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Trade-offs and Synergies of Ecosystem Services in Karst Area of China Driven by Grain-for-Green Program

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Abstract: As an important means regulating the relationship between human and natural ecosystem, ecological restoration program plays a key role in restoring ecosystem functions. The Grain-for-Green Program (GFGP, One of the world's most ambitious ecosystem conservation set-aside programs aims to transfer farmland on steep slopes to forestland or grassland to increase vegetation coverage) has been widely implemented from 1999 to 2015 and exerted significant influence on land use and ecosystem services (ESs). In this study, three ecological models (InVEST, RUSLE, and CASA) were used to accurately calculate the three key types of ESs, water yield (WY), soil conservation (SC), and net primary production (NPP) in Karst area of southwestern China from 1982 to 2015. The impact of GFGP on ESs and trade-offs was analyzed. It provides practical guidance in carrying out ecological regulation in Karst area of China under global climate change. Results showed that ESs and trade-offs had changed dramatically driven by GFGP . In detail, temporally, SC and NPP exhibited an increasing trend, while WY exhibited a decreasing trend. Spatially, SC basically decreased from west to east; NPP basically increased from north to south; WY basically increased from west to east; NPP and SC, SC and WY developed in the direction of trade-offs driven by the GFGP, while NPP and WY developed in the direction of synergy. Therefore, future ecosystem management and restoration policy-making should consider trade-offs of ESs so as to achieve sustainable provision of ESs.

Keywords: ecosystem service; trade-off and synergy; Grain-for-Green Program; partial correlation analysis; Karst area; China

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1 Introduction

Ecosystem services (ESs) are the resource and environmental basis for the survival and sustainable development of human society (Constanza et al., 1997; Daily, 1997; Fu et al., 2009). Complex trade-off and synergy relationships exist between multiple ESs (Rodríguez et al., 2006; Firbank et al., 2013; Yang et al., 2015). Under the background of global climate change, human's unconscionable exploitation and utilization have led to global environmental destruction and ecological degradation (Foley et al., 2005). Loss of biodiversity and decreased provision of ESs impair ecosystem health and resilience, which in turn threaten human well-being and create new disturbances to the relationships between ESs (Parr et al., 2003). Vegetation restoration program aims to initiate or promote the restoration process of degraded ecosystems through human intervention,

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which is an important means to cope with ecological degradation problems and to improve ESs (Zhang Kun et al., 2016). In order to improve ecological environment and promote human well-being, the Chinese government has launched large-scale ecological restoration program such as the Grain-for-Green Program (GFGP) (Lü et al., 2012). GFGP aims to transfer farmland on steep slopes to forestland or grassland to increase vegetation coverage and reduce soil erosion, and thus to restore regional ecosystems. Therefore, assessing ESs driven by ecological programs could reveal benefits and deficiencies of ecological policy and provide guidance for future ecosystem management and implementation of restoration programs (Tallis et al., 2008).

The comprehensive analysis of ESs trade-offs is the basis and core of ecological regulation, which has become the frontier and hotspot of international ecology, geography and other disciplines (Lee et al., 2016; Hou et al., 2017). In recent years, the research on ESs trade-offs has attracted wide attention, and has made great progress (Dai et al., 2015). For example, Cord et al. (2017) systematically analyzed trade-offs and synergies of ESs, and identified four main study objectives as well as three cross-cutting themes that deserve more research attention. Due to the high complexity of trade-offs between ESs, research on ESs integration at regional scale has become a new trend (Fu and Yu, 2016). ESs trade-offs and its driving mechanisms are new research hotspots. For example, Feng et al. (2017) used redundancy analysis to clarify the effects of environmental factors on ESs and trade-offs. It was concluded that environmental factors have complex influence on trade-offs and this influence has scale dependence. Therefore, quantifying and simulating spatial-temporal characteristics of ESs trade-offs and synergies is an important part of ESs trade-offs (Dai et al., 2016). The current research mainly manifests in the following aspects: temporally, most of previous studies only considered trade-offs and synergies of ESs at two time nodes (Tomscha and Gergel, 2016; Wang Pengtao et al., 2017), and concentrated in between 2000 to 2015; spatially, scholars have carried out a variety of researches on global, intercontinental, national, regional and watershed scales. However, the geological structure of Karst watershed is complex and significant, research on Karst watershed ESs trade-offs and synergics relationship is relatively rare. Wang et al. (2018) selected five key types of ESs including water conservation, soil conservation, nutrient retention, carbon storage, and biodiversity to analyze and assess trade-offs among different ESs in the Shiyang Rvier Basin from 2005 to 2015 at the whole and sub-basin scales respectively. Pan and Li (2017) estimated four key types of ESs including food supply, water retention, soil conservation, and carbon storage to study trade-offs and synergies among different ESs in arid inland river basin in 2000 and 2010 at the regional and county scales. All results showed that trade-offs relationship of ESs has a certain scale effect. Therefore, it is urgent to carry out research between ESs in long time series, which can effectively improve the reliability of trade-offs results and avoid misjudging due to unexpected factors and time-lagged in the long-term evolution of ecosystems (Dallimer et al., 2015).

Three key restoration projects have been launched in Karst area of China. In details, the Yangtze River and Zhujiang River Shelter Forest Project was launched in 1989; The Natural Forest Protection Project was initiated in 1988; GFGP was initiated in 2000. However, GFGP is regarded as the world's largest ecological restoration program in terms of scale and investment. Therefore, the study mainly considered the impact of the GFGP on ESs trade-offs (Uchida et al., 2005; Chen et al., 2009). GFGP aims to transfer farmland on steep slopes to forestland or grassland to increase vegetation coverage and reduce soil erosion, and thus to restore regional ecosystems (Li et al., 2016; Zhang et al., 2016). There are complex trade-offs among multiple ESs, and the implementation of ecological restoration program may result in different ESs changing in opposite directions at different scales (Bennett et al., 2009). Studies reveal that by increasing vegetation coverage and decreasing ruoff and soil erosion, the GFGP can improve the ESs ability of maintaining soil fertility (Ma and Fan, 2005; Long et al., 2006; Xu et al., 2006).

As a whole, the result of correlation analysis among ESs in different regions has not been unified (Mouchet et al., 2014), especially for some regions where human-land conflicts are prominent, the relationship between multiple ESs has not been clarified (Wu et al., 2017). The Karst area is a typically eco-fragile and sensitive area for global climate change (Tian et al, 2016), which also is a typical research area for ESs trade-offs. Through many years' efforts, the GFGP has improved ESs and ecological benefits, which provides a scientific basis for the study of the relationship between ESs at the large scale. Therefore, this study accurately calculated three key types of ESs including water yield (WY), soil conservation (SC), and net primary productivity (NPP) from 1982 to 2015 in Karst area of China based on multi-source data and models. What's more, the trade-offs relationship of ESs in different land use types were explored. Finally, the spatial-temporal changes of ESs trade-offs were discussed in GFGP area driven by the ecological program. Understanding how GFGP alters ESs could help to provide implication for future ecosystem management and GFGP implementation (Lü et al., 2012).

