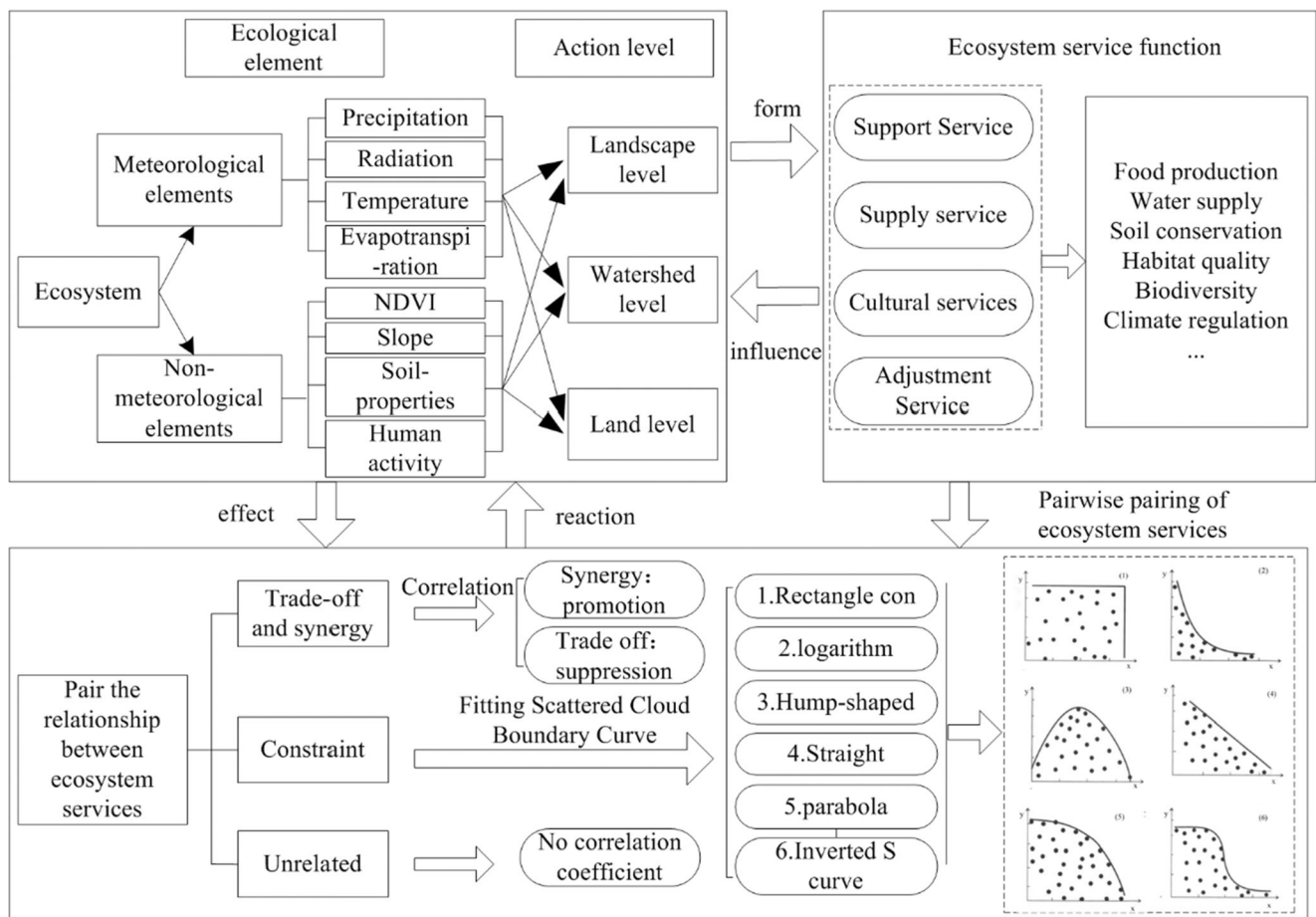


Fig. 9 Diagram of the role of ecosystem services

Table 5 Correlation coefficients between impact factors of the Yangtze River Economic Belt and annual ecological service functions

