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Changes in Ecosystem Services and Trade-offs/Synergies in the Nanpan and Beipan River Basin

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Abstract

Understanding the complex relationships among ecosystem services (ESs) is crucial for their joint management, particularly in vulnerable karst areas where ES dynamics are intricate. This study, focusing on the Nanpan and Beipan River Basin (NBPRB), examines seven key ESs—food supply (FP), water supply (WS), soil retention (SR), carbon storage (CS), water purification (WP), habitat quality (HQ), and landscape aesthetics (LA)—over 1985-2020, to analyze their spatiotemporal trends and their trade-offs and synergies for sustainable development. This study innovatively introduces a method to identify trade-offs and synergistic effects among services, including the recognition of positive and negative synergies, as well as determining which service reduction leads to the trade-off relationship. Additionally, by constructing land use transition matrices, the research analyzes how changes in land use affect the trade-offs and synergies among services, offering scientific guidance for the implementation of sustainable land management. The results indicate that (1) FP and LA have risen, and SC have fluctuated, and WP and CS have remained stable, though HQ has decreased. Regionally, ESs differ, with the south of NBPRB leading in FP and the north of NBPRB basin excelling in WS, CS, SR, LA, and HQ. (2) Among 21 combinations of ESs, seven exhibit trade-offs and eight synergies. Trade-offs are mostly between provisioning, regulating, and supporting services, with cultural services not involved. Positive synergies occur between FP, WP, and CS, while negative synergies relate to regulating services. Geographically, positive synergies are more pronounced in the east, negative ones in the south, and trade-offs are concentrated in the southern watershed. (3) Land-use changes affect ESs differently. Forests are crucial for CS, and grasslands and shrublands are important for SR. Expanding cultivated land and impervious surfaces can degrade WP and SR but can improve LA and FP. The study offers insights for managing ESs and informs better land-use planning in the watershed.

Keywords: Karst mountainous area, ecosystem services, spatiotemporal analysis, trade-offs and synergies, land-use change

1. Introduction

ESs are benefits provided by nature that can directly or indirectly contribute to sustainable human well-being (Finlayson et al., 2005; Cord et al., 2017; Costanza et al., 2017). Approximately 60 percent of ESs (ESs) have experienced a reduction in quality or quantity, attributable to unsustainable land management practice (Vihervaara et al., 2010).Consequently, it is imperative to implement strategies aimed at the restoration and improved stewardship of these essential services.

Understanding ES relationships is a prerequisite for developing sustainable ecosystem management strategies to effectively improve human well-being (Rodríguez et al., 2006; Raudsepp-Hearne et al., 2010; Dittrich et al., 2017; Gao and Zuo, 2021). Diversity of ecosystem types, spatial heterogeneity of ecosystems, and human management lead to complex interactions among ecosystems, which often include trade-offs, synergies(Raudsepp-Hearne et al., 2016; Spake et al., 2017; Xu et al., 2021).Trade-offs occur when the supply of one ES is reduced by an increase in another ES, and synergies occur when multiple ESs are enhanced simultaneously(Qiu and Turner, 2013; Spake et al., 2017). Many researchers have explored the interplay of trade-offs and synergies among ESs using pairwise correlation coefficients (Vihervaara et al., 2010; Locatelli et al., 2014; Chen et al., 2019; Orsi et al., 2020). However, this approach typically results in binary findings that simply indicate whether trade-offs or synergies are present, without considering the spatial context. However, these approaches have not clearly delineated the specific directional dynamics of these relationships, such as whether synergies imply a "win-win" scenario where both services increase simultaneously or a "lose-lose" scenario where both services decrease concurrently. Similarly, within trade-off relationships, it remains unclear which service's reduction leads to the trade-off phenomenon, and these nuanced questions have not been adequately addressed.

In recent years, studies on trade-offs and synergies among ESs have been increasing, but cultural services have been slightly understudied. For example, (Pan et al., 2020)used correlation coefficients to explore the trade-offs and synergies among four typical ESs (food provisioning, carbon sinks, soil conservation, and water retention) in the Ajiu region, while (Wang et al., 2022) modeled the trade-offs among food production, livestock production, and habitat quality in Xilinhot based on various future scenarios. In addition, (Li et al., 2022) explored the trade-offs among five typical ESs (food production, water supply, soil conservation, carbon sinks, and biodiversity maintenance) in the Huainan CMA-HGT area using correlation analysis and significance tests. However, these studies mainly focused on the trade-offs between provisioning services and regulatory/support services, with little attention paid to the trade-offs between cultural services and other services. Cultural services, which bridge the natural sciences and the humanities and society and are essential for promoting rural revitalization strategies, are rarely involved in the selection of ES functions. This is largely due to the inability to accurately quantify cultural services.

In addition, weighing synergistic short-term features is difficult to reflect the panorama of interactions under continuous dynamic changes in ESs. Neglecting spatial and temporal scales may lead to the risk of misinterpreting the spatial and temporal co-occurrence of ESs (Cord et al., 2017). First, trade-offs/synergies in ESs may strengthen, weaken, or change direction altogether over time (Renard et al., 2015; Zhu et al., 2021); and second, changes and feedbacks in ecosystem processes are time-lagged, e.g., regulating and supporting services have a cycles are long and factors affecting ecosystem provisioning are time-varying (Lautenbach et al., 2011; Deng et al., 2016; Zhang et al., 2020), and thus trade-offs/synergies of ESs obtained at a single point in time may be temporary; Third, identifying temporal variations in ecosystem trade-offs/synergies can facilitate policy makers' understanding of future ecosystem management and land use decision-making priorities to effectively design policy interventions that promote synergies among ecosystems (Paul et al., 2005; Feng et al., 2021). Therefore, in addition to focusing on the spatial heterogeneity of ES interactions, their changes over time should not be ignored, as spatio-temporal analysis enables us to understand ES dynamics (Renard et al., 2015). In this regard, the exploration of ES trade-off synergistic patterns based on long time series will help to improve the reliability of driver analysis. (Aryal et al., 2022) showed through a systematic review that there is a lack of current trade-off synergistic relationship studies based on long time series (>30 years).