2 Materials and Methods

2.1 Study area

The Karst area is located in the southwestern China (20°13′24″N–34°18′3″N, 97°20′35″E–117°10′19″E), including the Sichuan, Chongqing, Hubei, Hunan, Yunnan, Guizhou, Guangzhou, and Guangxi (Fig. 1). The study area is 1.93 × 10^6 km^2. The geomorphic types are mainly the Tibetan Plateau, the Yun-Gui Plateau, the Sichuan Basin, middle-lower Yangtze plains and southeast hills. The study area has strong landscape heterogeneity, special geological background, strong karstification, and many kinds of mountainous disasters such as collapse, landslides, and debris flow. The ecological environment capacity in this region is low, and the background of ecological environment is very fragile. Sharp human-land conflicts have led to increasingly serious soil erosion, vegetation degradation, and rocky desertification (Zhang et al., 2011). It has greatly restricted the ecological protection and sustainable development in this region. Land-use data of 2000 and 2015 are used to detect GFGP area and generate land-use transformation matrix.

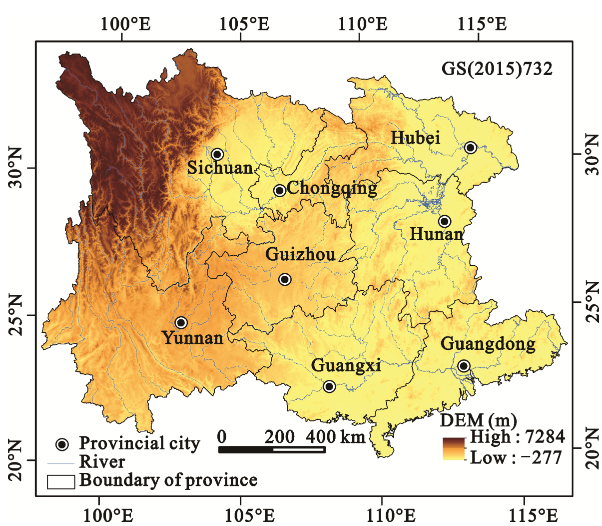

Fig. 1 Location, terrain and watersheds of the study area

2.2 Quantifying ecosystem service

2.2.1 Net Primary Production (NPP)

In this study, NPP (net primary productivity) is estimated by the process-based Carnegie-Ames-Stanford Approach (CASA) (Potter et al., 1993). The formulas for calculating NPP are expressed below:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \tag{1}$$

$$APAR(x,t) = SOL(x,t) \times 0.5 \times FPAR(x,t) \tag{2}$$

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max} \tag{3}$$

where $NPP(x, t)$ is NPP in the geographic coordinate of given location x and time t (g C/(m^2·yr)); $APAR(x, t)$ is the photosynthetically active radiation (MJ/m^2); ε(x, t) is the actual light use efficiency (g C/MJ); $SOL(x, t)$ is the total solar radiation (MJ/m^2); the coefficient of 0.5 is the ratio of the effective solar radiation against the total solar radiation (wave length ranges 0.38–0.78 μm); $FPAR(x, t)$ is the fraction of photosynthetically active radiation absorbed by vegetation canopy; $T_{\varepsilon 1}(x, t)$ and $T_{\varepsilon 2}(x, t)$ are temperature stress coefficients, and $W_{\varepsilon}(x, t)$ is the water stress coefficient. ε_{max} is the maximal light use efficiency of the specific biome under an ideal condition.

2.2.2 Soil conservation

In this study, SC (soil conservation) is evaluated by Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991). The formulas for calculating SC are expressed below:

$$SC = Ap - Ar = R \times K \times L \times S \times (1 - C \times P) \tag{4}$$

$$R = \sum_{i=1}^{12} 1.735 \times 10^{1.5 \times \lg\left[\frac{p_i^2}{p} - 0.8188\right]} \tag{5}$$

$$K = \{0.2 + 0.3\exp[-0.0256SAN(1 - \frac{SIL}{100})]\} \times (\frac{SIL}{CLA + SIL})^{0.3} \times [1 - \frac{0.25TOC}{TOC + \exp(3.72 - 2.95TOC)}] \times [1 - \frac{0.7SNI}{SNI + \exp(22.9SNI - 5.51)}] \tag{6}$$

$$L = (\lambda / 22.1)^m \tag{7}$$

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 5^\circ \\ 16.8\sin\theta - 0.50 & 5^\circ \le \theta \le 10^\circ \\ 21.9\sin\theta - 0.96 & \theta \ge 10^\circ \end{cases} \tag{8}$$

$$C = \begin{cases} 1 & f = 0 \\ 0.6508 - 0.3436\lg f & 0 < f \le 78.3\% \\ 0 & f > 78.3\% \end{cases} \tag{9}$$

$$f = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{10}$$

$$P = 0.2 + 0.03\alpha \tag{11}$$

where SC represents the average annual soil conservation (t/(ha·yr)); Ap represents the potential soil erosion (t/(ha·yr)); Ar represents the actual soil erosion (t/(ha·yr)); R represents the rainfall-runoff erosivity (MJ·mm/(ha·h·yr)), which was estimated by monthly precipitation (p_i) and annual precipitation (p); K represents the soil erodibility factor (t·h/(MJ·mm)), which was estimated by the Erosion Productivity Impact Calculator (EPIC) using the soil clay (CLA), silt (SIL), sand (SAN), $SNI = 1 - SAN/100$, and total organic carbon (TOC); L represents the slope length factor, which was estimated by slope length (λ) and slope length index (m); S represents the gradient factor, which was estimated by slope (θ) extracted from DEM; C represents crop/vegetation management factor, and f was vegetation coverage, which was calculated by $NDVI$; P represents support practice factor adopting slope-based Wener's method (Lufafa et al., 2003), where α is the percentile slope gradient.