Function	Time	PPT	TEM	RA	ETO	SLOPE	NDVI	GDP
FP	2000	0.046	0.045	0.031	0.108	0.013	-0.035	-0.018
	2005	0.034	0.047	0.028	0.102	0.014	-0.010	-0.030
	2010	0.058	0.049	0.029	0.095	0.014	-0.029	-0.039
	2015	0.046	0.048	0.030	0.096	0.014	0.025	-0.004
NPP	2000	0.058	0.059	0.031	0.113	0.028	0.023	-0.013
	2005	0.030	0.076	0.054	0.148	0.017	0.010	-0.036
	2010	0.091	0.063	0.061	0.145	0.016	0.008	-0.029
	2015	0.041	0.057	0.050	0.141	0.020	0.028	-0.024
HQ	2000	0.033	0.029	0.013	0.027	-0.005	0.028	-0.019
	2005	0.010	0.031	0.011	0.035	-0.005	0.008	-0.032
	2010	0.021	0.016	0.008	0.014	-0.005	0.019	-0.040
	2015	0.016	0.017	0.011	0.035	-0.002	0.000	-0.008
WY	2000	0.169	0.111	0.009	0.194	0.063	0.035	0.037
	2005	0.081	0.133	0.118	0.272	0.031	0.003	0.105
	2010	0.174	0.172	0.178	0.378	0.035	0.034	0.096
	2015	0.177	0.198	0.135	0.406	0.049	0.028	0.054
SC	2000	0.009	-0.010	-0.059	-0.034	0.007	0.013	-0.006
	2005	-0.012	-0.037	-0.052	-0.074	0.001	0.008	-0.005
	2010	-0.023	-0.029	-0.057	-0.064	0.003	0.019	-0.010
	2015	-0.011	-0.022	-0.044	-0.049	0.009	0.003	-0.009

Table 6 Comparison of different research method

Study area	Method	scale	Years	Analysis content	Author
YERB	Constraint line method Correlation analysis	Landscape Basin Category	2000-2015	(a) Constraint relationship bundle curve of ES (b) Constraint relationship threshold of ES (c) Trade-off relationship of ES (d) Coefficient of interaction between ES and factors	This study
Grassland Farming and Pastoral Zone Biscay, northern Spain	Constraint line method Correlation analysis	Landscape Basin	2000 2005-2015	Constraint relationship bundle curve of ES (a) Space trade-off relationship of ES (b) Coefficient of interaction between ES and factors	Hao et al. (2017) Onaindia et al. (2018)
Quebec of Canada	Correlation analysis	Landscape	2009	Space trade-off relationship of ES	Raudsepp-Hearne et al. (2009)
Southern African river basin	Scene setting related analysis	Basin	2000-2030	The trade-off between ES and space-time scale	Bohensky et al. (2010)
Hangzhou Xixi Wetland	Multiple regression analysis	Category	2012-2013	The contribution rate of multiple factors to ES	Zhang et al. (2017)
Countryside of Netherlands	Local autocorrelation	Landscape	2009	(a) ES trade-off relationship (b) Space cold and hot spots	Willemen et al. (2010)
Farmland in Chongqing	Stochastic regression model	Category	2007-2016	Interaction strength coefficient between ES and factors	Kong et al. (2019)

describe the threshold characteristics of the relationship between ESs in the study area, but only from the overall trend illustrates the simple correlations that exist between ESs, and cannot describe the spatial relationship between them in a detailed and detailed manner. The constraint line characterizes the “scattered” cloud distribution of ES values in two-dimensional manner, which contains information from factors that affect the spatial distribution of ESs such as terrain, climate, and vegetation coverage.