To address the deficiencies in previous studies, this research, based on the MA classification system, selected FD and WY to represent the supply service capacity of the study area, NDR, CS, and SDR to represent the regulatory service capacity, HQ as an indicator for the support service capacity, and CL to characterize the cultural service capacity. The study covers the time span from 1985 to 2020. The objectives of this study are as follows: (1) We selected seven key ESs that encompass supply, support, regulation, and cultural services, quantitatively assessed the service function quantities from 1985 to 2020, and analyzed their trends. (2) We innovatively proposed a method to distinguish the direction of trade-offs and synergies among services, differentiating between positive synergies and negative synergies, and identifying which specific service reduction leads to the trade-off effect. (3) By utilizing the land use transition matrix, we analyzed the impact of land use changes on the trade-off/synergy relationships among services, providing a scientific basis for sustainable land management.

2. Method

2.1 Data Sources

Multisource datasets were used to spatially evaluate ESs and spatial determinants (Table 1). The land use/land cover data represented ten thematic classes: cropland, forest, grassland, wetland, lake, shrubland, water body, impervious surface, and bare land. All raster data in Table 1 with different spatial resolutions were resampled to a consistent spatial resolution of 1 km × 1 km to quantify ESs and spatial social-ecological drivers.

Table 1. Summary of the primary data

Data type	Data format	Data source/ processing	Spatial resolution
Land use/land cover	Raster	global 30 m land-cover dynamic monitoring product with fine classification system from 1985 to 2022	30m
Precipitation	Raster	1-km monthly precipitation dataset for China (1901-2021)	1km
Evapotranspiration	Raster	1-km monthly potential evapotranspiration dataset for China (1901-2023)	1km
Root depth	Raster	Depth-to-bedrock map of China at a spatial resolution of 100 meters	30 arcsecond
Carbon density	Spreadsheet	National Ecosystem Science Data Center, National Science & Technology Infrastructure of China. (http://www.nesdc.org.cn)	/
Food yield	Spreadsheet	Yunnan/Guizhou/Guangxi Statistical Yearbook, (https://www.stats.gov.cn/sj/ndsj/)	province
Digital elevation model (DEM)	Raster	Resource and Environment Science and Data Center (http://www. resdc.cn/)	90m
Net Primary Productivity (NPP)	Raster	Monthly Net Primary Productivity (NPP) 1-kilometer Grid Dataset of Terrestrial Ecosystems North of 18°N in China (1985-2015)/MOD17A3HGF Version 6.0(https://lpdaac.usgs.gov/product_search/)	500m
Harmonized World Soil Database	Bil	Soil map based Harmonized World Soil Database (v1.2)	/
Road network data	Shp	Center for International Earth Science Information Network	/

2.2 Methodology

Based on the framework of the Millennium Ecosystem Assessment (MA) and the characteristics of the ecosystems in the study area and the ecological pressures they are facing, this study integrated seven indicators, including FP, WS, SR, CS, WP, HQ and LA, to characterize the overall level of regional ESs (Table 2), in accordance with the four categories of services: provisioning, regulating, supporting and cultural services. The overall level of regional ESs was characterized by seven indicators. The ESs were assessed by InVEST model and Arc map10.8.

Table 2. Indicators for the valuation of ecosystem services

Type of service	Evaluation indicators	Abbreviation
Supply service	food production、water supply	FP、WS
Regulating service	soil retention 、 Carbon storage 、 Water Purification	SR、CS、WP
Supporting service	Habitat quality	HQ
Cultural service	Landscape aesthetics	LA

2.2.1 Ecosystem Services Assessment Methodology

1) Food production

The supply of agricultural/forest products addresses the most basic human needs, while NPP reflects the growth of vegetation. Using NPP and statistical data, the production of major agricultural/forest crops is allocated to cropland and woodland pixels. Since the supply of agricultural crops is directly related to cropland only, and the supply of forest products is directly related to forest land only, this paper assigns the production statistics of agricultural products to cropland pixels according to NPP in each year, and the production statistics of forest products to forest land pixels according to NPP in each year, and assigns the value of 0 to other land categories.

$$FP_{x,i} = \frac{NPP_{x,i}}{NPP_{total,i}} \times FP_{NSP,i} \tag{1}$$

Where： i denotes each statistical year， x denotes each pixel, and $FP_{NSP,i}$ denotes the production of total agricultural/forest products in the year i.

2) Water Supply

The WS module of the InVEST ES model is an accounting method based on the water balance method, where the rainfall minus the actual evapotranspiration of a grid cell is the WS and the more water supply per unit area, the stronger the WS service. The main calculation method is as follows: the annual water yield Y_{xj}(in mm) of the jth land use type in grid x is derived from the average annual rainfall P_x minus the annual actual evapotranspiration AET_{xj} of the corresponding year. The ratio of annual actual evapotranspiration to rainfall， $\frac{AET_{xj}}{P_x}$， was calculated according to Budyko's coupled hydrothermal equilibrium assumptions (Sun et al., 2015; Wu et al., 2023b). The expression is given below:

$$Y_{xj} = \left(1 - \frac{AET_{xj}}{P_X}\right) \cdot P_x \tag{2}$$

$$\frac{AET_{xj}}{P_x} == \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + 1/R_{xj}} \tag{3}$$

Where: Budyko dryness index R_{xj} is specific to land use type j of grid x, reflecting the degree of aridity in the region. The ratio of effective water content of vegetation to average annual rainfall ω_x, which represents the ratio of effective water content of vegetation to average annual rainfall on raster x, is used to characterize the utilization efficiency of vegetation on water.

3) Soil conservation

SRis calculated in the InVEST ES model sedimentation module, which calculates the actual soil erosion for each image element of the watershed based on the modified soil circulation equation; then the potential soil erosion is derived without considering the vegetation and management factors and assuming that the landscape is bare, and the difference between the latter and the former is the SR(Sougnez et al., 2011; Cavalli et al., 2013; López-Vicente et al., 2013). The expression is given below:

$$RKLS = R \times K \times LS \tag{4}$$

$$USLE = R \times K \times LS \times P \times C \tag{5}$$

$$SD = RKLS - USLE \tag{6}$$

Where: RKLS is the actual soil erosion,USLE is the potential soil erosion,SR is the amount of soil retention R for the rainfall erosivity factor, the factor is estimated using the annual rainfall erosivity model based on the annual rainfall; K for the soil erodibility factor, the factor adopts the method in the EPIC model; LS for the slope length and slope gradient factor; C for the vegetation and management factor, P for the factor to support the protection measures, the value C and the value of the P are determined in conjunction with the relevant literature.

