Response and Simulation of Trade-offs/synergies Among Ecosystem Services to Ecological Restoration Program: a Case Study of the Chengdu-Chongqing Urban Agglomeration, China

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Response and simulation of trade-offs/synergies among ecosystem services to ecological restoration Program: A case study of the Chengdu-Chongqing urban agglomeration, China

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Abstract: The Grain to Green Program (GTGP), as a policy tool for advancing ecological progress, has been operating for 20 years and has played an important role in improving ecosystem service values. However, there are few studies on the trade-off/synergy changes in ecosystem services during the implementation of the GTGP and how to select the optimal scheme for regional ecological security based on the trade-off relationship. Thus, we took the Chengdu-Chongqing urban agglomeration (CCUA) in southwestern China as the study area; we used multisource data and the corresponding models and methods to estimate the regional food production, carbon sequestration, water yield, soil conservation and habitat quality services. Then, we clarified the trade-off/synergy relationships among ecosystem services from 2000 to 2015 by spatial analysis and statistical methods and evaluated the influential mechanism of the GTGP on trade-offs between ecosystem services. Finally, different risk scenarios were constructed by the ordered weighted average algorithm (OWA), and the regional ecological security pattern was simulated under the principle of the best protection efficiency and the highest trade-off degree. We found that (1) the trade-offs/synergies of regional ecosystem services changed significantly from 2000 to 2015. Among them, food production, water yield and soil conservation have always had trade-off relationships, while carbon sequestration, soil conservation and habitat quality have all had synergistic relationships. The relationships between carbon sequestration and water yield and food production changed from non-correlated to trade-off/synergistic, and the relationship between habitat quality and food production and water yield was not obvious. (2) Except for carbon sequestration service, the trade-off intensity between other ecosystem services decreased, indicating that the change trend of ecosystem services in the same direction was obvious. (3) The GTGP has been an important factor affecting the trade-off intensity of regional ecosystem services. On the one hand, it has strengthened the synergistic relationships among carbon sequestration, soil conservation and habitat quality; on the other hand, it has increased the constraints of water resources on soil conservation and vegetation restoration. (4) The decision risk coefficient α= 1.6 was the most suitable scenario, the total amount of regional ecosystem services was high, and the allocation was balanced under this scenario. The ecological security area corresponding to this scenario was also the area with high carbon sequestration and habitat quality services. The purpose of this study was to provide a scientific reference for the precise implementation of the GTGP.

Keywords: Ecosystem services • Trade-off/Synergy • Multi-scenarios • Grain to Green Program (GTGP) • Chengdu-Chongqing urban agglomeration (CCUA)

Introduction

Ecosystem services refer to the conditions and processes provided by natural ecosystems and species to meet and maintain the needs of human life. They are all the benefits that human beings obtain directly or indirectly from ecosystems (Fu et al. 2013; Norgaard 2010). In recent years, due to the rapid development of the economy and society, the increase in human disturbance to ecosystems has led to the decline of ecological functions and the intensification of conflicts between ecosystem services. It is of great significance to fully understand the trade-offs/synergies between ecosystem services and to avoid damage to other services while improving one service to promote the sustainable management of regional ecosystems, guide the rational development of natural resources and improve human well-being (Accatinoa et al. 2019; Berbes-Blazquez 2012).

Currently, research on the trade-offs/synergies of ecosystem services has mainly focused on the identification of trade-offs/synergies and the simulation of trade-off decisions. Among them, the identification of trade-offs/synergies was mainly based on cartographic and statistical methods. The cartographic method includes overlay analysis (Salmonella et al. 2018) and service cluster analysis (Wu et al. 2015). Statistical methods mainly include correlation analysis, regression analysis, cluster analysis and redundancy analysis (Wu et al. 2013; Maes et al. 2012). In recent years, the root mean square error (Bradford and D'Amato 2012) and production possibility boundary (Yang et al. 2015) have been gradually introduced into the discrimination of trade-off relationships. The methods used to simulate trade-offs have mainly included the Cellular Automata (CA) Markov model (Shui et al. 2019) and the Conversion of Land Use and its Effects at small region extent (CLUE-S) model (Wu

2017) based on land-use change and the ordered weighted average algorithm (OWA). The OWA has been proven to be able to solve multi-attribute decision-making problems, balance internal conflicts and determine priority protection areas and has been widely used by scholars (zhang et al. 2019). Overall, current research has mainly focused on the processes and patterns of trade-offs/synergies of ecosystem services, and the mechanism of interaction on ecosystem services has not been fully analyzed, especially in relation to impact assessments of ecological restoration projects where there is more human regulation.

As the ecological restoration project with the widest coverage and the largest number of people affected in China, the grain to green program (GTGP) provides cash and food subsidies for afforestation and grass planting on cultivated land to increase surface vegetation coverage and improve the regional ecological environment. As expected, the GTGP has played an important role in increasing vegetation coverage and promoting carbon storage (Zhou et al. 2009; Wu et al. 2019), reducing soil erosion (Deng et al. 2012), increasing seasonal water yield (Yang et al. 2018), reducing annual sediment transport (Wang et al. 2015), and promoting nonagricultural employment (Lin and Yao 2014). However, studies in some areas have also found that the GTGP has led to a reduction in arable land area, thus threatening food security (Deng and Shangguan 2011), aggravating social inequality (Yao and Li 2010), reducing biodiversity (Hua et al. 2016), and intensifying the water-soil-sand contradiction (Lu and Tian 2021). The GTGP has not only improved some ecosystem functions but also weakened other related ecosystem services and even intensified the conflicted relationship between ecosystem services. Under the background of the GTGP, the trade-offs/synergies of regional ecosystem services has become an important research topic. Currently, related research has mainly focused on ecologically fragile areas such as the Loess Plateau and Karst regions. In contrast, there has been little research on urban agglomerations, especially mountainous urban agglomerations, which are the main trend of urban development in China, high incidence areas of ecological environmental problems and ecosystem service conflicts, and priority test areas of the GTGP.