2.2.3 Water yield

In this study, WY (water yield) is modeling by Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) (Shaper et al., 2016). Based on the water balance method, the annual WY is calculated as:

$$WY(x) = (1 - \frac{AET(x)}{P(x)}) \times P(x) \tag{12}$$

$$\frac{AET(x)}{P(x)} = 1 + \frac{PET(x)}{P(x)} - \left[1 + (\frac{PET(x)}{P(x)})^w\right]^{1/w} \tag{13}$$

$$PET(x) = K_c(x) \times ET(x) \tag{14}$$

$$w(x) = \frac{AWC(x) \times Z}{P(x)} + 1.25 \tag{15}$$

where $WY(x)$ is the annual water yield (mm) on pixel x; $AET(x)$ is the actual annual evapotranspiration (mm); $P(x)$ is the annual precipitation (mm); $PET(x)$ is the potential evapotranspiration (mm); $ET_o(x)$ is the reference evapotranspiration, which mainly reflects local climatic conditions; $K_c(x)$ is the plant (vegetation) evapotranspiration coefficient, which is largely determined by the vegetation characteristics of the LUCC; $w(x)$ is an empirical parameter. $AWC(x)$ is the plant available water content, which is defined by the soil texture and effective rooting depth. Z is the Zhang coefficient (Zhang et al., 2001; Zhang et al., 2004).

2.3 Quantifying trade-offs and synergies of ecosystem services

The geographic system is a complex system composed of multiple elements. The changes of any element in the system will inevitably affect other elements. Therefore, the change of one service is affected not only by other services, but also by climate and LUCC (Su et al., 2012). In order to accurately analyze the impact of ecological restoration program on ESs, it is necessary to firstly eliminate the impacts of climate change, and then analyze the relationship between ESs. This statistical analysis method is called partial correlation analysis, which can clearly explain the relationship among ESs and reflect spatial heterogeneity. We consider that the annual precipitation as an important climatic factor has a significant impact on WY, SC, and NPP. So we controlled annual precipitation and respectively calculated the partial correlation coefficients between WY and NPP, WY and SC, NPP and SC (Li et al., 2017). The formulas are as follows:

$$r_{xy(ij)} = \frac{\sum_{n=1}^{n}(x_{n(ij)} - \overline{x_{(ij)}})(y_{n(ij)} - \overline{y_{(ij)}})}{\sqrt{\sum_{n=1}^{n}(x_{n(ij)} - \overline{x_{(ij)}})^2 \sum_{n=1}^{n}(y_{n(ij)} - \overline{y_{(ij)}})^2}} \tag{16}$$

$$r_{xy \cdot z(ij)} = \frac{r_{xy(ij)} - r_{xz(ij)} r_{yz(ij)}}{\sqrt{(1 - {r_{xz(ij)}}^2)(1 - {r_{yz(ij)}}^2)}} \tag{17}$$

where i, j respectively represent the row and column numbers in raster image; n represents the time series, and $n = 34$ in this study; $r_{xy(ij)}$ represents the correlation coefficient of x and y; similarly, $r_{xz(ij)}$ and $r_{yz(ij)}$ can be obtained; $r_{xy \cdot z(ij)}$ represents the partial correlation coefficient of x and y when the variable z (annual precipitation) remains unchanged.

2.4 Data collection and processing

The data used in this paper mainly included digital elevation model (DEM), meteorological data, land use and land cover data, and NDVI. Among these data, DEM data was provided by the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). Meteorological data mainly included solar radiation, precipitation, temperature, which were collected from Karst area and its surrounding stations from the China Meteorological Data Sharing Service System (http://data. cma.cn/). Besides, the precipitation and temperature data were interpolated by the professional meteorological interpolation software ANUSPLIN, with a spatial resolution of 8 km. Land use and land cover data in 1980, 1990, 2000, 2010, and 2015 were provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www. resdc.cn/). The NDVI data was based on the GIMMS global dataset produced by the GLCF (Global Land Cover Facility) research group of the University of Maryland, USA (https://ecocast.arc. nasa.gov). The 15-day GIMMS NDVI was aggregated into monthly values using an MVC approach, and then we calculated the annual mean NDVI, with a spatial resolution of 8 km.

3 Results

3.1 Land use and land cover changes

Land use and land cover changes not only induces considerable changes in surface structure, but also greatly affects the regional climate (Carlson et al., 2000; Wu et al., 2014), hydrology and water resources (Weber et al., 2001; Sterling et al., 2012), soil erosion and accumulation (Islam and Weil, 2000), biodiversity (Crist et al., 2000), carbon cycle (Tian et al., 2012) and biogeochemical cycle. The land use changed greatly in Karst area from 1982 to 2015 (Table 1). The grassland and farmland obviously decreased by 7.13% and 2.52%, respectively. Among them, the grassland keeps decreasing in 1982–2000 and 2010–2015, while increased in 2000–2010 driven by the GFGP. The farmland keeps decreasing from 1982 to 2010, while increased in 2010–2015. The forestland and built-up land obviously increased by 7.21% and 1.63%, respectively during 1982–2015. The continuous increase of built-up land indicated that the urbanization process is accelerating. The spatial distribution of land use change and slope statistics of GFGP area during 2000–2015 were obtained in Fig. 2. It can be seen that the GFGP area is mainly distributed in the central northerly region of the Karst area. Besides, the slope degree ranging of GFGP area mainly distributes in 2°–6° and 6°–15°, accounting for 27.42% and 34.43% of the total GFGP area.

3.2 Changes in ecosystem services

Land use change and climate change together drive the change of ESs. SC and NPP showed an upward trend, while WY showed a downward trend (Fig. 3). In detail, the annual average of SC was 3436.5 t/(ha·yr), with the minimum in 2011 (2626.3 t/(ha·yr)) and the maximum in 1998 (4762.79 t/(ha·yr)), and increasing at a rate of 3.71 t/(ha·yr). Temporally, SC showed a fluctuating growth trend in 1982–1998, and with a decreasing trend in 1998–2011, and a growth trend after 2011. The annual average of WY was 185.16 mm, with the minimum in 2011 (–57.02 mm) and the maximum in 1996 (404.45 mm), and decreasing at a rate of 0.83 mm/yr. In terms of time series, WY showed a fluctuating growth trend in 1984–1996, and with a decreasing trend in 1996–2011, and a growth trend after 2011. The annual average of NPP was 735.15 g C/(m^2·yr), with the minimum in 1982 (683.34 g C/(m^2·yr)) and the maximum in 2015 (804.4 g C/(m^2·yr)), and increasing at a rate of 1.95 g C/(m^2·yr).