4) Carbon sequestration

CS in the InVEST ES model takes each land use type or vegetation type as an assessment unit, and the average carbon density of the four carbon pools is multiplied by the area of each assessment unit to assess the regional ecosystem CS, and the carbon density table mainly refers to the results of related papers(Xu et al., 2019; Luo et al., 2023),and the calculation formula is as follows:

$$C_{tot} = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{7}$$

where: total carbon sequestration; aboveground biogenic carbon sequestration; belowground biogenic carbon sequestration; belowground biogenic carbon sequestration; and litter carbon sequestration.

5) Water purification

This study utilized the Nutrient Delivery Ratio (NDR) module of the InVEST ESs model to quantify WP services.

The model calculates the proportion of nutrients transported in surface and subsurface streams to determine the amount of nutrient loads reaching the stream.The NDR value reflects the ability of downstream pixels to transport nutrients without retention and is calculated as follows.

$$NDR_i = NDR_{0,i}[1 + \exp(\frac{IC_i - IC_0}{k})]^{-1} \tag{8}$$

$$NDR_{0,1} = 1 - eff_i' \tag{9}$$

$NDR_{0,i}$denotes the proportion of nutrients not retained in the downstream pixel,$IC_i$is the topographic index, and $IC_0$and$k$are calibration parameters.$NDR_{0,1}$is calculated based on the maximum retention efficiency of the land between the pixel and the river, where eff_i'denotes the total retention, and its upper limit is the maximum retention value due to the contribution of different land use types in the watershed.

WP services were assessed using the WP index (WP), whose formula was obtained by refining on the basis of (Jaligot et al., 2019)：

$$WP = ((TN - NS) + (TP - PS)/(TN + TP)) \tag{10}$$

Where WP is the WP index, TN represents the surface N transport load of each pixel, NS is the amount of N load that eventually reaches the river for each pixel, TP represents the surface P transport load of each pixel, and PS is the amount of P load that eventually reaches the river for each pixel.The WP value ranges from 0-1, with higher values implying a higher WP rate and lower values implying a lower purification rate, i.e., that most of the nutrient load will reach the water body.

6) Habitat Quality

HQ is assessed by linking land use to threat sources in the HQ module, entering threat factor weights and sensitivity data for each land use type. Habitat score values range from 0 to 1, with higher values indicating better habitats. The calculation formula is as follows:

$$Q_{xj} = H_j[1 - (\frac{D_{xj}^2}{D_{xj}^2 + k^2})] \tag{11}$$

Where $Q_{xj}$is the habitat quality; H_j is the habitat suitability of landscape j, and D_{xj} is the degree of disturbance to grid x in landscape j; k is the half-saturation constant (0.5). In this paper, based on the description of InVEST ES model manual and referring to related literature, the relevant parameter table is developed (Wu et al., 2023a).

7) Cultural landscape services

Cultural services are calculated using the value equivalence method, which is modified based on the equivalence table of values of (Xie et al., 2015) to confirm the value equivalence factor of cultural services in the Southern Beipan River Basin. 1 standard unit of ES value equivalence factor refers to the economic value of the annual natural grain yield of farmland with a national average yield of 1hm², and the value of grain yield of the agricultural ecosystems is calculated mainly based on the three major grain staples of rice, wheat and corn (one of the three major grain staples of corn). maize three major grain staple products is calculated (an expert knowledge-based ES valorization method). The calculation formula is as follows:

$$E_{AL} = \frac{1}{7}\sum_{i=1}^{n}\frac{m_i p_i q_i}{M} \tag{12}$$

Where E_{AL} is the equivalent value of cultural services in the year; m_i is the area of crops in the year; p_i is the average price of the three agricultural products; q_i is the yield of the agricultural products; and n is the type of agricultural products (wheat, rice and corn)

2.2.2 Quantification of Trade-Offs/Synergies between ES Pairs

In measuring trade-offs and synergies among ESs, traditional methods such as Pearson correlation coefficient (Sun and Li, 2017; Liu et al., 2019) and Spearman correlation coefficient (Xu et al., 2021) have been widely used to explore the relationship between pairs of ES from a statistical perspective, but the expression of spatial relationships is missing. In this study, we propose a segmentation method based on the amount of ES change to define trade-offs and synergies among ESs, and further discriminate the types of trade-off synergy relationships. The trade-off synergy criterion (TSC) can be described as follows:

$$TSC = (10 * \Delta ES_i + \Delta ES_j) \tag{13}$$

$$\Delta ES_i = ES_{i,t_2} - ES_{i,t_1} \tag{14}$$

$$\Delta ES_j = ES_{j,t_2} - ES_{j,t_1} \tag{15}$$

where ES_{i,t_2} and ES_{i,t_1} refer to the value of ESs of type i in time periods t2 and t1, respectively; ES_{j,t_2} and ES_{j,t_1} refer to the value of ESs of type j in time periods t2 and t1, respectively. When |TSC|>$10 * \Delta ES_i$, which means both ES_i and ES_j are positive or both ES_i and ES_j are negative, then pairs of ES_i and ES_j are recognized as synergistic relationship; for further judging, if TSC>0, which means both ES_i and ES_j are positive, then ES_i and ES_j are recognized as positive synergy. ES_i and ES_j are recognized as positive synergistic relationship and both ES_i and ES_j increase; otherwise, they are recognized as negative synergistic relationship and both ES_i and ES_j decrease. When |TSC|<$10 * \Delta ES_i$, it means that there is a positive number and a negative number between ES_i and ES_j, then the pairs of ES_i and ES_j are recognized as trade-offs; if TSC>0, it is recognized as a trade-off relationship in which ES_i increases and ES_j decreases, whereas when TSC<0, it is recognized as a trade-off relationship in which ES_i decreases and ES_j increase.

