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Trade-off Analysis of Ecosystem Services in a Mountainous Karst Area, China

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Abstract: Diversity in ecosystem services and variation in land use by humans leads to reciprocal trade-offs or synergistic relationships between different ecosystem services. To achieve the dual goals of improving human welfare and developing sustainable ecosystems, understanding and clarifying these relationships is an important step. This study selected a mountainous karst area of China as a study area and used the InVEST (Integrate Valuation of Ecosystem Services and Trade-offs) model and the production possibility frontier analysis method to evaluate the spatio-temporal variations in ecosystem services and analyze the trade-off or synergic relationship between different services. The results showed that from 1990 to 2010, the percentage variations in annual mean water yield, soil conservation, carbon storage, and nutrient retention in the mountainous karst area were 2.47, 39.43, −0.34, and −1.16%, respectively. Water yield had trade-off relationships with soil conservation, nutrient retention, and carbon storage, increasing water yields were correlated with decreases in soil conservation, nutrient retention, and carbon storage. Soil conservation and nutrient retention also showed a trade-off relationship, decreasing soil conservation was correlated with gradually increasing nutrient retention. Carbon storage had synergic relationships with nutrient retention and soil conservation, continuous increases in carbon storage were correlated with incremental increases in nutrient retention and gradual decreases in soil conservation.

Keywords: ecosystem services; trade-off; synergy; production possibility frontier; InVEST model; mountainous karst area of China

1. Introduction

Ecosystem services, maintained by the ecosystem and its ecological processes, refers to the environmental conditions and utilities that humans rely on for survival. They are the foundation of human survival and development and are closely related to human welfare [1,2]. Since the term ‘ecosystem services’ was first defined, it has gradually become a research focus in ecology and its related disciplines [3–5]. In particular, the Millennium Ecosystem Assessment has evaluated the consequences of changing ecosystems to meet human welfare. Further, it established a scientific foundation for taking specific measures to strengthen the protection and sustainable use of ecosystems, thereby enhancing the contribution of ecological systems to human welfare [6–9]. The variety of different ecosystem services are mutually influenced and restricted [10–12]. The diversity of ecosystem services and selectivity of human usage lead to a reciprocal trade-off or synergic relationship between different ecosystem services [13–15]. The provision of ecosystem services is a result of complex ecological processes, with inevitable trade-offs between different ecosystem services that are not fixed variables; spatial heterogeneity and temporal dynamics are common [16,17]. Therefore, an in-depth understanding and accurate characterization of trade-offs between ecosystem services are the scientific foundation for realizing the dual goals of improving human welfare and developing sustainable ecosystems [18–21].

A trade-off is a situation where you make a compromise between two things, or where you exchange all or part of one thing for another [17]. In recent years, this trade-off has the focus of many studies on ecosystem services [22,23]. A number of scholars have extensively researched this topic, from the perspectives of interactions between ecosystem services, trade-off mechanisms, the scale effects, and scenario simulations [24–26]. Ecosystem services show a complex, dynamic, and nonlinear variable relationship with a given ecosystem [27,28]. For example, Maskell et al. [29] investigated the relationship between soil carbon storage and net primary production (NPP) using correlation analysis, and showed that there was a positive feedback relationship between soil carbon storage and NPP. Chisholm et al. [30] discovered a trade-off relationship between water yield and carbon storage, and established a dynamic ecological-economic model to determine the water yield loss due to increasing carbon storage. In a similar study using GIS technology, Onaindia et al. [31] spatially mapped three types of ecosystem services: biodiversity, carbon storage, and runoff regulation, for a biosphere storage in northern Spain; they characterized the trade-off and synergic relationships between these services by analyzing the consistency of their spatial distributions. In addition, Swallow et al. [32] quantitatively analyzed the competitive trade-off relationships between different ecosystem services using linear regression analysis and basic descriptive statistics.

To study the trade-off mechanisms in ecosystem services, Wang et al. [33] quantitatively analyzed ecosystem services in the Sanjiang Plain, China and found that transformations from wetland to cultivated land increased grain yield, but led to significant losses in carbon storage and biodiversity in this region. Similarly, Bryan et al. [34] found that market incentive policies and measures—such as commodity market, carbon tax, water cap and trade, biodiversity auction, and biomass energy marketization—can ultimately affect the trade-off and synergy of ecosystem services through land use. Nelson et al. [35] demonstrated that global land use change had significant effects on ecosystem services and biodiversity.