As the third interregional urban agglomeration approved by the Chinese government, the Chengdu-Chongqing urban agglomeration (CCUA) has experienced rapid economic development and drastic changes in land use, which have caused certain ecological damage and conflicts. Additionally, the CCUA is an important ecological barrier area in the upper reaches of the Yangtze

River and the first area in China to implement the GTGP; thus, ecological protection is of the utmost importance in this region. Therefore, this study used the CCUA as the object, selected five main types of ecosystem services, and estimated their ecosystem service values through the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model and related algorithms. Then, we used a relevant analysis method to reveal the trade-off/synergy evolution between ecosystem services and identified the impact of the GTGP on regional ecosystem service relationships through principal component analysis (PCA). Based on the trade-offs/synergies of ecosystem services, we set different scenarios through the OWA to clearly clarify the ecological security pattern suitable for the development of urban agglomerations to provide a scientific reference for regional ecological security assessment and the precise implementation of the GTGP.

Study area and data

Study area

The CCUA in this study includes 25 districts (counties) in Chong city and 15 cities in Sichuan Province (Fig. 1a, 27°39′N-32°20′N，102°51′E-108°54′E); the study has a geographical area of 169,000 km^2, accounting for approximately 2.5% of China’s total land area. The CCUA is a national-level urban agglomeration leading the development and opening of the western region. It is an important support for implementing the western development strategy of China, improving the level of inland opening, and promoting regional development. As of 2018, its permanent population was approximately 95 million, accounting for 7.2% of China’s total population; the gross domestic product (GDP) reached 5.72 trillion yuan, accounting for 6.4% of China’s total GDP; and its urbanization rate increased from 46.3% in 2010 to 53.8% in 2018. With the development of the regional economy and society, large changes in regional land use have occurred, resulting in the loss of some ecosystem services and the intensification of their conflicts. To this end, the Chinese government has promulgated some policies and implemented much ecological restoration work, aiming to improve the ecological environment and alleviate ecological conflicts.

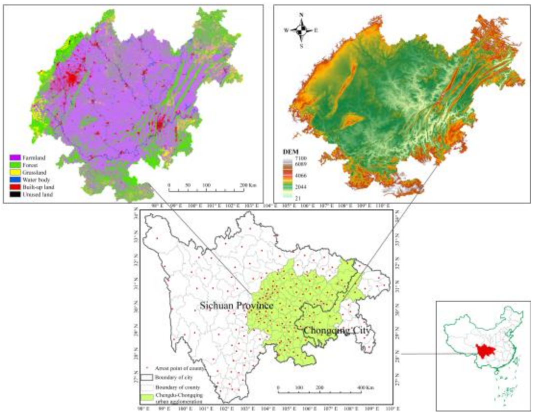

Fig. 1a Location of the CCUA

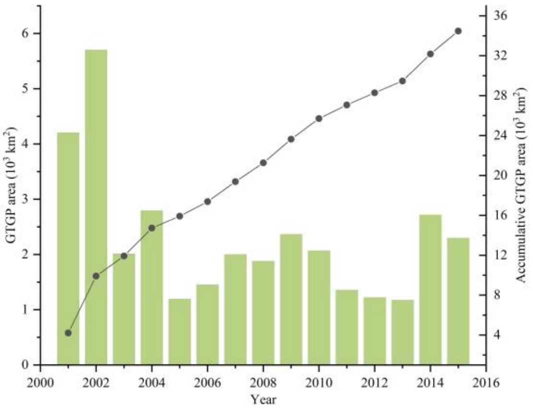

Fig. 1b Forested land area under the GTGP from 2001 to 2015

Design and implementation of the GTGP

The GTGP is designed to transfer farmland on steep slopes (>25°) to forest or grassland to increase vegetation coverage and reduce soil erosion and thus restore regional ecosystems (Wang et al. 2017). Sichuan Province and Chongqing city were selected as pilot regions of the GTGP in 1999 and 2000, respectively. The GTGP is paid for by the central government; it directly engages millions of rural households as core agents of project implementation, with the stated principal of volunteerism (Guo et al. 2014). The government offers farmers grain or money per ha of converted farmland per year. In addition, a 300 yuan per ha per year living allowance and a one-time grant of 750 yuan per ha for seeds or seedlings are provided. The duration of these subsidies depends on the outcome of farmland conversion: 2 years if the farmland is converted into grassland, 5 years if it is converted into commercial forest, or 8 years if it is converted to ecological forest (Liu et al. 2008). After the first phase, government subsidies were renewed in a second phase to encourage farmers to return farmland to forests and consolidate the achievements of the GTGP. There were 130 districts (counties) in the CCUA, and the forested area first increased, then decreased and then increased. By 2015, the total forested area was 34.48 × 10^3 km^2, which was 20.4% of the total area (Fig. 1b).

Data sources and processing

The basic geographic data used in this study, such as regional boundaries, were from the Ministry of Natural Resources of the People's Republic of China. Soil data, mainly including soil organic carbon content, soil bulk density and soil layer thickness, came from the Big Data Center of Sciences in Cold and Arid Regions of China (http://bdc.casnw.net/index.shtml). The land-use and vegetation type data were from the Resource and Environment Science and Data Center, Chinese

Academy of Sciences China (https://www.resdc.cn/). The digital elevation model (DEM) data were the SRTMDEM-V2 product, and its spatial resolution is 30 m. The biomass data were from the Intergovernmental Panel on Climate Change (IPCC) in 2006. The meteorological data, mainly including temperature and precipitation, were from the China Meteorological Data Network (http://data.cma.cn/). The thin disk spline method of ANUSPLIN software was used to interpolate the meteorological data, and the grid images of multiyear time-series data were obtained. Net primary productivity (NPP) data were the product of MODIS 17A3 with a spatial resolution of 500 m (https://modis.gsfc.nasa.gov/). The social and economic data came from the Sichuan Statistical Yearbook and Chongqing Statistical Yearbook; the GTGP statistics in each district (county) from 2001 to 2015 were obtained from the Chinese Forest Statistical Yearbook. Other relevant data came from the related literature.