2.3 Study Area

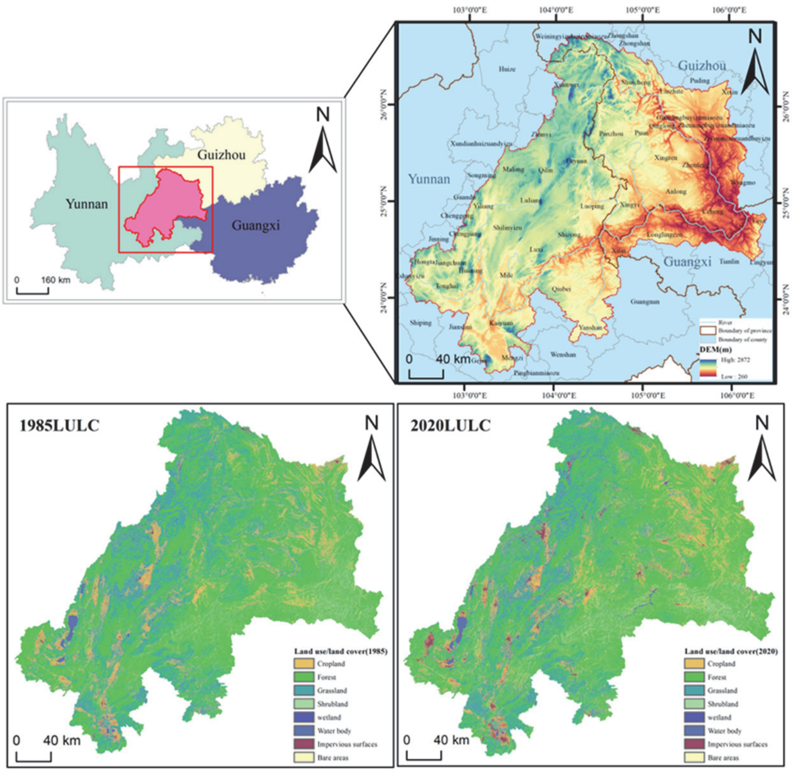

Figure 1. Study area

The karst region is one of the most vulnerable ecological zones globally, with soil degradation, rocky desertification, and habitat fragmentation severely threatening the function and services of these ecosystems. China has the world's most extensive distribution of karst landforms, concentrated in three main regions: the Southern Karst centered around Guizhou Province, the Northern Karst centered around Shanxi Province, and the high mountain plateau karst of the Qinghai-Tibet Plateau. In comparison, the Northern Karst and the high mountain plateau karst are less developed in terms of karst area, geomorphic development, diversity, and ecosystem preservation than the Southern Karst (Figure 1).

The NBPRB originates from the Maqiong Mountain, a remainder of the Wumeng Mountain Range in Qujing City, Yunnan Province, and are in the upper reaches of the Xijiang River System of the Pearl River Basin (102°—106°E, 23°—26°N). They serve as an extremely important ecological barrier within the Pearl River Basin, spanning three provinces (autonomous regions) — Yunnan, Guizhou, and Guangxi — with a total length of 1363 km and an area of 83,449 km². The basin is situated in a subtropical monsoon climate zone, with an average annual temperature of 16.6°C and an annual rainfall of 1182.4 mm, with rainfall increasing from southwest to northeast. The region has a topography that is higher in the northwest and lower in the southeast, with significant elevation differences. Approximately 70% of the basin is characterized by typical karst topography, dominated by carbonate rock strata, with extensive coal measures distributed in the middle and upper reaches, showcasing distinct karst geological features. Its geographical location, climatic conditions, topography, and biodiversity all fully exhibit the characteristics of the southern karst region of China. At the beginning of the 21st century, in response to ecological and environmental issues, a series of ecological restoration projects were implemented in the NBPRB, such as returning farmland to forests and grasslands, effectively mitigating rocky desertification and enhancing the region's ecological service functions. In summary, the NBPRB are not only typical areas of karst topography in China but also important locations for studying the ecological vulnerability and restoration of karst regions. Their representativeness and uniqueness hold a significant position in national and global karst research.

3. Results

3.1 Spatial-Temporal Variations of Ecosystem Services

The analysis showed that the trend of ES changes in the NBPRB varies (错误!未找到引用源。). WS showed fluctuating changes from 1985 to 2020. There was a small increase from 1985 to 1990, then a decrease from 1990 to 1995, followed by a recovery in 2000 but below the 1990 level. 2005 saw a significant decrease to 131.745 × 10^8 t, and 2010 saw a slight recovery but still below the 2000 level. 2015 saw a significant increase to 284.011 × 10^8 t but declined again to 151.535×10^8 t in 2020.FP increased year by year from 392.15×10^4 t in 1985 to 578.33×10^4 t in 2000, and then fluctuated slightly but stayed at a high level overall, reaching 644.22×10^4 t in 2020, showing a long-term growth trend. CS remained stable overall, with values ranging from 11.6 to 12.1 × 10^8 t fluctuating without a clear long-term trend but with a slight decrease from 2015 to 2020.SC shows a significant increase from 1985 to 1990, from 56.939 × 108 t to 59.783 × 108 t. It declines in 1995 and then rebounds slightly in 2000.It continues to decline in 2005 and 2010, with an increased significantly to 75.078 × 108 t in 2015, but then declined to 51.671 × 108 t in 2020.The WP indicator fluctuated around 0.703, remaining stable overall with no clear trend. HQ gradually declined from 0.672 in1985 to 0.533 in 2020, showing a long-term downward trend. The economic value of LA increased from 1985 of $261 million to $2,774.2 million in 2020, showing a significant upward trend.

Table 3. Evolution of ecosystem service volume in the Nanbei Panjiang River Basins, 1985-2020

Year	WS/10^8t	FP/10^4t	CS/10^8t	SR/10^8t	WP	HQ	LA/billion
1985	176.565	392.15	12.132	56.939	0.707	0.672	2.610
1990	183.205	469.44	12.121	59.783	0.707	0.665	4.539
1995	170.161	386.22	12.069	54.771	0.706	0.664	12.449
2000	175.211	578.33	11.714	55.037	0.703	0.621	8.313
2005	131.745	584.57	11.684	48.760	0.703	0.615	13.947
2010	133.007	573.34	11.665	50.405	0.703	0.602	21.259
2015	284.011	635.58	11.639	75.078	0.703	0.585	26.276
2020	151.535	644.22	11.624	51.671	0.702	0.533	27.742

(1) Supply Service

From Figure 2, the FP in the study area was consistent from 1985 to 1995. Starting from 2000, FP showed clear regional differences, with the northern NBPRB generally lower than the south. This could be due to significant elevation changes affecting FP across different elevations. The Beipanjiang Basin, on the Yunnan-Guizhou Plateau's slope with a northwest-high and southeast-low terrain and a 400-700m elevation difference, contrasts with the flatter NBPRB, which has more arable land. The Beipan River Basin has better agricultural conditions and can supply more food compared to the Beipan River.

WS service exhibits a pattern of higher values in the northeast and lower values in the southwest. The WS in the northern part is superior to that in the southern part. High WS is concentrated in the central and northeastern parts of the basin, while low WS is primarily found in the southwestern region. Between 1985 and 2000, there was a significant increase in WS in the eastern part. At the beginning of the 21st century, the distribution of WS showed an increase at the periphery and a decrease in the center. From 2010 to 2020, WS increased in the northern part, while a portion of the southern part experienced a decline.