Table 1 Changes in land use and land cover (LUCC) during 1982–2015 (%)

Year	Forestland	Grassland	Farmland	Wetland	Built-up land
1982	51.60	17.82	26.58	1.67	1.12
1990	59.12	10.82	25.08	2.38	1.57
2000	59.26	10.76	24.67	2.50	1.79
2010	59.66	10.81	23.64	2.55	2.34
2015	58.81	10.69	24.05	2.65	2.75
1982–1990	↑7.52	↓7.01	↓1.50	↑0.72	↑0.45
1990–2000	↑0.14	↓0.06	↓0.40	↑0.12	↑0.22
2000–2010	↑0.40	↑0.40	↓1.04	↑0.04	↑0.55
2010–2015	↓0.85	↓0.12	↑0.42	↑0.11	↑0.41
1982–2015	↑7.21	↓7.13	↓2.52	↑0.99	↑1.63

Notes: ↑ represents increasing trend;↓ represents decreasing trend

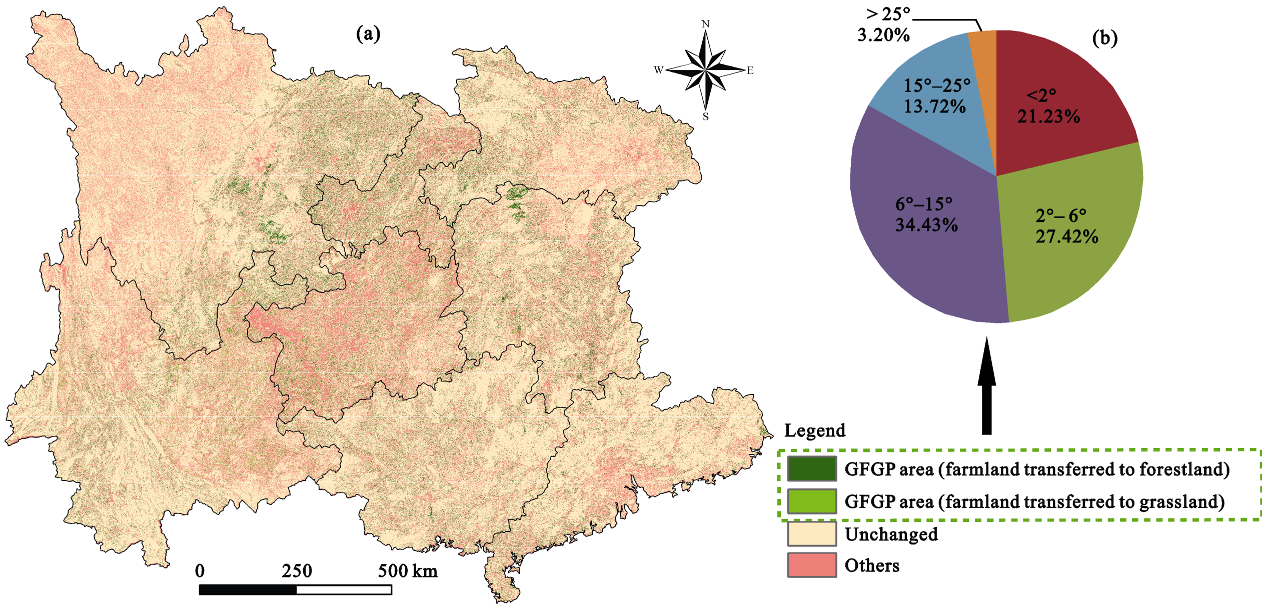

Fig. 2 Land use changes of Karst area in China during 2000–2015 (a) and slope distribution of GFGP area (b)

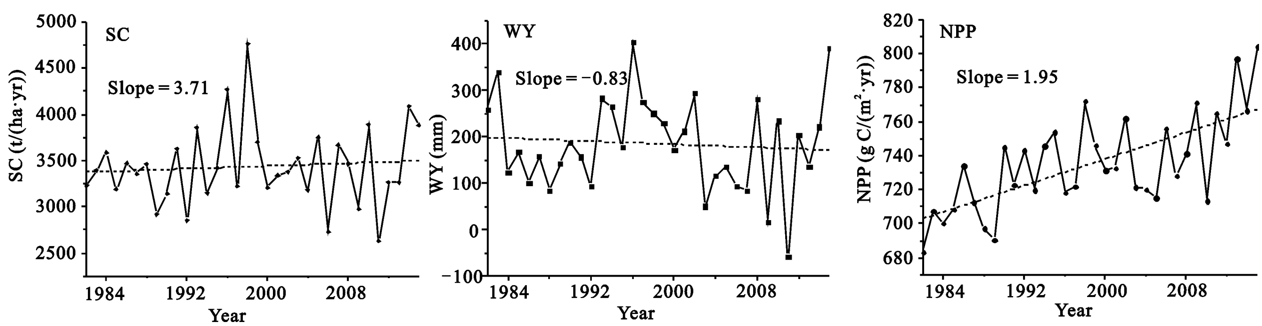

Fig. 3 The temporal changes of soil conservation (SC), NPP and water yield (WY) in Karst area of China from 1982 to 2015

The spatial distribution pattern of SC basically decreased from west to east (Fig. 4). The SC in the Northwestern Tibetan Plateau and Southwestern Yun-Gui Plateau is high, where the SC is higher than 5000 t/(ha·yr). The low-value areas of SC are mainly distributed in Sichuan Basin, the Yangtze plain and the hilly of southeast China, where the SC is generally lower than 1000 t/(ha·yr). Combined with the boundary of GFGP, we can find that the annual average of SC was 2740.86 t/(ha·yr) in 1982–2000 and 2676.96 t/(ha·yr) in 2000–2015. Besides, in GFGP area, SC increased at a rate of 19.59 t/(ha·yr) in 1982–2000 and 17.75 t/(ha·yr) in 2000–2015.

The spatial distribution of WY basically increased from west to east (Fig. 4). The WY in Sichuan and Yunnan provinces of western Karst area is generally lower than 600 mm, while the WY in Hunan, Hubei, Chongqing and Guizhou provinces of northeastern Karst area is higher than 600 mm. The WY in Guangdong and Guangxi of southeastern Karst area has changed greatly, where the WY is generally less than 0 in 1982 and 2000 but higher than 900 mm in 2015. Combined with the boundary of GFGP, we can find that the annual average of WY was 196.13 mm in 1982–2000 and 138.19 mm in 2000–2015. In GFGP area, WY increased at a rate of 3.31 mm/yr in 1982–2000 and 2.11 mm/yr in 2000–2015.