Ecosystem service estimation methods

Carbon sequestration

Carbon sequestration in terrestrial ecosystems mainly depends on four aspects: aboveground biomass carbon sequestration, underground biomass carbon sequestration, soil carbon sequestration and organic carbon sequestration. In this paper, we estimated the carbon sequestration services of the CCUA based on the InVEST model without considering organic carbon sequestration. The calculation formula is as follows:

$$C = C_{above} + C_{below} + C_{soil} + C_{dead} \tag{1}$$

where C is the total carbon sequestration service; C_{above} is the aboveground biomass carbon sequestration; C_{below} is the underground biomass carbon sequestration; C_{soil} is the soil carbon sequestration; and C_{dead} is the organic carbon sequestration.

According to relevant studies (Lyu et al. 2019; Gao et al. 2020), carbon density is mainly affected by climate, topography, hydrological conditions and vegetation types. However, it cannot be quantified due to vegetation types and hydrological conditions; therefore, the annual mean temperature and annual precipitation were selected as the influencing factors to modify the carbon density. The specific correction formulas are as follows:

$$C_{SP} = 3.3968 * MAP + 3.3996.1 \tag{2}$$

$$C_{BP} = 6.798 * e^{0.0054 * MAP} \tag{3}$$

$$C_{BT} = 28 * MAT + 398 \tag{4}$$

where C_{SP} is the soil carbon density (kg/m^2); C_{BP} and C_{BT} are the biomass carbon density obtained from precipitation and temperature (kg/m^2), respectively; *MAP* is the average annual precipitation (mm); and *MAT* is the annual mean temperature (°C).

The annual average temperature and annual precipitation data in the study area and China were substituted into the formula, and the carbon density coefficient was obtained according to the ratio of these indexes in the study area and in China. Based on the national carbon density data table, the carbon density data table of the study area was calculated, and then the carbon sequestration service was calculated.

Water yield

This paper used the water yield module of the InVEST model to calculate the water yield of the CCUA. The basic principle is as follows:

$$Y_{xj} = (1 - \frac{AET_{xj}}{P_x}) \times P_x \tag{5}$$

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \tag{6}$$

$$\omega_x = Z \frac{AWC_x}{P_x} \tag{7}$$

$$R_{xj} = \frac{K_{xj} ET_{0_x}}{P_x} \tag{8}$$

where $Y(x)$ is the water supply of year (mm); $AET(x)$ is the actual evaporation of year (mm); and $P(x)$ is the annual precipitation of year (mm). R_{xj} is the dryness index, dimensionless, indicating the ratio of potential evaporation to precipitation; w_x is the ratio of annual available water to precipitation, which is dimensionless; Z is the constant of precipitation characteristics in the study area, which is dimensionless and takes the default value according to the model test experience; AWC_x is the available water content of plants; and K_{xj} is the potential evapotranspiration of grid x. Specific content can be seen at Redhead et al. (2016).

Soil conservation

Based on the soil loss equation in the InVEST model, this paper calculated the regional soil conservation service, and the expressions are as follows:

$$SEDRET_x = R_x \times K_x \times LS_x \times (1 - C_x \times P_x) + SEDR_x \tag{9}$$

$$SEDR_x = SE_x \sum_{y=1}^{x-1} USLE_y \prod_{z=y=1}^{x-1} (1 - SE_z) \tag{10}$$

$$USLE_x = R_x \times K_x \times LS_x \times C_x \times P_x \tag{11}$$

where $SEDRET_x$ and $SEDR_x$ are the soil conservation capacity and sediment retention capacity of grid x (t/(hm^2•a)), respectively; $USLE_x$ and $USLE_y$ are the actual erosion amount of grid x and its uphill grid y (t/(hm^2•a)), respectively; SE_x is the sediment retention sufficiency of grid x; R_x is the precipitation erosivity factor (MJ.mm/hm^2•h•a); LS_x is the topographic factor; K_x is the soil erodibility index (t•hm^2•h/MJ•hm^2•mm); C_x is the vegetation cover management factor; and P_x is the soil and water conservation factor. Specific index size can be found in Borji and Samani (2019).

Food production

Based on the grain yield, combined with the significant correlation between crops and the NPP (Wondmagegne et al. 2012), the spatial distribution of grain yield was determined according to the proportion of NPP in each grid to the regional total NPP, and the spatial distribution map of food production services was obtained. The specific formula is as follows:

$$G_i = G_{sum} * \frac{NPP_i}{NPP_{sum}} \tag{12}$$

where Gi is the food production service in grid x (t), G_{sum} is the total grain yield (t), NPP_i is the NPP of grid i, and NPP_{sum} is the sum of regional NPP.