(2) Regulating service

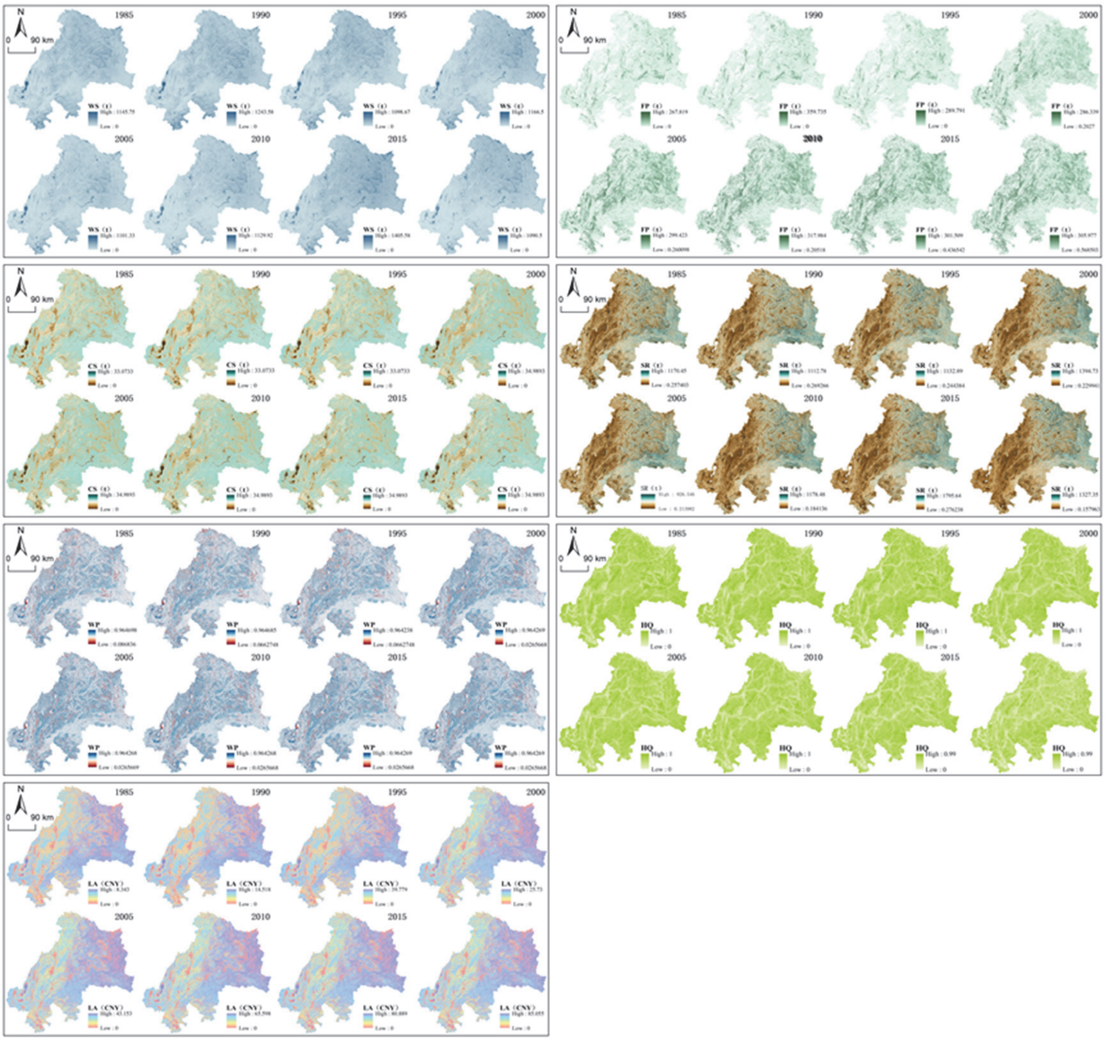

Figure 2. Spatial pattern of seven key ESs in Nanbei panjiang River Basin from 1985 to 2020

The eastern region has a strong capacity for SR services, making it a high-value area. These high-value areas are primarily clustered towards the east and northeast, while low-value areas are mainly concentrated in the west. Over time, there is a tendency for high-value areas to extend northward, and low-value areas to expand westward.

The distribution pattern of WP has remained stable, indicating that the basin's WP capacity is relatively balanced and sufficient, showing good natural regulatory functions. The WP service is slightly higher in areas of higher elevation compared to lower elevation areas. High WP is mainly concentrated in the central part of the basin at higher elevations, where steep slopes facilitate the rapid migration and influence of nutrients in the water body, which then flow to the middle and lower reaches of the river, positively affecting the overall water ecosystem of the basin.

(3) Support services

In the NBPRB, high HQ was observed in most areas, except around developed land and road networks where it was lower. The north of the watershed generally had better HQ than the south, with more degradation seen in southern urban and cultivated areas like the outskirts of Yuxi, Qujing, and Honghe. HQ was also higher in higher altitudes due to less human activity, which helps preserve HQ. This indicates a negative correlation between human activity intensity and HQ; less disturbed areas tend to have better ecological services. (4) Cultural service patterns

The LA in the NBPRB is higher in the east and lower in the west, forming a clear division. Karst landforms contribute to the uneven distribution of cultural services. Areas with features like peak forests, caves, and sinkholes have higher cultural service values. High-value zones are mainly in Xingyi City, Cecheng County, Zhenning County, Pu'an County, Guizhou Province, and Longlin Autonomous Prefecture, Guangxi Province. These zones are in low-elevation areas with abundant water and forests, offering a solid base for cultural services. Since 1995, cultural landscape values have increased in the west, while high-value areas in the east have expanded westward.

3.2 Trade-Offs and Synergies Between ES Pairs

3.2.1 Identification of Trade-Offs/Synergies between ES Pairs

From 1985 to 2020, this study analyzed seven ESs in the NPRB and obtained 21 different service combinations (Figure 3). Among them, seven combinations had dominant trade-off relationships in spatial distribution, while eight combinations showed synergistic relationships. We define the relationship between a service pair as a trade-off or synergistic relationship when their trade-off/synergistic relationship image element share exceeds 60%.