Comparison of ecosystem service constraints at different scales

The constraint of ES is often affected by the research scale (Hao et al. 2019). To better analyze the effect of changes in the types of constraint lines of ESs at different scales in the study area, we summarize the types of constraint lines at three scales, as shown in Tables 3 and 4.

At landscape (Table 3), ES constraints produce four different types of constraints. First, the four pairs of ES relationships were rectangular constraint relationships, which have the largest number of such constraints. Second, the logarithmic, hump-shaped, and parabolic constraints each have 2 pairs, and the overall constraint fit is better. The types of constraints at the landscape level were highly generalized, influencing factors at different scales. At the watershed (Table 3), 10 pairs of ecosystem services have a total of 5 types of constraints in the upper, middle, and lower reaches of the watershed. Compared with the landscape level, the constraints of negative straight lines are increased. The constraint relationship of the

upstream level is consistent with the landscape level, and the linear constraint begins to appear in the middle and lower reaches of the river basin. The reason for this difference was that the topography, climate, and surface vegetation in the upper, middle and lower reaches of the river basin change greatly, causing different constraints. In the upstream area of the study area, the terrain is steep, mostly mountainous, the surface vegetation is sparse, and soil erosion is more serious. The terrain in the middle reaches is gentler than that in the upstream areas, and the vegetation is rich in growth; the terrain in the downstream areas is flat, mainly based on cultivated land types, close to the coast, and rich in precipitation.

In the land category (Table 4), the type of constraint line was similar to that in the watershed. The constraint effect shows the effect of changing with land use/cover change, which also shows that land use/cover is an important reason for the change in the constraint effect. Changes in ESs were mainly due to changes in the structure and pattern of regional ecosystems caused by urbanization and land use changes, which are caused by spatial differences or imbalances in the supply and demand of regional ESs. Different land use/covering conditions had different levels of vegetation coverage and vegetation types, which could change the intensity of restraint by affecting precipitation, evapotranspiration, soil structure, and nutrients.

At the three levels, the constraints of FP, NPP, WY, SC on HQ, and WY-SC were relatively stable, and there was no change in the type of constraint relationship due to the difference in scale, while other constraints generated change with the scale altered.

Constraint mechanism impact analysis and management

(1) Analysis of ecosystem service constraint mechanism

Previous studies have shown that changes in ESs were affected by climate and human activities (Mills et al. 2009; Hao et al. 2019; Jiang et al. 2018; Wang and Wang 2020). We have divided three modules to explain ES processes and relationships (Fig. 9). In this process, ecological elements are combined with biophysical and chemical effects on different scales to produce ES functions; and the temporal and spatial patterns of ES will affect ecological elements and processes at differ levels. The relationship between paired ESs will affect the scale effect of ES, which is of great significance to the management of ecosystem services. Therefore, we selected precipitation (PPT), temperature (TEM), evapotranspiration (ETO), radiation (RA), NDVI, Slope, and GDP to quantify their relationship with ESs (Table 5).

a. Analysis of the influence of rectangular constraints

The constraint among the quality of habitat and the other four ESs are rectangular and does not change due to scale. The vertical spatial characteristics of HQ (Bagstad et al. 2013; Lester et al. 2013) make the ecosystem service relationship stable. According to the Table 5, it is found that Slope and GDP have negative impact on HQ, GDP has negative correlation with FP and SC, and the coefficient range (-0.004 , -0.039); almost all factors have a weak positive correlation with NPP and WY (0.1). The results show human activities, slope, etc. are important factors that affect the spatial position of the paired ES scatter points under the rectangular constraint curve. Therefore, we can use these influence factors to adjust the constraint relationship.