Habitat quality

Based on different land-use types, the habitat quality in the study area was explored by the habitat quality module of the InVEST model, which showed habitat quality values between 0 and 1. The calculation formulas are as follows:

$$Q_{xj} = H_j \left[1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right] \tag{13}$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y_r} \left(w_r / \sum_{r=1}^{R} w_r \right) r_y i_{rxy} \beta_x S_{jr} \tag{14}$$

$$i_{rxy} = 1 - \left(\frac{d_{xy}}{d_{r\max}} \right) \tag{15}$$

$$i_{rxy} = \exp\left(- \left(\frac{2.99}{d_{r\max}} \right) d_{xy} \right) \tag{16}$$

where Qxj is the habitat quality of grid x in land-use type j, H_j is the habitat suitability index, Dxj is the habitat stress level of grid x in land-use type j, K is the scaling parameter, R is the number of stress factors, Y_r is the number of grids of stress factor r; r_y is the number of stress factors in each grid; S_{jr} is the sensitivity of land type j to stress factor r; i_{rxy} is the effect of stress factor r on grid x in grid y; d_{xy} is the distance between grid x and grid y; d_{rmax} is the influence range of stress factor r; and β_x is the degree of legal protection. The specific content can be seen at Yohannes et al. (2021).

Identification and quantitation of ecosystem service synergies and trade-offs

In this paper, we calculated the Pearson correlation coefficient between two different ecosystem services and tested the significance to characterize the trade-off/synergistic relationships between ecosystem services. When the correlation coefficient between two ecosystem services was positive, there was a synergistic relationship between them. When the correlation coefficient was negative, there was a trade-off relationship. The Pearson correlation coefficient is calculated as follows:

$$R_{xy} = \frac{\sum_{i=1}^{n}[(x_i - \bar{x})(y_i - \bar{y})]}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{17}$$

where R_{xy} is the correlation coefficient between ecosystem services x and y; x_i and y_i are the i-th year values of x and y, respectively; $\bar{x}$ and $\bar{y}$ represent the average value of the two ecosystem services in the corresponding year, respectively; and n is the total number of grids. The significance of the Pearson correlation coefficient was tested by t test. The statistical formula is as follows:

$$t = R \cdot \sqrt{\frac{n-2}{1-R^2}} \tag{18}$$

where R is the correlation coefficient, and n is the total number of grids.

The root mean square error (RMSE) was employed to quantify the trade-off relationship between two ecosystem services (trade-off intensities) and to quantify how the synergistic development of two ecosystem services was biased towards one of those services (Yu et al., 2020). This method used the distance from points to straight lines to express the relationship between two ecosystem services. The greater the distance was, the more severe the trade-off relationship between the two ecosystem services was. In contrast, the relationship between the two ecosystem services tended to be more synergistic as the distance decreased. When the distance was zero, an ideal synergistic relationship existed between the two services. Its formula is as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(ES_i - \overline{ES}\right)^2}{n-1}} \tag{19}$$

where *RMSE* is the ecosystem service tradeoff intensity, *n* is the number of ecosystem services, ES_i is the ecosystem service value after standardization and $\overline{ES}$ is the mathematical expectation of the two ecosystem services.

Selection of factors influencing ecosystem service synergies and trade-offs

We selected seven factors from the natural and human aspects, among which the natural factors included the DEM, topographic relief (DXQFD), annual mean temperature (TEM) and annual precipitation (PRE). In terms of human aspects, the GDP, urbanization rate (CZH) and cumulative afforestation area ratio (cumulative afforestation area/total regional area, ZL) were selected, in addition, ZL value means the intensity of GTGP implementation. Since most of the study area began to implement the GTGP after 2000, this paper used 2000 as the base year and 2015 as the comparison year to reveal the impact of each factor on the trade-off/synergistic relationship of regional ecosystem services. First, the difference in the trade-off intensity of ecosystem services and each factor was calculated from 2000 to 2015. Then, PCA was used to study the correlation between trade-off intensity and influencing factors. All of these were completed using CANOCO 5.2 software, and the specific content can be found in Chen et al. (2017).

Identification of ecological safety zone

The OWA is a kind of decision-making method that can choose the importance degree between the indexes arbitrarily according to the decision risk coefficient. It includes the criterion weight (u_j, $j=1,2,\ldots,n$) and order weight (v_j, $j=1,2,\ldots,n$), where u_j represents the relative importance of an indicator in all indicators, and v_j is obtained by standardizing the indicators of the evaluation unit and arranging them in descending order. It is defined as follows:

$$QWA_i = \sum_{j=1}^{n} \left(\frac{u_j v_j}{\sum_{j=1}^{n} u_j v_j} \right) Z_{ij} \tag{20}$$

where u_j is the criterion weight of the *j*-th index, v_j is the order weight of the *j*-th index, and Z_{ij} is the attribute value of the *j*-th index in descending order according to the attribute value of *i*.

In general, *vj* is determined by the importance grade of index (*wk*), and the formula is as follows:

$$v_j = \left(\sum_{k=1}^{j} w_k \right)^{\alpha} - \left(\sum_{k=1}^{j-1} w_k \right)^{\alpha} \tag{21}$$

where α is the decision risk coefficient, and w_k is the importance grade of the index, which is usually determined according to the index value, and its formula is as follows:

$$w_k = \frac{n - r_k + 1}{\sum_{l=1}^{k} (n - r_l + 1)} \quad (k = 1,2,\ldots, n) \tag{22}$$

where r_k is the grade value of the importance index according to the numerical value; usually, the maximum value is 1, the second maximum value is 2, and the minimum value is *n*.

The OWA has a trade-off concept in addition to the risk coefficient. The calculation formula is as follows:

$$tradeoff = 1 - \left\{ \left[n \sum_{j=1}^{n} (v_j - 1 / n)^2 \right] / (n - 1) \right\}^{0.5} \tag{23}$$

where *n* is the total number of ecosystem services, and v_j is the order weight of the *j*-th grid.