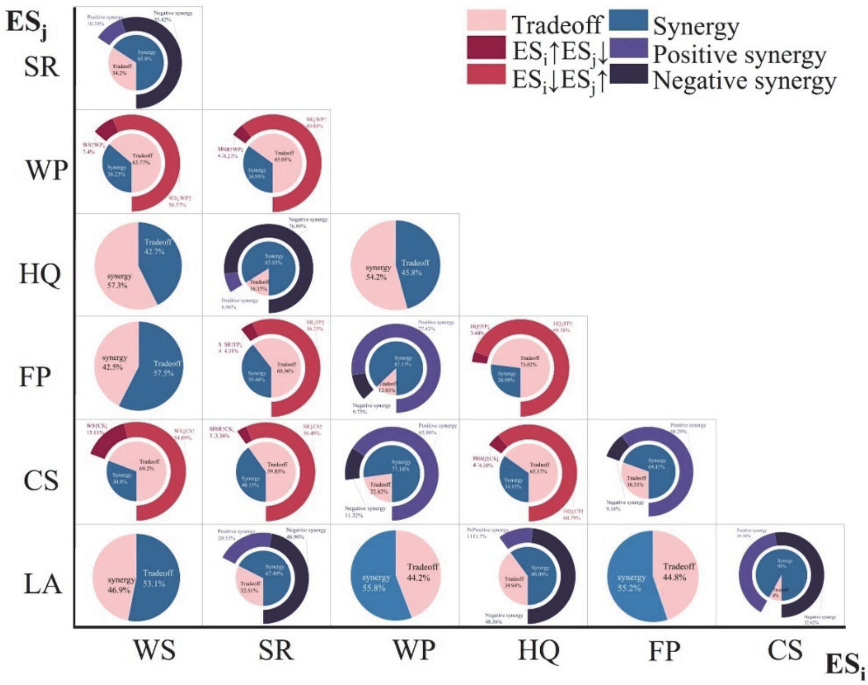

Figure 3. Pie chart of the spatial proportion of trade-offs/synergies between ES pairs

The trade-off relationships existed between the three service categories of support services, regulating services, and provisioning services, and did not involve cultural services. These trade-off relationships include mutual trade-offs within each service category, such as trade-offs between elements within provisioning services, WS vs. FP, and between elements within regulating services, SR vs. CS; as well as trade-offs across service categories, including trade-offs between provisioning services and supportive services, HQ vs. FP; regulating services vs. supportive services, HQ vs. CS; provisioning services vs. regulating services trade-offs between supply services, WS and CS, WS and WP, and SR and FP. The trade-offs arise as a result of reductions in FP in supply services, SR in regulating services, and HQ in support services.

Synergistic effects were mainly observed in the interactions between regulating services and supply services, support services, and cultural services, as well as in the interactions between support services and cultural services. In particular, synergies were also observed within regulating services. Among the eight synergistic pairs identified, five pairs showed negative synergistic effects, including SR-WS, SR-HQ, SR-LA, CS-LA, and HQ-LA. It can be seen that regulating services appear in multiple combinations, which reflects the centrality of regulating services in the ecosystem, and the weakening of regulating services may have negative knock-on effects on the other categories of services in the ecosystem. The synergistic effect between LA-CS service pairs was extremely significant, and the percentage of its spatial distribution was as high as 92%, indicating the broadness and consistency of the spatial distribution of this negative relationship. Positive synergies occur between FP, WP, and

CS, suggesting that these services are able to mutually reinforce each other through interactions and thus grow together.