Ecosystem services have obvious scale effects. For different temporal and spatial scales, there are clear differences in natural and socioeconomic conditions, which result in certain differences in types, supply and demand capabilities, spatial characteristics, and interactions of ecosystem services [36]. Lu et al. [37] observed complex relationships between ecosystem services in the Loess Plateau, accompanied by significant regional and gradient differences. There was a very high trade-off between biodiversity and soil water content, but a relatively low trade-off between soil organic carbon and total nutrient content. Turner et al. [38] investigated the scale characteristics of 11 different ecosystem services in Denmark using the spatial autocorrelation method; they found that livestock production, food production, and fresh water supply services showed an aggregate distribution within a 150 km spatial scope, while the other eight ecosystem services showed an aggregate distribution within a 50 km spatial scope. Tallis et al. [39] pointed out that determining the trade-off between various ecosystem services at different scales can be clearly conveyed, thereby providing a decision-making framework for ecosystem services through geographical, ecological, and social economic scales; in addition, scientists and policymakers can better understand the potential consequences of the trade-offs between different ecosystem services in land use management.

The goal of ecosystem services trade-off analysis is to optimize the overall benefits [40]. Therefore, the focus is on identifying the best social and economic development and land use change scenario for a synergistic development of different ecosystem services. Bai et al. [41] analyzed the trade-off relationships between ecosystem service agricultural production, water supply, and water quality maintenance using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model. They evaluated five scenarios: non-agricultural land conversion, non-urban expansion, agricultural development, forestry development, and river bank afforestation, in the Baiyang Lake Region of the province Hebei and determined the optimal land use scheme for ecological and economic development. Yang et al. [42] investigated the trade-off and synergic relationships between ecosystem services using a rose diagram and the production possibility frontier method; they also simulated land use scenarios, finally obtaining an optimal plan for land use types that maximizes ecosystem services.

The trade-off and synergic relationships between various ecosystem services are closely related to ecosystem stability. Although the number of studies on trade-offs in ecosystem services has gradually increased, there are still many unsolved issues. For example, the methods that were usually adopted in trade-off research include statistical analysis and spatial mapping. The defects of the statistical analysis method are difficult to quantify the relationship of ecosystem services in spatial terms. The defects of the spatial mapping method are the instability and the unreliability in research results. In addition, the understanding of the mechanisms driving trade-offs in ecosystem services is still in its infancy, trade-off analysis methods are immature, expressions are too simplified, and often data from only two study periods are compared for investigation. Studies on the trade-off relationships between ecosystem services remain scarce in karst mountainous area.

For this study, we selected a mountainous karst area of China with a fragile ecological environment to perform a trade-off analysis of ecosystem services using the InVEST model and production possibility frontier method. The research goals are as follows: (1) assess spatio-temporal variations of four different ecosystem services: water yield, soil conservation, nutrient retention, and carbon storage, from 1990 to 2010; (2) compare the differences in ecosystem services between six land use types; and (3) introduce the production-possibility boundary curves to reveal the trade-off and/or synergic relationships between the four ecosystem services.

2. Methods and data

2.1. InVEST Model

The InVEST model is an assessment model for ecosystem services. It was jointly developed by researchers from Stanford University, The Nature Conservancy (TNC), and the World Wildlife Fund (WWF) and has been widely used in different fields, such as ecology, water resources and hydropower, land resources, and aquaculture [43,44]. The model contains various sub-modules, including water yield, soil conservation, habitat quality, carbon storage, nutrient retention, and timber production [45,46]. In this study, the water yield module, sediment delivery ratio module, carbon module, and nutrient retention module were used to assess the trade-offs between ecosystem services in a mountainous karst area of China.

2.1.1. Water Yield Model

The water yield module is a simplified hydrologic cycle model. It ignores the influence of groundwater and is determined from the precipitation, evapotranspiration, and soil depth. Water yield can be defined as the precipitation in a certain grid unit minus the actual evapotranspiration, which is calculated as