Combining the OWA with GIS, the normalized ecosystem services were weighted and integrated according to different decision risks, and the evaluation layer was obtained. To effectively protect regional ecosystem services, the top 20% of each evaluation layer was selected as the ecological protection area under the different risk scenarios. By calculating the protection efficiency and trade-offs of ecological protection areas under each risk scenario, the final ecological safety zone was determined. The calculation formula of the protection efficiency of the ecological safety zone is as follows:

$$E_i = \frac{ES_i}{ES_o} \tag{19}$$

where E_i is the protection efficiency of the ecosystem services in the ecological protection area, ES_i is the average value of the ecosystem services in the ecological protection area, and ES_o is the average value of the ecosystem services in the whole study area. When E_i>1, the protection efficiency of the ecological protection area is higher than that of the whole study area; in contrast, when E_i<1, the protection efficiency of the ecological protection area is lower than that of the whole study area.

Results

Identification of synergies and trade-offs among ecosystem services

The correlation of five ecosystem services was analyzed by taking district (county) as a unit. The relationship between F2000 and C2000 evolved from a nonsignificant to a synergistic relationship in 2015, while the relationship between C2000 and W2000 developed from a nonsignificant to a trade-off relationship in 2015. The relationship between food production and water yield was a trade-off relationship, and the correlation increased, while food production and soil conservation showed a decreasing trade-off trend from 2000 to 2015. Carbon sequestration and soil conservation, carbon sequestration and habitat quality, and soil conservation and habitat quality showed synergistic trends. The Pearson's correlation coefficients of food production and habitat quality and of water yield and habitat quality were insignificant from 2000 to 2015, so there was no significant trade-off and no synergistic relationship was observed. The relationship between water yield and soil conservation changed from a synergistic relationship to being insignificant (Table 1). This result shows that the relationships among the five ecosystem services changed differently from 2000 to 2015.

Table 1 Pearson correlation analysis of the five ecosystem services

	F2000	C2000	W2000	S2000	H2000	F2015	C2015	W2015	S2015	H2015
F2000	1		-0.268**	-0.509**						
C2000		1		0.41**	0.825**					
W2000	-0.268**		1	0.208*						
S2000	-0.509**	0.41**	0.208*	1	0.538**					
H2000		0.825**		0.538**	1					
F2015						1	0.178*	-0.333**	-0.398**	
C2015						0.178*	1	-0.226**	0.488**	0.917**
W2015						-0.333**	-0.226**	1		
S2015						-0.398**	0.488**		1	0.58**
H2015							0.917**		0.58**	1

N =129; ** and * show significant correlations at the P = 0.05 and P = 0.1 levels (two-tailed), respectively. F2000/2015 means food production in 2000 and 2015, respectively; C2000/2015 means carbon sequestration in 2000 and 2015, respectively; W2000/2015 means water yield in 2000 and 2015, respectively; S2000/2015 means soil conservation in 2000 and 2015, respectively; H2000/2015 means habitat quality in 2000 and 2015, respectively.

3.2 Trade-off intensity analysis of ecosystem services

The main goal of the GTGP is to convert farmland on steep slopes (>25°) to forest or grassland, which is always conducive to the change in carbon sequestration and food production; as a result, the trade-off intensity between food production capacity and carbon sequestration services developed from 0.126 in 2000 to 0.136 by 2015 (Fig. 2). From 2000 to 2015, there was not only a change in the trade-off intensity between food production and carbon sequestration but also changes in the trade-off intensities between other ecosystem services, e.g., the trade-off intensities between carbon sequestration and soil conservation and habitat quality increased from 0.117 and 0.103 to 0.122 and 0.112, respectively, and the trade-off intensities between water yield and food production, soil conservation, and habitat quality decreased from 0.172, 0.159, and 0.159 to 0.153, 0.142, and 0.143, respectively. Therefore, the trade-off intensities among the five ecosystem services changed differently from 2000 to 2015.

In 2010, the trade-off intensities between food production, carbon sequestration, water yield, soil conservation and habitat quality were food production-water yield (F-W) > water yield-soil conservation (W-S) = water yield-habitat quality (W-H) > carbon sequestration- water yield (C-W) > food production-soil conservation (F-S)> food production-habitat quality (F-H)> food production-carbon sequestration (F-C) = soil conservation-habitat quality (S-H)> carbon sequestration-soil conservation (C-S)> carbon sequestration-habitat quality (C-H) (Fig. 3). In 2015, the trade-off intensities of these five ecosystem services were F-W > C-W > W-H > W-S > F-C > F-S > F-H > C-S > S-H > C-H. Compared with 2000, the trade-off relationships of F-W, F-S, F-H, C-W, W-S, W-H, and S-H weakened. However, the trade-off relationships of F-C, C-S and C-H strengthened.