The spatial distribution of NPP basically increased from north to south (Fig. 4). The NPP in southwestern Yunnan and Guangdong provinces is generally higher than 1100 g C/(m^2·yr). In terms of annual change, the NPP in northern Karst area is generally lower than 500 g C/(m^2·yr) in 1982 but higher than 500 g C/(m^2·yr) in 2015. Combined with the boundary of GFGP, we

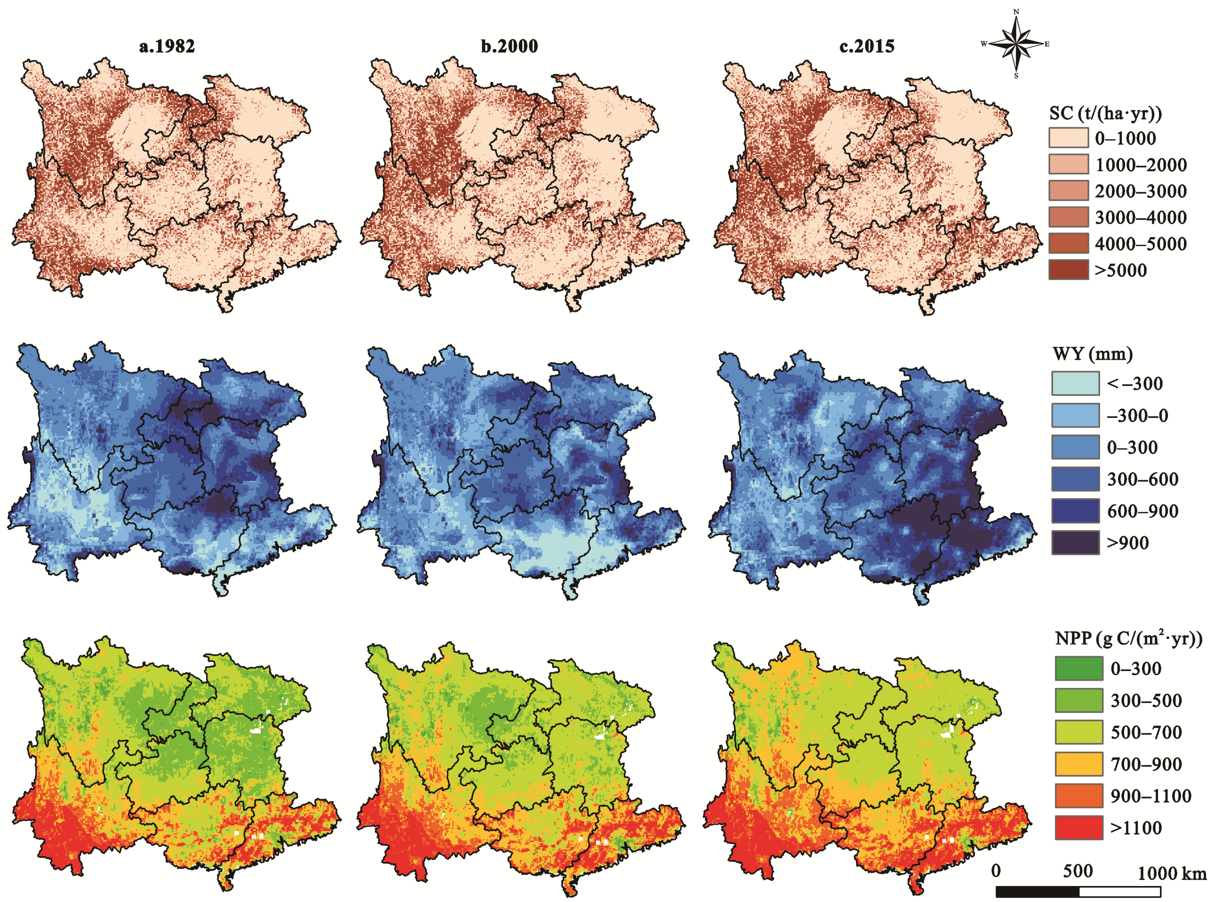

Fig. 4 Spatial distribution of ecosystem services in Karst area of China in 1982, 2000, and 2015

can find that the annual average of NPP was 694.95 g C/(m^2·yr) in 1982–2000 and 720.61 g C/(m^2·yr) in 2000–2015. Besides, in GFGP area, NPP increased at a rate of 3.31 g C/(m^2·yr) in 1982–2000 and 4 g C/(m^2·yr) in 2000–2015.

3.3 Relationship between ESs in different land use types

In the same land use type, the existence modes of different ESs are in different forms. The same ESs also varies at different land use types. In this paper, the mean values of different ESs in different land types including forestland, grassland, and farmland were obtained. Given that the three ESs differ in magnitude orders, this paper used the relationship among the different ESs as the key research point to make the result real, analyzable and visible. In this paper, based on land use types, the SC, WY, and NPP were normalized to 0–1. Using ggplot2 to process and visualize the data, and then the polar coordinate map were produced, which was also known as a rose map. It can be seen from Fig. 5 that for same land use type, NPP and SC in forestland and grassland are the higher, while WY is lower. For different land use types, the SC basically showed as follows: forestland>grassland>farmland. The NPP in forestland is the highest. For different years, the NPP firstly increased and then decreased and finally increased in the three land use types. In the forestland, the SC keeps increasing, while the WY firstly decreased and then increased. In the grassland, the SC and WY firstly decreased and then increased, decreased and finally increased. In the farmland, the SC and WY firstly decreased and then increased.

On the whole, The NPP and WY in the forestland changed in the opposite way, while the SC keeps increasing. In the forestland and farmland, the SC and WY changed in the same way, while the SC and NPP, WY and NPP changed in the opposite way.