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

where Y_{xj} is the annual water yield of land use type j for grid unit x , AET_{xj} is the annual actual evapotranspiration of land use type j for grid unit x , and P_x is the annual precipitation for grid unit x . AET_{xj}/P_x is the approximate value of the Budyko curve, which can be calculated as

$$\frac{AET_{xj}}{P_x} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \quad (2)$$

where R_{xj} is the Budyko dryness index of land use type j for grid unit x , which is the ratio of potential evapotranspiration to precipitation. ω_x is the modified, dimensionless water amount available for vegetation, which can be used to estimate annual precipitation. The definition of ω_x is as defined in Zhang et al. [47]. It is a non-physical parameter used to describe the natural climatic soil properties, and can be calculated as

$$\omega_x = Z \frac{AWC_x}{P_x} \quad (3)$$

In Equation (3), AWC_x , in units of mm, is the water amount available for vegetation, and its value is determined from the soil texture and depth; Z is an empirical constant, sometimes referred to as the 'seasonality factor', which captures the local precipitation pattern and additional hydrogeological characteristics.

The Budyko dryness index can be expressed using the formula

$$R_{xj} = \frac{k_{xj}ETo_x}{P_x} \quad (4)$$

where ETo_x is potential evapotranspiration for unit x , k_{xj} is the vegetation evapotranspiration coefficient for land use type j for grid unit x ; k_{xj} is defined by the vegetation type, and ETo calculated as

$$ETo = 0.0013 \times 0.408 \times RA \times (T_{avg} + 17) \times (TD - 0.0123P)^{0.76} \quad (5)$$

where RA is the solar irradiation on the top of the atmosphere, which can be obtained from the total solar irradiation divided by 50%, T_{avg} is the mean value of the average daily maximum and minimum temperatures, TD is the difference in the average values of daily maximum and minimum temperatures, and P is the average monthly precipitation.

Available water amount can be calculated based on the physical and chemical properties of the soil according to the formula [48]

$$AWC = 54.509 - 0.132 \times sand\% - 0.003 \times (sand\%)^2 - 0.055 \times silt\% - 0.006 \times (silt\%)^2 - 0.738 \times clay\% + 0.007 \times (clay\%)^2 - 2.688 \times OM\% + 0.501 \times (OM\%)^2 \quad (6)$$

where $sand\%$, $silt\%$, $clay\%$, and $OM\%$ represent the sand content (%), silt content (%), clay content (%), and organic matter content (%), respectively.

2.1.2. Sediment Delivery Ratio Model

The soil conservation module in the InVEST model assesses the potential soil loss according to geographic, geomorphic, and climatic conditions and evaluates the soil conservation ability using the general soil loss equation.

First, the potential soil erosion amount from denudation is calculated using the formula [49]

$$RKLS = R \times K \times LS \quad (7)$$

Second, taking into account vegetation coverage and engineering measures, potential soil loss is calculated by the general soil loss equation as [49]

$$USLE = R \times K \times LS \times C \times P \quad (8)$$

where R is precipitation erosivity ($\text{MJ} \cdot \text{mm} \cdot \text{hm}^{-2} \cdot \text{h}^{-1} \cdot \text{a}^{-1}$), K is soil erodibility ($\text{t} \cdot \text{hm}^2 \cdot \text{h} \cdot \text{hm}^{-2} \cdot \text{MJ}^{-1} \cdot \text{mm}^{-1}$), LS is the steepness factor of the slope length, C is the vegetation coverage and management factor, and P is the engineering measure factor.

R can be calculated as [50]

$$R = \sum_{i=1}^{12} 1.735 \times 10^{[(1.5 \times \lg \frac{p_i^2}{p}) - 0.8188]} \quad (9)$$

where p_i is the average monthly precipitation and p the average annual precipitation.

K can be calculated as [50]

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.025 \text{sand\%} \left(1 - \frac{\text{silt\%}}{100} \right) \right] \right\} \times \left[\frac{\text{silt\%}}{\text{clay\%} + \text{silt\%}} \right]^{0.3} \times \left[1 - 0.025 \frac{\text{OM\%}}{\text{OM\%} + \exp(3.72 - 2.95 \text{OM\%})} \right] \times \left[1 - 0.7 \frac{\text{sn1}}{\text{sn1} + \exp(22.9 \text{sn1} - 5.51)} \right] \quad (10)$$

where sand\% , silt\% , clay\% , and OM\% represent the sand content (%), silt content (%), clay content (%), and organic matter content (%), respectively, and $\text{sn1} = 1 - \text{sand\%}/100$.

Thus, the soil conservation ($\text{t} \cdot \text{hm}^{-2} \cdot \text{a}^{-1}$) can be obtained by subtracting $USLE$ from $RKLS$.