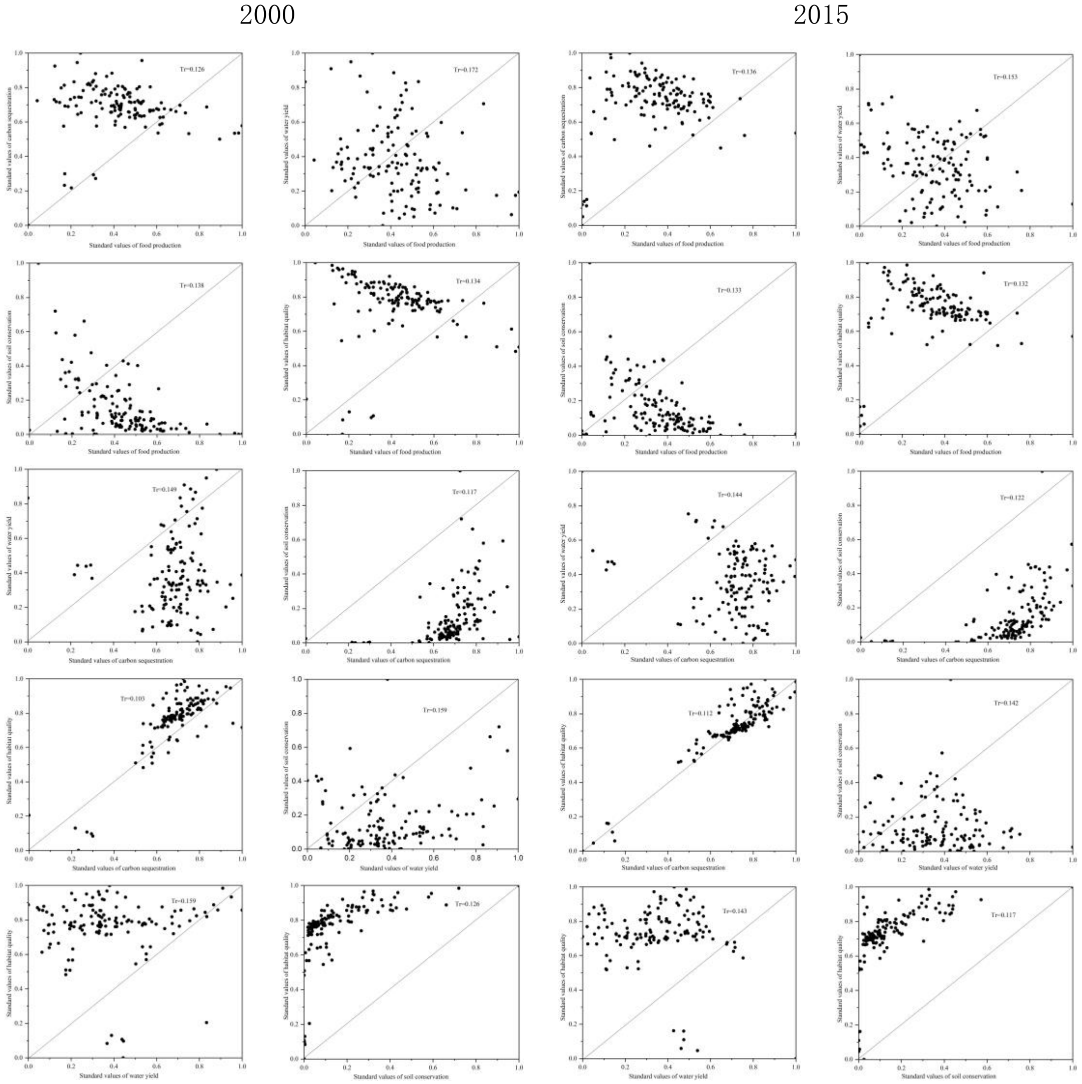

Fig. 2 Trade-off maps of five ecosystem services in 2000 and 2015 (each point represents a district; Tr indicates trade-off intensity)

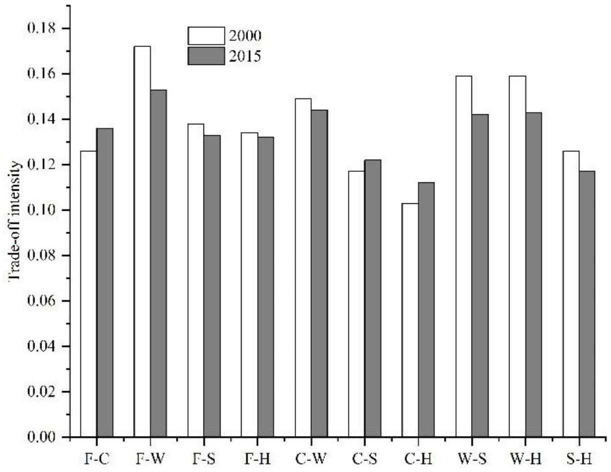

Fig. 3 Comparison of the trade-off intensities among these five ecosystem services

Analysis of the causes of the effects of the GTGP on ecosystem service synergies and trade-offs

Table 2 shows that the contribution rate of influencing factors to trade-off intensities is different, but their cumulative contribution rate is over 85%. Therefore, we can analyze the drivers of trade-off intensity changes. It can be seen from the PCA figure (Fig. 4) that there is a positive correlation between the cumulative afforestation area ratio (ZL) and F-C, F-H, F-S, F-W, W-H, W-S; that is, the GTGP would accelerate the trade-offs between food production and other ecosystem services and strengthen the constraints of water yield on habitat quality and soil conservation. There was a negative correlation between ZL and C-H, S-H, and C-S, indicating that the trade-off intensities among carbon sequestration, habitat quality and soil conservation weakened with the increase in afforestation area. The GTGP strengthened the synergistic relationships among carbon sequestration, habitat quality and soil conservation. The GTGP is an important factor affecting changes in the trade-offs between regional ecosystem services.

Table 2 Contribution rate of influencing factors to trade-off intensities

	Principal component (%)				
	1st	2nd	3rd	4th	Total
Factors	59.16	18.6	7.49	4.67	89.92

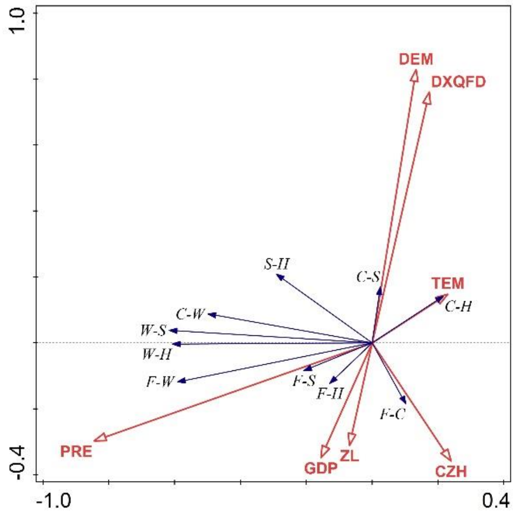

Fig. 4 Correlation analysis of the trade-off intensity and influencing factors from 2000 to 2015