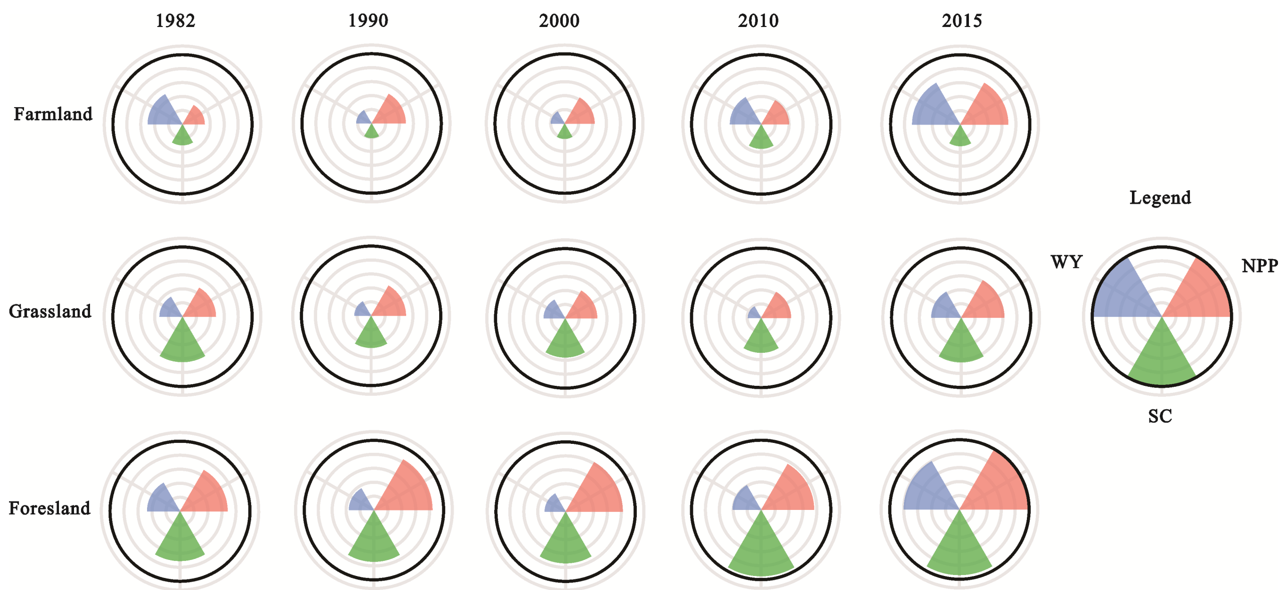

Fig. 5 Rose map of ecosystem services in Karst area by land-use type from 1982 to 2015

3.4 Trade-offs and synergies analysis of ESs in GFGP region

Land use change and climate change together drive the change of region ESs. Therefore, in order to accurately analyze the impact of ecological restoration program on trade-offs and synergies of ESs, it is necessary to eliminate the impacts of climate change on ESs. In this paper, based on the MATLAB software platform, the partial correlation coefficient of three types of ESs in Karst area during 1982–2000 and 2000–2015 were calculated by controlling annual precipitation. The results were t-tested and divided into seven grades: strong synergies ($r > 0$, $0.01 < P < 0.05$); medium synergies ($r > 0$, $0.05 < P < 0.1$); weak synergies ($r > 0$, $P > 0.1$); strong trade-offs ($r < 0$, $0.01 < P < 0.05$); medium trade-offs ($r < 0$, $0.05 < P < 0.1$); weak trade-offs ($r < 0$, $P > 0.1$); No relationship ($r = 0$). Fig. 6 showed the spatial pattern of trade-offs and synergies between multiple ESs in the study area.

The trade-offs and synergies between NPP and SC in 1982–2000 and 2000–2015 are shown in Figs. 6a1 and 6a2. It can be seen that the relationship between NPP and SC were mainly synergies in 1982–2000. In details, the pixel proportion of synergies was 51.68%, but trade-offs accounted for 40.15%. However, the relationship between NPP and SC were mainly trade-offs in 2000–2015. In details, the pixel proportion of synergies was 35.48%, but trade-offs accounted for 56.35%. Spatially, the trade-offs were mainly distributed in Western Karst area including Yunnan, Sichuan and Guangdong provinces in 1982–2000. While the trade-offs spatially shifted eastward in 2000–2015, mainly in Guangdong, Guangxi, Hunan, Hubei provinces. The statistics of trade-offs and synergies between NPP and SC in GFGP area are shown in Fig.7a. It can be seen that the proportion of synergies decreased significantly in 2000–2015, while the proportion of trade-offs increased obviously. In other words, NPP and SC developed toward trade-offs driven by GFGP.

The trade-offs and synergies between NPP and WY in 1982–2000 and 2000–2015 are shown in Figs. 6b1 and 6b2. It can be seen that NPP and WY presented as trade-offs in 1982–2000 and 2000–2015. But the proportion of strong trade-offs in 1982–2000 was significantly higher than those in 2000–2015. In details, strong trade-offs accounted for 32.79% in 1982–2000 and 17.38% in 2000–2015. Spatially, the strong trade-offs were mainly distributed in Northern Karst area including Sichuan, Chongqing, and Hubei and Guizhou provinces in 1982–2000. While in 2000–2015 the strong trade-offs was mainly distributed in Southwestern Guizhou, Eastern Hubei and Eastern Yunnan. The statistics of trade-offs and synergies between NPP and WY in GFGP area are shown in Fig. 7b. It can be seen that the proportion of synergies increased significantly, the proportion of strong trade-offs decreased obviously. In other words, NPP and WY developed toward synergies driven by GFGP.

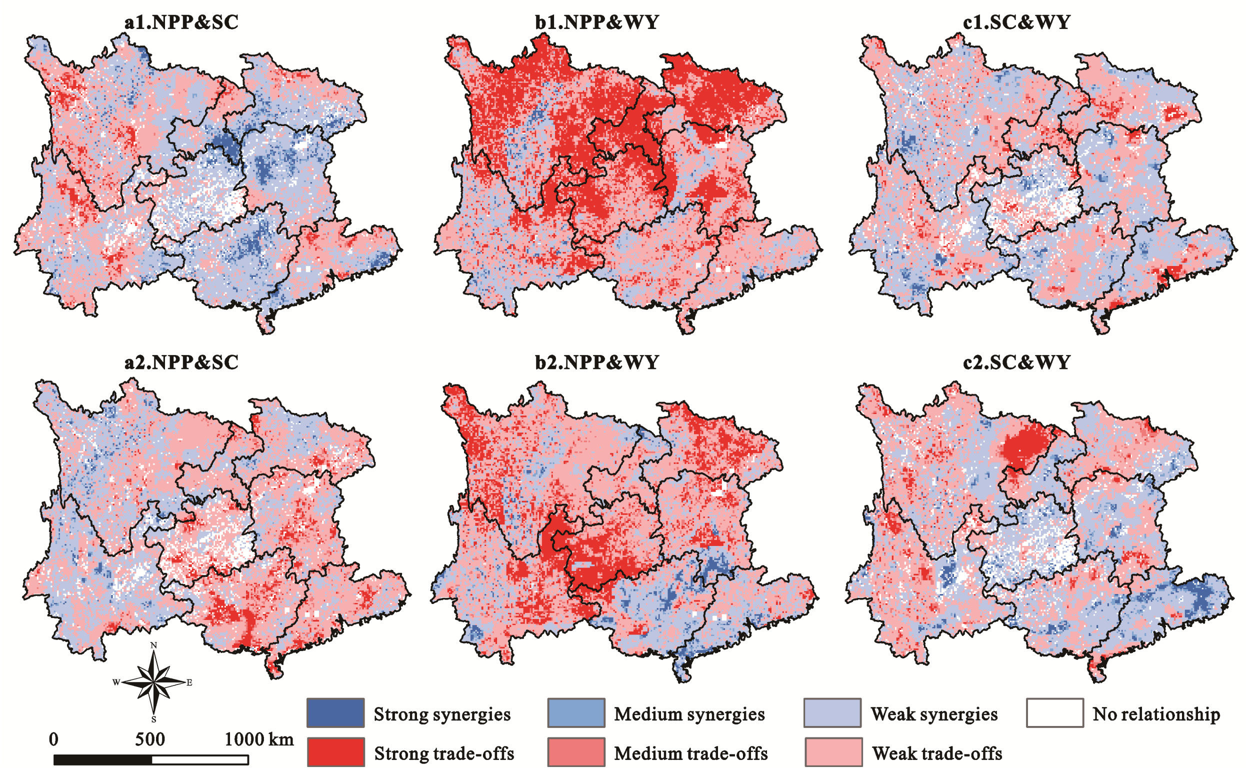

Fig. 6 The spatial patterns of pairwise ecosystem services interactions in Karst area from 1982 to 2000 and from 2000 to 2015. a1, b1 and c1 represent pairwise ecosystem services interactions from 1982 to 2000; a2, b2 and c2 represent pairwise ecosystems services interactions from 2000 to 2015