2.1.3. Carbon Model

Carbon storage in the ecosystem primarily consists of four basic carbon pools, namely aboveground, belowground, soil, and dead organic carbon. The carbon module in the InVEST model can evaluate the total carbon storage for each grid through summing the four carbon storage, according to the formula

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

where C_{total} represents the total carbon storage, C_{above} represents the aboveground carbon storage, C_{below} represents the belowground carbon storage, C_{soil} represents the soil carbon storage, and C_{dead} represents the dead organic carbon storage.

2.1.4. Nutrient Retention Model

The nutrient retention module in the InVEST model is used to assess the ability of the ecosystem to purify water by evaluating the nutrient retention ability of the vegetation and soil. This model first calculates the annual average runoff volume using the water yield model and then the contaminant retention amount, using the formula

$$ALV_x = HSS_x \times pol_x \quad (12)$$

where ALV_x is the nutrient output value for grid x , HSS_x is the hydrological sensitivity score for grid x , and pol_x is the output coefficient for grid x . Then, HSS_x can be obtained from the formula

$$HSS_x = \frac{\lambda_x}{\overline{\lambda_W}} \quad (13)$$

where λ_x is the runoff index and $\overline{\lambda_W}$ represents the average runoff index in the region; λ_x can be calculated as

$$\lambda_x = \lg \left(\sum_u Y_u \right) \quad (14)$$

where $\sum_u Y_u$ is the sum of water yields from all other grids to grid x ; after obtaining the output quantities for the nutrients nitrogen (N) and phosphorus (P); the total nutrient retention is the sum of N and P.

2.2. The Production possibility frontier

2.2.1. Basic Production possibility frontier Concept

The production possibility frontier (PPF) represents the combination of the largest number of various commodities produced from an economic society with the given resources and technology conditions [51,52]. It usually manifests as a comparison of the production possibilities of two commodities and can reflect the economic characteristics of resource scarcity and selectivity; these can illustrate the potential and excess problems, and determine the optimal combination for production. Assuming that the given resources can generate two products, the quantity of products is fixed, and PPF can express the production collocation of the two products.

The primary PPF assumptions are as follows. Given the resources, products A and B are configured for production. If all given resources are used for product A, 400 items can be produced, while the quantity of product B is zero. Taking the quantity of product A as the x -axis and that of product B as the y -axis, then the point coordinates are 400, 0. If 300 items of product A are produced, then 150 items of product B can be produced, which corresponds to the point coordinates of 300, 150. If 200 items of product A are produced, then 225 items of product B can be produced, which corresponds to the point coordinates of 200, 225. If 100 items of product A are produced, then 275 items of product B can be produced, which corresponds to the point coordinates of 100, 275. If all given resources are used to produce product B, 300 items can be produced, while the quantity of product A is zero, which corresponds to the point coordinates of 0, 300. Thus, as shown in Figure 1, we can obtain a PPF curve for the production of A and B.

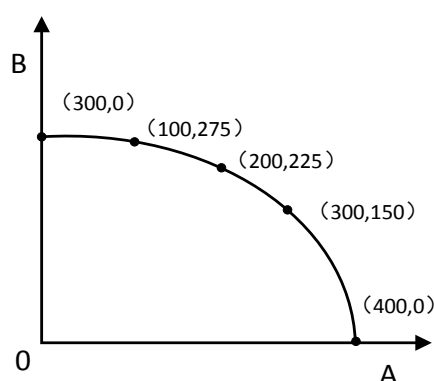


Figure 1. An example of a production possibility frontier curve for two products, A and B.

2.2.2. Application of the Production possibility frontier

The production possibility frontier is a production concept, whereas ecosystem services are also the output to the environment, and provide services for both humans and ecosystems. Therefore, the trade-off between different ecosystem services can be analyzed as an economic problem in which the trade-off and synergistic relationships between two types of ecosystem services can be described using the production-possibility boundary curve.

First, natural resources are fixed resources for ecosystem services. Due to differences in natural and social economic conditions, there is a trade-off between different ecosystem services. Therefore, to ensure one ecosystem service, it is inevitable to sacrifice the others. Moreover, their intrinsic spatial and temporal heterogeneity makes any two ecosystem services have an optimal combination for the largest overall profit, in agreement with the production possibility frontier concept.