b) Analysis of the effect of logarithmic constraints

In most cases, FP-NPP and FP-SC are logarithmic constraints, indicating that the increase FP will reduce NPP and SC. In Table 5, Slope and NDVI have a positive correlation with SC, and PPT, TEM, RA, and GDP have a negative correlation with SC. NDVI and GDP have a negative correlation with FP; PPT (0.030–0.091), TEM (0.057–0.076), and NDVI (0.013–0.014) have weak positive correlation with NPP. Water easily erodes the soil (Renard et al. 1991; Qiu and Turner 2013; Liu and Zhou 2019), and runoff is the main driving force of SC. Due to the lower vegetation coverage under the cultivated land types, soil erosion is more likely to occur, which is why FP and SC have a strong trade-off relationship. In addition, areas with a large amount of soil conservation are generally located in mountain forest areas. The FP-

NPP constraint curve becomes stable after being reduced to a certain value. It may be that the high-yield area of grain is flat and the water interception by plant canopy and litter avoids loss of soil and nutrients. In plain areas, attention should be paid to water and soil protection work, so that FP-NPP and FP-SC are in an appropriate restraint stage.

iii) Analysis of the influence of hump-shaped constraints

The constraint line may be determined by single factor, but in most cases it is determined by multiple factors (Medinski et al. 2010; Mills et al. 2009; Peng et al. 2020). NPP-SC and WY-SC are hump-shaped constraints. The correlation coefficient between SC and PPT and TEM are between -0.009 and -0.037 , which are weak negative correlation, and the effects of other influencing factors are positive correlations. The main reason is that the higher the TEM leads to the decrease of soil cohesion, suitable precipitation can promote the protection of the soil by vegetation, and it will cause soil erosion if it exceeds a certain threshold. This is similar to the NPP-SC constraint carried out in arid regions of China (Jia et al. 2014), indicating that NPP, WY, and SC may have similar constraint mechanisms in different research fields. The adjustment of this constraint can increase the coverage of vegetation, thereby indirectly adjusting the climate to achieve the best results.

iv) Analysis of the influence of parabolic and linear constraints

FP-WY and NPP-WY are mainly parabolic constraints under the three scales, and FP-WY, FP increases and WY slightly decreases. The main potential reasons are as follows: 1) the growth of FP requires a certain amount of nutrient water and scientific management mode; 2) excessive PPT will cause soil erosion on the cultivated land, causing soil fertility declines; 3) PPT, TEM, and RA are higher in the study area. The latter two points are the reason for the slight decrease of the restraint line of NPP-WY. From Table 5, PPT, TEM, NDVI, GDP, etc. are the main factors that affect FP-WY and NPP-WY constraints. The spatial distribution of vegetation has a huge impact on FP and NPP, and plants can also affect precipitation through evaporation. The linear constraint does not appear at the landscape level, but it appears at the watershed level and the land category level. Such as FP-NPP at the midstream, FP-WY at the downstream, NPP-WY at the grassland, NPP-SC, NPP-WY under the water area etc. In addition to influencing factors, scale is a factor that must be considered when managing linear constraints.

(2) Ecosystem service management and decision-making

According to the trade-offs and constraints of ESs, it can provide a stronger guarantee for the management, protection,

and scientific decision-making of regional ecosystems (Peng et al. 2017; Li et al. 2013; Wu et al. 2014; Yao et al. 2018). For example, the Chinese government's implementation of the YREB Shelter Forest Project has effectively guaranteed the ecological environment of the region. High vegetation coverage strengthens the ability of vegetation to adjust the climate, reducing the annual variation of regional temperature, precipitation and other climatic factors; at the same time, stable precipitation, temperature and vegetation increase the regional water supply, soil conservation and other ESs. In addition, the implementation of ecological compensation policies in the YREB has provided shelter for lakes, arable land, and woodland in the region, which has promoted the restoration of the regional ecological environment quality and increased the function of arable land for food production services. Judging from previous policies, the government may only promote the increase of certain types of ecosystem services through human intervention in certain influencing factors (improvement of vegetation coverage, protection of cultivated land, etc.). But in fact, there is a constraint relationship between ESs, and this relationship will cause certain ESs to increase while other services decrease. Our research not only shows that there are checks and balances between ESs, but also clarifies the constraints between the main ESs in the YREB, which can provide a basis for the subsequent government to regulate certain types of ESs based on restraint relationships in the management and protection of ecosystem services.