3.2.2 Spatial-Temporal Patterns of Trade-Offs/Synergies Between ES Pairs

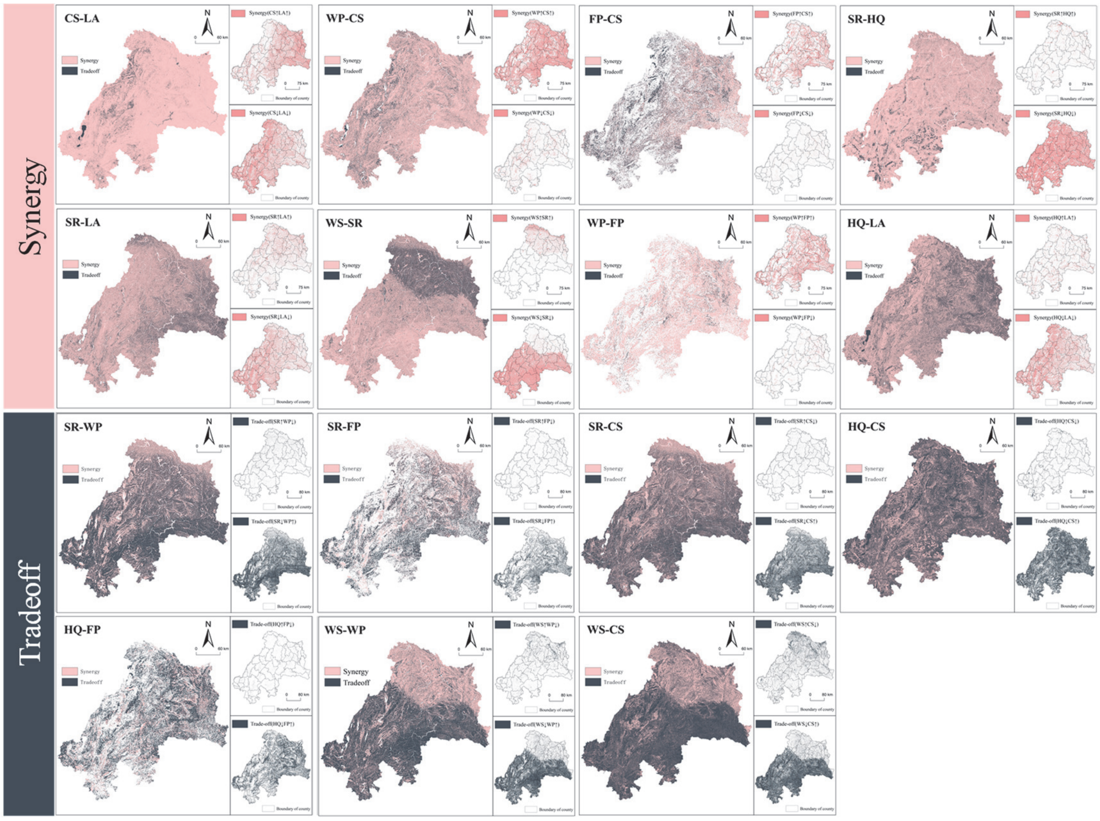

Figure 4. Spatial distribution pattern of trade-off synergistic relationship

Spatially (Figure 4), positive synergies were mainly concentrated in the north, while negative synergies were mostly seen in the south. synergies between CS-LA showed significantly different characteristics in the eastern and western parts of the watershed. In the eastern part of the basin, the positive synergy between CS and cultural landscape suggests that maintaining and improving the cultural landscape may have a positive effect on enhancing CS capacity. In the west, on the other hand, the synergistic relationship was negative, which may imply that some changes in the cultural landscape may weaken the CS capacity in the region. The synergistic effects of WP-CS, FP-CS, and WP-FP were generally positive, and the positive synergisms were more pronounced in the eastern region. This suggests a positive synergy between FP WP, and CS that is mutually reinforcing and strengthening in the eastern region. Generally, there is a negative synergistic trend between SR-HQ in the watershed, which implies that a decrease in SR efficacy may be accompanied by a degradation of HQ.WS-SR In the southern part of the watershed, the negative synergistic effect between the two may imply that a decrease in WS may be associated with a weakening of SR capacity, which may adversely affect the stability and quality of the soils.SR-LA, as well as HQ- LA, both of which showed negative synergies in the western part of the watershed, may indicate that degradation of cultural landscapes may be accompanied by a simultaneous decline in soil retention and HQ, which emphasizes the need to emphasize ecological preservation in the planning and development of cultural landscapes in order to avoid further negative impacts on soils and habitats.

At the watershed scale, a trade-off relationship between HQ-CS was prevalent, implying that the enhancement of CS capacity and the improvement of FP capacity may be accompanied by some negative impacts on HQ.WS-WP, WS-CS showed a trade-off effect in the southern part of the watershed, where the enhancement of WP and CS services was accompanied by a decline in WS services, implying that the pursuit of improving water quality and enhancement of ecosystem CS capacity may be accompanied by sacrificing or reducing WS. In particular, the trade-offs between SR-WP, SR-CS were more pronounced in the lower elevation regions of the south, suggesting that enhanced CS and improved water quality may need to be pursued at the expense of soil retention in these regions. In the eastern portion of the watershed, the trade-off between SR-FP and HQ-FP was more pronounced than in the western portion, suggesting that in the eastern portion of the watershed, enhanced FP may have greater negative impacts on ecosystem and HQ.

3.2.3 The Impact of LULC on the Trade-Offs/Synergies between ES pairs

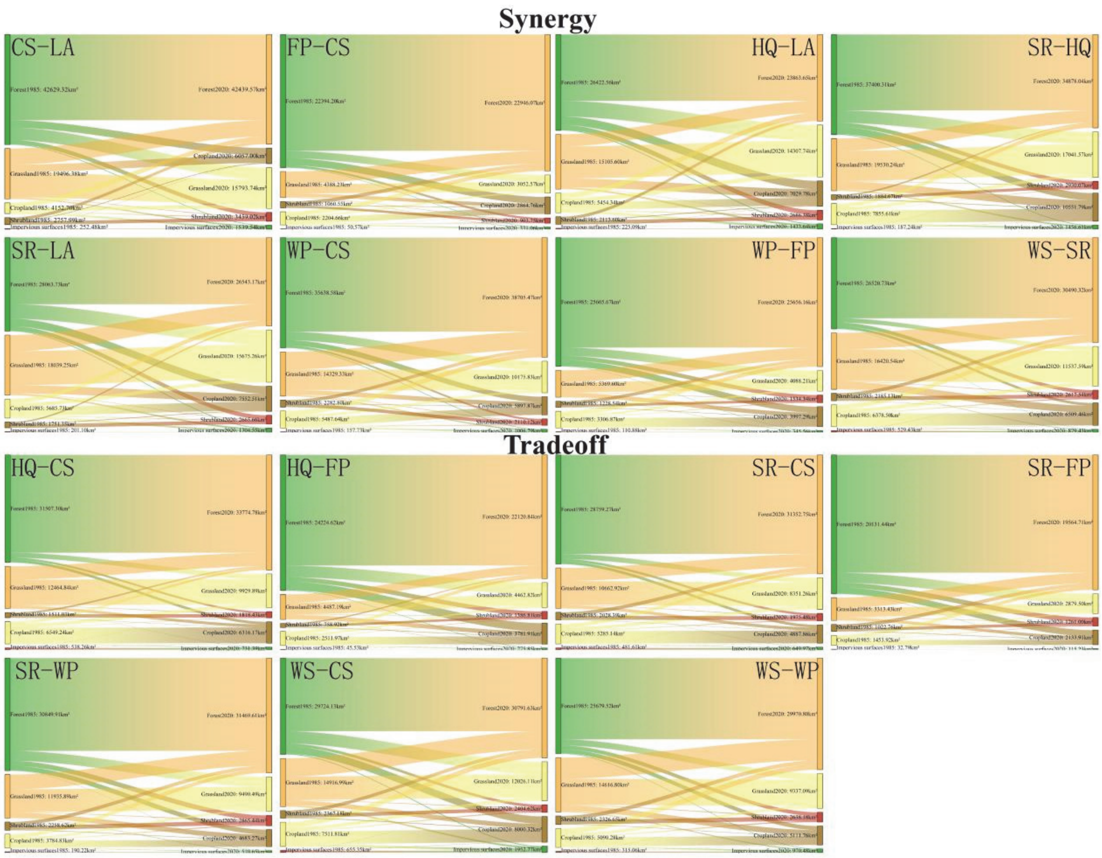

Figure 5. Land use changes in trade-offs/synergies between ES pairs

LULC is one of the key factors driving changes in ES functions. There are significant differences in the contribution of different land use types, such as forest land, grassland and construction land. We use land use transfer matrixes to quantify the impact of LULC on trade-offs/synergies between ES pairs (Figure 5).

CS-LA: LULC shows stable forest cover and increased shrubland, which are crucial for CS. However, the expansion of cropland and impervious surfaces negatively impacts CS and LA. Negative synergistic effects slightly outweigh positive ones in the watershed

HQ-LA: The reduction of forest, grassland, and shrubland areas, along with the increase in agricultural and built-up land, results in negative synergistic effects. This land use change diminishes cultural services and biodiversity by reducing natural landscapes.

SR-HQ: The reduction of forests and grasslands weakens natural barriers to soil erosion and biodiversity. Meanwhile, the increase in cropland and urbanization poses a dual threat to soil and HQ, leading to degradation and fragmentation.

SR-LA: The conversion of forests and grasslands to cropland and urban use significantly alters the natural landscape, affecting aesthetics and cultural values. Tillage activities and increased impervious surfaces enhance erosion risk and reduce soil conservation, showing negative synergies.