The trade-offs and synergies between SC and WY in 1982–2000 and 2000–2015 are shown in Fig. 6c1 and 6c2. It can be seen that the relationship between SC and WY were mainly synergies in 1982–2000. In details, the pixel proportion of synergies was 46.40%, but trade-offs accounted for 45.79%. However, the relationship between SC and WY were mainly trade-offs in 2000–2015. In details, the pixel proportion of synergies was 45.47%, but trade-offs accounted for 46.74%. Spatially, the distribution of trade-offs and synergies was scattered in 1982–2000, and there was no obvious clustering characteristics. The trade-offs were mainly distributed in Western Karst area in 2000–2015 among which strong trade-offs mainly distributed in eastern Sichuan, while synergies were mainly distributed in Southeastern Karst area. The statistics of trade-offs and synergies between SC and WY in GFGP area are shown in Fig. 7c. It can be seen that the proportion of the strong trade-offs in 2000–2015 was significantly higher than that in 1982–2000. In other words, SC and WY developed toward trade-offs driven by GFGP.

4 Discussion

4.1 Effects of climate change and GFGP on ecosystem services

Ma (2005) divided the main factors affecting the regional ESs into climate factors and changes on land use patterns. Precipitation and temperature are the main climate factors that affect water yield, soil conservation, and NPP. The 5th assessment report of the Intergovernmental Panel on Climate change (IPCC) clearly points out that the global average surface temperature increased by 0.85℃ from 1980 to 2012, and the temperature will continue to rise in the 21st century. Climate change affects the structure, composition and function of ecosystem, which consequently affects the supply of ESs. The precipitation and temperature of Karst area from 1982 to 2015 were analyzed (Fig. 8). Precipitation was found to increase annually with an average of 0.82 mm and temperature was found to increase annually by an average of 0.04℃. So we can draw a conclusion that the regional climate condition of the Karst area has

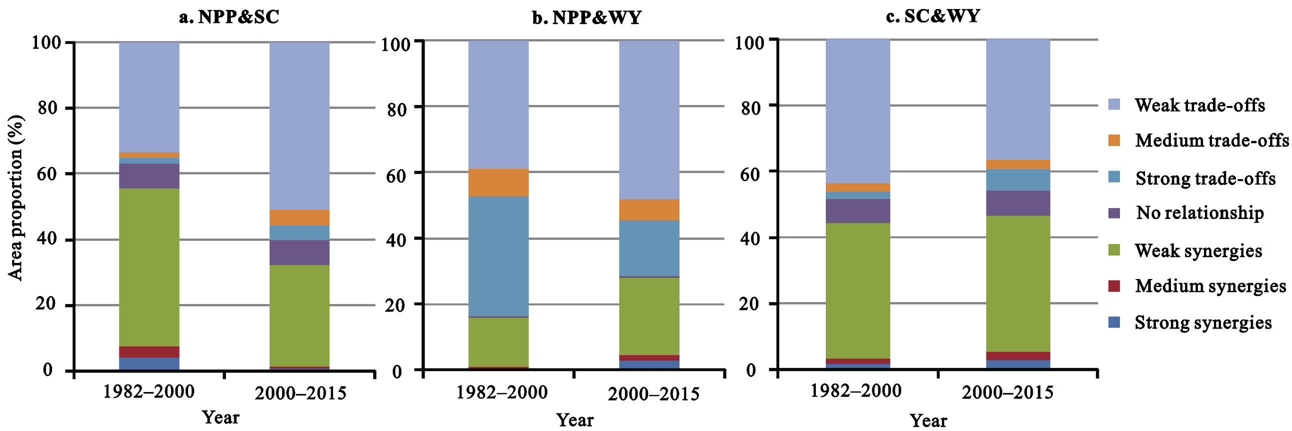

Fig. 7 The area proportion of pairwise ecosystem services interactions in the GFGP (Grain-for-Green program) area from 1982 to 2015

exhibited a warming and wetting trend. In detail, precipitation determines erosivity, namely the R factor in RUSLE. Therefore, high precipitation increases the quantity of soil conservation. Besides, high precipitation increases water yield, but high temperature increases evaporation of the canopy and decreases water yield. NPP is constrained by actual light use efficiency, which is reflected in the water stress and temperature stress coefficients part of CASA. Ecological restoration programs affect regional ESs mainly by changing the land use and land coverage. At the end of the 20th century, a series of ecological environmental problems occurred (e.g., land deterioration, water and soil loss, and vegetation deterioration) because of unreasonable land utilization. To protect and restore impaired ecosystems, the Chinese government performed many vegetable restoration plans, including the GFGP, Natural Forest Protection Project, and the Sloping Land Conversion Project (Uchida et al., 2005; Bennett, 2008; Yin et al., 2010). GFGP, which started in 1999, is an ecological project with the strongest policy, highest investment amount, widest coverage area and highest public participation. GFGP aims to transfer farmland on steep slopes to forestland or grassland to increase vegetation and reduce soil erosion, and thus to restore regional ecosystems (Li et al., 2016; Zhang Baoqing et al., 2016). At present, a large number of literatures have studied the effectiveness of the GFGP on ESs trade-offs in different time and space scales. For example, Ouyang et al. (2016) carried out a national ESs assessment, which showed that ecosystem restoration achieved soil conservation and climate regulation but led to a decline in water yield. Jia et al. (2014) analyzed the ESs relationships driven by GFGP in the Loess Plateau of northern Shaanxi. The results showed that NPP and soil conservation presented synergies, while NPP and water yield presented trade-offs. Wang J T et al. (2017) studied the impact of GFGP on ESs in North-Western Yunnan. The conclusion was that increasing extent of GFGP implementation improved soil conservation but decreased NPP and water yield. In this study, we draw a conclusion that NPP and SC, SC and WY developed in the direction of trade-offs driven by the GFGP, while NPP and WY developed in the direction of synergies. So our conclusion is similar to that of Wang J T et al. (2017) because of similar study area. Hence trade-offs exist between ESs under the scenario of ecological restoration. This makes ecological policy making and ecosystem management more complicated. According to the regional ecological needs and geographical characteristics, appropriate goals, extent, and approaches of ecological restoration should be established to achieve sustainable supply of ESs.