Comparison of different methods

Choosing an appropriate method to explain the ES constraint mechanism is an important content in the current research on the process of ecosystem action (Hao et al. 2017). Many researchers have quantified the driving effects of ES and factors at specific scales to varying degrees according to needs, but few studies on the influence of factors and ES thresholds and the relationship between factors and ecosystems. Table 6 shows the comparison result of different methods about ES relationships. These methods focused on describing the balance of ecosystem services and the relationship with factors from the perspective of average variables, and simply characterized the relevance of ecosystem services as whole, and cannot describe detailed methods or processes. Although multiple regression can be used to analyze the contribution of multiple independent variables toward the dependent variable, it is difficult to explain the ecological mechanism. In this study, we determine the influencing factors from the aspects of the meteorological and nonmeteorological, and then use the constraint relationship model to fit the 10 paired ecosystem services constraints of the YREB from three scales, and quantify the trade-offs and relationship coefficient among them, combine with ecological principles, analyze the ecosystem service constraint mechanism. The results illustrate that the

method of constraint line combined with statistical analysis can be selected to explain the ecological information contained in the constraint line. Seen from Table 6, we find that Hao et al. (2017) used the constraint line to fit the ES constraint relationship of the northern pasture interlace, but no explanation for the restraint effect from multi-scale. Therefore, we suppose that combining the constraint line with statistical analysis to illustrate constraint mechanisms from multiple scales has great significance for ecological management.

In this study, the constraint line method effectively simulates the scenario of multi-scale ES constraint relationships. Through the comparison of ES constraint relationships and impact evaluations at different scales, the results of ES constraint relationships can provide more realistic suggestions for the management and protection of ESs, because it can not only meet the needs of ecological development and ensure ecological safety. However, it should be noted that there is a lack of comprehensive influence of factors in the exploration of the constraint relationship mechanism. The current methods and models are difficult to analyze the combined effects of two or more influencing factors. For example, principal components and cluster analysis can only determine the main components of contradictions, but cannot achieve comprehensive analysis. Therefore, in future research, efforts should be made to build a comprehensive impact analysis model and explore the influence mechanism of constraint relations.

Conclusion

During the study period, the spatial changes of the five ecological services in the YREB did not change much, but the spatial distribution of the ecological services was different. From 2000 to 2015, YREB paired ecological services show a high degree of fit. Under the three constraint scales of landscape, watershed and land category, the types of service constraints were diverse, including linear, logarithmic, parabolic, hump-shaped, and rectangular. Comparing different constraints, the rectangular constraints of FP, NPP, WY, SC, and HQ were the most stable; WY-SC was hump-shaped on three scales; FP-NPP, FP-SC, FP-WY, NPP-WY, and NPP-SC had scale effects and changes on the spatial scale. The influencing factors of the constraint relationship of ecological services are complex and diverse and cross each other. Climate, terrain and GDP all have an impact on the constraints. The results showed that meteorological factors determine the scale of the water supply and directly or indirectly affect soil retention and net primary productivity; soil structure, organic matter, and topographic factors had important influence mechanisms on FP and vegetation coverage but also on

NPP and HQ. Except for NPP and HQ, the impact of GDP on most ecosystem services was negative.

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Author contribution L.Z. and G.D. designed the study. L.Z. performed the analysis and prepared the manuscript. L.Z. and Z.L. assembled input data, implemented the model and analyzed output data and results. L.Z. conducted data collection and preliminary analysis. G.D. and Z.Y. revised the original manuscript. G.D. and L.Z. validated modelling results and discussed the results and implications. All authors (L.Z., G.D., Z.L., and Z.Y.) participated in the writing of the manuscript.

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Data availability All data are processed by the author, true and effective, and all data generated or analysed during this study are included in this article.

Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The manuscript is approved by all authors for publication.

Competing interests The authors declare no competing interests.

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