WP-CS: Increased forest cover enhances CS and WP services. Although decreased grassland has a minor negative impact, overall positive synergies are observed in improving carbon and water quality services.

WP-FP: Slight increases in forest area and significant decreases in grassland area, along with expanded cropland

and impervious surfaces, show positive synergies between WP and FP. Forests and cropland contribute to both services.

WS-SR: Significant grassland loss, increased shrubland, and slight expansions of cropland and impervious surfaces negatively impact and SR services. Reduced grassland leads to increased erosion risk and diminishes natural WP processes.

FP-CS: Increased forests and cropland, along with decreased grassland and shrubland areas, show positive synergy between FP and CS. Forest expansion enhances CS capacity, while cropland growth boosts agricultural productivity.

HQ-CS: Rapid urbanization threatens natural habitats and biodiversity but is offset by large-scale afforestation. This creates a trade-off between reduced HQ and increased CS services.

HQ-FP: Decreased forests and grasslands, along with increased shrubland, cropland, and impervious surfaces, lead to a decline in HQ and biodiversity. FP increases at the expense of ecosystem quality.

SR-CS: Increased forests, decreased grassland and shrubland, and significant impervious surface growth create a trade-off between enhanced CS and weakened SR services.

SR-FP: Decreased forests and grasslands, along with increased cropland and impervious surfaces, reduce SR services due to vegetation loss. Meanwhile, FP increases with cropland expansion.

SR-WP: Moderate forest increase, significant grassland loss, and expanded cropland and impervious surfaces show a complex interaction. The positive impact of forests on is offset by the negative effects of grassland loss.

WC-CS: Significant forest increase, grassland loss, and large impervious surface growth create a trade-off between enhanced CS and reduced water infiltration due to urbanization.

WS-WP: Increased forests, decreased grassland, stable cropland, and significant impervious surface expansion show a mixed impact. Forests enhance WP services, while grassland loss and impervious surfaces negatively affect WS.

4. Discussion

This paper investigates seven ESs (FP, WY, CS, SR, NDR, HQ, CL) in the NBPRB, which encompass provisioning, regulating, supporting, and cultural services. The study period spans from 1985 to 2020, a timeframe of 35 years. Long-term sequential research allows for the observation of the trends and periodic characteristics of ESs across different timescales, aiding researchers in identifying and analyzing the trade-offs and synergies among these services. Moreover, this paper proposes a new method that starts from the concept of trade-offs and synergies (where two ESs increase or decrease is considered synergy, and one increasing while the other decreases is considered trade-off) to identify trade-off and synergy effects spatially and further distinguish the types of trade-off and synergy actions. Finally, by utilizing the land use transition matrix, the study analyzes the impact of land use type conversions on the formation of trade-off/synergy relationships, providing useful and feasible suggestions for the management of regional ESs from the perspective of land use. However, there are some limitations and uncertainties that need further refinement.

Firstly, the mechanisms behind the trade-offs and synergies among ESs are complex, and this paper only analyzes the formation of the spatial pattern of trade-offs and synergies from the perspective of land use, with a lack of quantitative explanation from multiple dimensions (natural and anthropogenic factors). Secondly, the analysis from the perspective of land use treats the study area as a "homogeneous plane." However, due to the complex vertical development of the karst terrain, neglecting this dimension may affect the overall accuracy of the model. The karst region, as a typical binary landscape, with underground caves, rivers, and karst systems, also plays a crucial role. Future research will focus on exploring this aspect, striving for a more comprehensive understanding and depiction of ESs in the karst region. Despite some shortcomings, this study attempts to gain a deeper understanding of the trade-offs and synergies among ESs and to perform qualitative and quantitative analyses of them. This paper selects seven key ESs that cover provisioning, supporting, regulating, and cultural services. The primary objective of this study is to quantitatively assess the service function quantities of these services at five-year intervals from 1985 to 2020 and reveal their evolutionary trends through spatiotemporal analysis methods. The innovation of this research lies in proposing a new method to determine the direction of trade-off and synergy effects among ESs. This method not only identifies the trade-off and synergy relationships but also further distinguishes between positive and negative synergies in the synergy effect and clarifies which service reduction leads to the trade-off effect. Ultimately, by constructing a land use transition matrix, we analyzed the specific impact of land use changes on the formation of trade-off and synergy relationships among ESs. This quantitative approach provides a new perspective on understanding how land use decisions affect ESs and offers a scientific basis for developing more sustainable land management policies. Moreover, the data and methods mentioned in this study can also be applied to other regions of the world and have case study and reference significance for the ecological management of karst regions.

5. Conclusion

This study evaluated seven ESs in the NBPRB, analyzing their spatiotemporal evolution and trade-off/synergy relationships. Key findings include:

(1) Temporal trends showed an upward trend for FP and LA value, with WS and SR exhibiting variability. WP and CS remained stable, while HQ declined. Spatially, the south of NBPRB excelled in FP, attributed to its flat terrain and cultivated land, while the north had advantages in WS, CS, SR, LA, and HQ.

(2) Among the 21 service pairs, seven exhibited trade-offs, primarily involving supply, regulation, and support services, with cultural services not participating. Specific trade-offs included WS-FP, SR-CS, HQ-FP, HQ-CS, WS-CS, WS-WP, and SR-FP, driven by reductions in supply, regulation, and support services. Synergy relationships were mainly negative, associated with regulation services, such as SR-WS, SR-HQ, SR-LA, CS-LA, and HQ-LA. Positive synergies were observed between FP, WP, and CS, indicating mutual promotion.

(3) Spatially, positive synergies were prevalent in the basin's eastern part, while negative synergies were more common in the south. The eastern region showed a positive synergy between CS and LA, contrasting with the western region. The southern region experienced a decline in WS associated with reduced SR capacity, affecting soil quality. In the western region, LA degradation could lead to declines in CS and HQ. Trade-offs were particularly evident in the southern part, where improvements in WP and CS often came at the expense of WS. In low-altitude southern areas, enhancing CS and WP might require sacrificing SR. The SR-FP and HQ-FP trade-offs were more pronounced than in the western region, suggesting that increasing FP could negatively impact on SR and HQ.

(4) Land use transitions played different roles in forming trade-off and synergy relationships among ESs. Overall, forests played a central role in providing ESs, especially in CS. Even when other natural landscape areas decreased, the appropriate expansion of forests could maintain stable CS.

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