4.2 Trade-offs and synergies among ecosystem services

At a specific time and space scale, the ESs are not completely independent, but show a complicated interaction, which forms trade-offs and synergies among multiple ESs. However, because of landscape heterogeneity and differences in ecosystem utilization and management, the relationship between ESs is different in different regions. For example, Chang et al. (2012) speculated

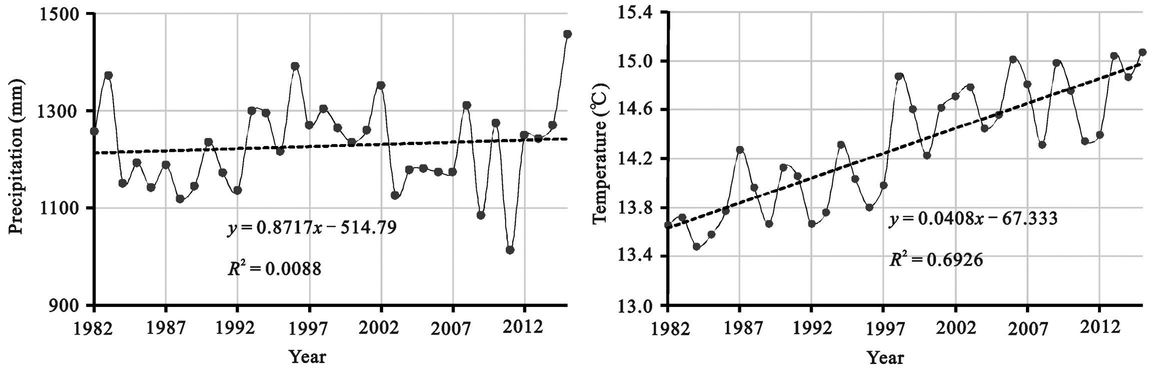

Fig. 8 The temporal changes of precipitation and temperature in the Karst area from 1982 to 2015

that a high soil conservation amount indicates minimal free water flow, good water conservation, and high vegetation carbon fixation. However, Qian et al. (2018) researched in Gansu Bailongjiang watershed and found that there are strong positive correlation synergies both between water and soil conservation, and between water and carbon storage, while there are weak negative correlation trade-offs between soil conservation and carbon storage. Wang Pengtao et al. (2017) researched in Upper reaches of Hanjiang River Basin and found that the interaction both between soil conservation and NPP and that between soil conservation and water yield presented trade-offs, while the interaction between NPP and water yield was prone to synergies. Wu et al. (2017) researched Ordos City and found that there was a synergistic relationship between water yield and soil conservation, and there was no significant positive correlation between carbon storage and soil conservation and between carbon storage and water yield. In this study, the synergistic relationship between NPP and soil conservation, soil conservation and water yield was dominant in 1982–2000, while the trade-offs relationship was dominant in 2000–2015. The interaction between NPP and water yield all presented trade-offs in 1982–2000 and 2000–2015.

In a world, the trade-offs relationship among ESs has spatial and temporal differences and uncertainties. The relationship between ESs has showen different in different regions and different time series. The possible reason is that different methods were used to quantify the relationship of ESs. At present, correlation analysis has been widely adopted, without considering local natural environment conditions, policies and socio-economic factors (Costanza et al., 2017). In this study, in order to exclude the influence of climate change and explore the impact of ecological program on the trade-offs relationship of ESs, partial correlation analysis was adopted to quantify the relationship among ESs. In addition to models and methods, regional differences, and scale effects have a great impact on the trade-off and synergistic relationship among ESs.

4.3 Limitation and future research directions

Previous studies on ESs assessment and the quantification of ESs relationship mainly focused on spatial analysis in a certain year or a short time period, instead of spatial-temporal analysis of long and continuous time series. Based on multi-source data and models, this study analyzed the trade-offs and synergies of ESs in Karst area from 1982 to 2015. For studies about the relationship among ESs, data with long and continuous time series data can effectively improve the reliability of trade-offs relationship and avoid misjudging due to unexpected factors and time-lagged effects in the long-term evolution of the ecosystems (Dallimer et al., 2015). In this study, the partial correlation analysis was adopted to control annual precipitation and exclude the influence of climate change on ESs, so as to precisely analyze the impact of ecological restoration program on ESs. However, there is a lack of research on biophysical mechanisms behind ESs process, which inevitably affect the driving analysis of ESs. In addition, stimulating different land-use scenarios can determine their impacts on ESs, which has a great significance to promote win-win regional environmental protection and sustainable development. Currently, due to the unclear classification of ESs, inadequate understanding of ecosystem complexity, insufficient understanding of complementarity and exclusiveness among multiple ESs, it often results in the repeated calculation of multiple ESs, which finally leads to large differences in assessment results of similar ESs (Fu et al., 2011). Therefore, future research aims to develop a new classification framework for ESs based on land cover types, spatial relationships and regional differences, and to further research towards driving mechanisms of ESs and scenario simulation (Cervelli et al., 2017; Kubiszewski et al., 2017).

5 Conclusions

Ecosystem services trade-offs arise from management choices made by humans, which can change the type, magnitude and relative mix of services provided by ecosystems. Overgrazed pastures and excessive reclamation of sloping lands for the interest of a rapidly growing population have caused severe geomorphologic changes and ecosystem degradation. The GFGP has provided huge ecological benefits for regulating climate, water cycling, and soil conservation. In this study, we mainly discussed the spatial-temporal differences in ESs trades-offs and Synergies driven by GFGP. It has practical guiding significance for deepening ESs formation and trade-off mechanism and carrying out ecological regulation in Karst area of China under climate change. The results are shown as follows: 1) Forestland, wetland, and built-up land increased, whereas farmland and grassland decreased. The GFGP mainly concentrated on slope degree ranging from 2^{o} to 15^{o}. 2) Temporally, SC and NPP exhibited an increasing trend, while WY exhibited a decreasing trend. Spatially, SC basically decreased from west to east; NPP basically increased from north to south; WY basically increased from west to east. 3) Among ESs in different land-use types, NPP and WY in the forestland changed in the opposite way, whereas SC keep increasing. In the forestland and farmland, SC and WY changed in the same way, while SC and NPP, WY and NPP changed in the opposite way. 4) NPP and SC, SC and WY developed in the direction of trade-offs driven by the GFGP, while NPP and WY developed in the direction of synergies.

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