Identification of ecological security pattern

In view of the current trade-off relationships of ecosystem services in this study area, to reduce the conflict between ecosystem services and maximize the ecosystem service functions, this study set different scenarios through the OWA to identify the regional ecological security pattern. First, the importance of each ecosystem service was ranked, and the importance level (r_k) of each evaluation unit was given a number: 1, 2, 3, 4, and 5. According to the above formula, the importance degree (w_k) of each ecosystem service was calculated as 5/15, 4/15, 3/15, 2/15 and 1/15. The interval of decision risk coefficient α was 0.1, and the value started from 0. The ordered weight and trade-off value under different decision risk coefficients were calculated according to the above formula. As shown in Fig. 5, when the risk increased gradually from 0, the change in the trade-off value showed an increasing trend and reached the highest value when the risk value was 1.6. Then, with the increase in the risk value, the trade-off value showed a decreasing trend. When the risk value increased infinitely, the trade-off value declined to zero.

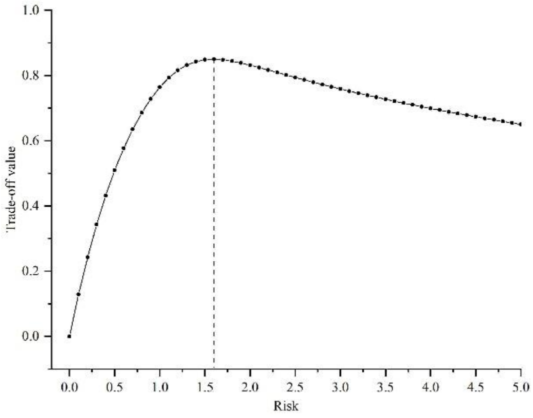

Fig. 5 The relationship between the risk index and trade-off value

The five weight values and their corresponding ecosystem services under different risk coefficients were multiplied to obtain the risk assessment result, and the assessment results were divided into five grades from low to high by the natural segment method. Due to space limitations, this study showed only the evaluation results under several typical decision risk levels (Fig. 6). The results showed that when α= 0, the decision-maker was pessimistic. At this time, the overall ecosystem security level of the CCUA was very poor, and most of the areas were in the ecological risk level 4; When α= 0.5, the ecological security level of the CCUA was also not high, most areas were in the state of level 3, and the area of the level 5 was increasing. When α= 1, the main risk statuses of the CCUA were levels 2 and 3, while the area of level 4 decreased. When α= 2, the area of the level 1 increased significantly, the areas of levels 4 and 5 decreased, the overall ecosystem was in a relatively safe state. When α= 10, the risk assessment results were consistent with the results of α= 2. When α= 1000, most regions were below ecological risk level 3.

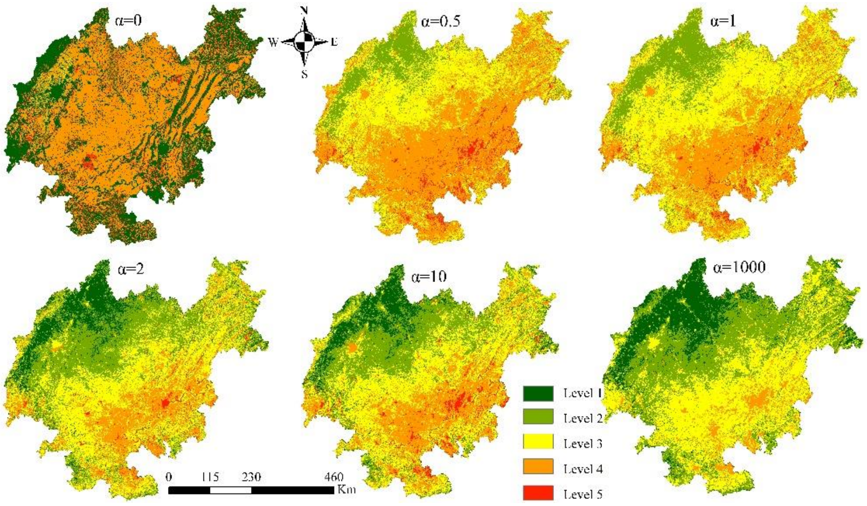

Fig. 6 Classification of ecosystem risk under different scenarios

Decision risk in the OWA is not the probability of an incorrect decision; rather, it is the risk-aversion attitude of decision-makers. Therefore, the higher the trade-off value in different scenarios is, the greater the average value of each ecosystem service is in the final result. Table 3 shows that when α= 1.6, the trade-off value was the maximum, and the protection efficiency of each ecosystem service was high. Therefore, this study focused on α= 1.6 as the final scenario, and the top 20% of the area was selected as the ecological protection zone. The results showed that the ecological protection zones were mainly located in northeastern Sichuan and northeastern Chongqing, China; additionally, most of them were distributed in areas with high carbon sequestration and habitat quality services (Fig. 7).

Table 3 Protection efficiency and trade-offs of different scenarios for ecosystem services

Risk	Food production	Carbon sequestration	Water production	Soil conservation	Habitat quality	Trade-off
0	1.465	1.949	0.991	0.835	0.993	0
0.5	1.012	1.929	1.144	1.245	1.014	0.509
1	1.001	1.927	1.148	1.244	1.014	0.765
1.6	0.976	1.942	1.22	1.486	1.022	0.85
2	0.97	1.939	1.218	1.457	1.022	0.831
10	0.868	1.92	1.271	1.37	1.02	0.483
10000	0.838	1.905	1.27	1.023	1.015	0

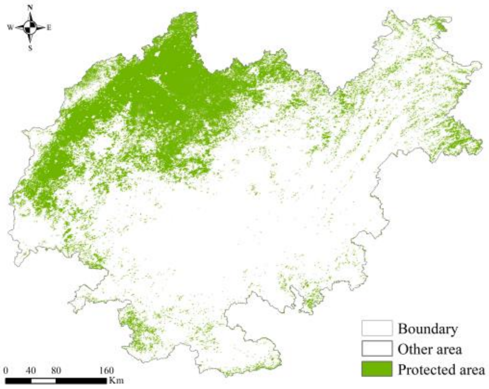

Fig. 7 Ecological security pattern of the CCUA

Discussion and conclusion

According to related studies, the implementation of the GTGP has increased carbon sequestration while simultaneously increasing the value of soil conservation services in the ecosystem, but it has neglected the food production services of the study area. This result caused an increase in the trade-off value between food production capacity and carbon storage services, hindering the stable development of ecosystem structure and function (Accatinoa et al. 2019). However, according to our study, there was no obvious trade-off relationship between food production and carbon sequestration in the study area. The correlation between them was not significant in 2000, and then it evolved into a synergistic relationship in 2015, which indicated that the implementation of the GTGP did not affect regional grain production. In contrast, the water yield service had obvious trade-off relationships with carbon sequestration and food production, and its correlation coefficient had an increasing trend, which may be because the improvement of vegetation coverage will absorb a large amount of water and then reduce the surface runoff and water yield service (Ronald et al. 2014), indicating that the constraint of water resources on vegetation growth has become tighter since the implementation of the GTGP. In terms of soil conservation and habitat quality, they basically maintained synergistic or insignificant relationships with the other three types of ecosystem services, but this result did not mean that their mutual relationship would not change with the change in the GTGP implementation intensity and direction. Therefore, in the process of regional GTGP implementation, we should pay attention to the change in trade-offs/synergies between ecosystem services, especially in relation to the relationships among food production, carbon sequestration and water yield. When adjusting the GTGP measures, we should not only focus on the improvement of carbon sequestration services but also improve the overall ecosystem service function of the study area.

Although the main objective of the GTGP is to convert the farmland on steep slopes (> 25°) into forest or grassland, according to the data, the grain yield in the study area has not decreased, the vegetation coverage has been improved, and the carbon sequestration service has increased significantly (Wu et al. 2019). The response of carbon sequestration services to the GTGP was more prominent. However, due to the inconsistent implementation intensity of policies in different districts (counties), there were obvious differences in carbon sequestration services among districts (counties), resulting in the inconsistent change direction between this service and other services in different districts (counties), and the trade-off intensity was improved. Among them, the trade-off intensity between carbon sequestration and food production increased most significantly, from 0.126 in 2000 to 0.136 in 2015, followed by that of soil conservation and finally that of habitat quality. Except for carbon sequestration, the trade-off intensity between the other four types of ecosystem services showed a slight downward trend because they were not directly affected by the GTGP.

Previous studies have shown that the GTGP will affect the trade-off/synergistic relationships between regional ecosystem services to a certain extent (Ji et al. 2021). Similarly, this study found that the GTGP slowed down the conflicted relationships among carbon sequestration, habitat quality and soil conservation, strengthened the constraint effect of water resources on soil conservation and habitat quality, and should focus on alleviating the conflict relationship between water yield and other ecosystem services in the future. The GTGP was an important factor affecting the trade-off of regional ecosystem services. It is worth noting that in the GTGP process, the trade-offs between carbon sequestration, soil conservation and habitat quality increased slightly, which seemed to be inconsistent with the conclusion here. In fact, the reason for this result was that although the GTGP slowed down the trade-offs between carbon sequestration, soil conservation and habitat quality, the urbanization rate, elevation and topographic relief would intensify the conflicted relationships between them, and their effects were obviously stronger than that of the GTGP (Figure 4). Additionally, Fig. 4 shows that GDP, temperature and precipitation had certain degrees of impact on the trade-off relationships between regional ecosystem services. For example, precipitation and GDP would also strengthen the trade-off between water yield and other services. There are many factors affecting the evolution of trade-off relationships on regional ecosystem services, which need targeted analysis.

To realize the sustainable development of ecosystems, it is necessary to incorporate the trade-off relationship between ecosystem services into the identification of ecological security patterns. Meanwhile, the construction of ecological security patterns is a typical multi-attribute decision-making problem that needs to simultaneously consider the rights and interests of policy implementers, farmers and other stakeholders. Therefore, it is necessary to simulate the decision-making behavior under different risks through multi-scenario settings. Based on this, this study started with the trade-off relationship between ecosystem services in the study area, set different decision-making risks through the OWA, simulated the distribution of regional ecological protection zones under different scenarios, and identified the ecological security pattern according to the principle of optimal protection efficiency and highest trade-off value; thus, the results provide a reference for improving the total amount and reasonable allocation of ecosystem services in the CCUA. However, urban agglomeration ecosystems are comprehensive systems (Liu et al. 2019) that contain a variety of ecosystem service functions. In addition to the five types of services considered in this study, pollution purification, entertainment and culture are very important ecosystem services, making these services important directions of follow-up research.

Appendix

Availability of data and materials: All the data analyzed during this study are included in this article.

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Author Contributions: Tiantian Chen and Li Peng designed the study, Tiantian Chen and Qiang Wang collected the data and analyzed the paper, Tiantian Chen wrote the paper and Li Peng revised

the paper.

Declarations

Ethics approval and Consent to participate: Not applicable.

Consent to publish: The authors have agreed to publish this manuscript.

Conflict of interest: The authors declare no conflicts of interest.

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