Second, there are six forms of the trade-off relationship for ecosystem services [35,53,54] (Figure 2), the points under the curve represent the quantitative relationship between two ecosystem services, and the curve is the optimal combination of this two ecosystem services. Figure 2a is an independent model. The optimal solution of the model is at the vertex of the two lines. Figure 2b is a linear model. In the model, the increase of one service usually results in a proportional decrease of the other services. Figure 2c is a convex-curve model. In the model, obtaining even a small increase of one kind of service is usually at the cost of a large sacrifice of other services. Figure 2d is a concave-curve model. Although trade-off exists in the model, there are still some special scenarios in the figure, i.e., the increase of one service did not lead to obvious changes of other services. Figure 2e is a non-monotonic concave-curve model. In the model, changes in one kind of ecosystem service can lead to two opposite changes of the other ecosystem service. There may be a synergism in the system. Figure 2f is a reverse 'S'-type curve model. In the model, within a certain interval range, one ecosystem service can increase without leading to the changes in other services. However, when reaching a threshold, the increase of one

ecosystem service can leading an obvious reduction of the other ecosystem services. In the six models, each model generates a curve that is similar to the production possibility frontier.

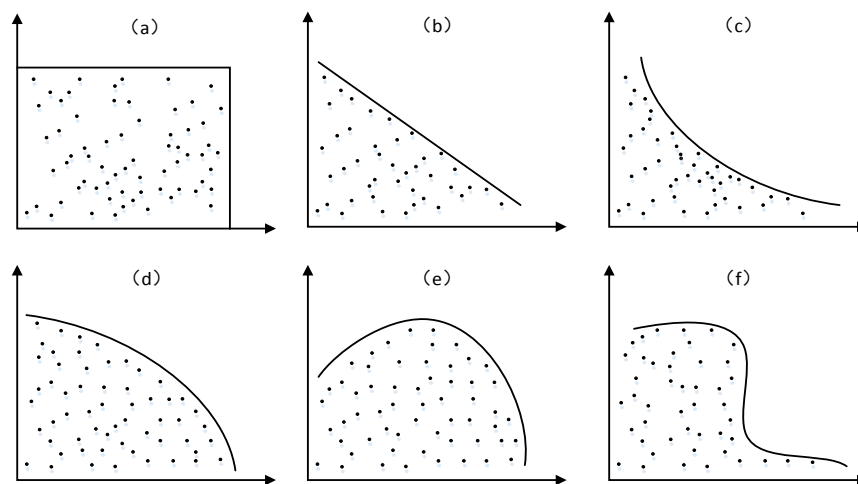


Figure 2. Six forms of the trade-off relationship for ecosystem services: the independent (a), linear (b), convex-curve (c), concave-curve (d), non-monotonic concave-curve model (e), and reverse 'S'-type curve (f) models.

Finally, the production possibility frontier reflects the scarcity and selectivity of resources and analyzes the optimal combination of different products. In comparison, the trade-off issue for ecosystem services also analyzes the reciprocal relationship between two ecosystem services to obtain an optimal solution. As a result, the production-possibility boundary curve has a certain applicability in investigating ecosystem services trade-offs. Therefore, we use the production possibility frontier to depict the trade-off and synergistic relationships between pairs of ecosystem services.

In this study, the production possibility frontiers for each pair of ecosystem services were analyzed using the InVEST model and the four ecosystem services of water yield, soil conservation, nutrient retention, and carbon storage. The production possibility frontier curves for the optimal combinations of each pair of ecosystem services were depicted, and specific analyses were conducted on the trade-off and synergistic relationships between those optimized pairs.

2.3. Data Sources

Land use data from 1990, 1995, 2000, 2005, and 2010 were obtained from the remote sensing monitoring database for current land use in China, at a scale of 1:100,000. Precipitation and temperature data were obtained from the China Meteorological Data [55]; 30 m digital elevation model (DEM) data were obtained from Geospatial Data Cloud [56]; soil depth data were obtained from the World Soil Database [57]; and soil sand, silt, clay, and organic carbon content data, and nutrient (Nitrogen and Phosphorus) data were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences [58]. All grid data used in this paper refer to 1000×1000 m.

3. Study Area

The mountainous karst study area in China is located between $42^{\circ}15' - 44^{\circ}55'$ N and $80^{\circ}5' - 84^{\circ}5'$ E (Figure 3). This region is located in south-southwest China, with a total area of about 214,100 km² and an elevation of 0–3000 m above sea level, gradually increasing in elevation from southeast to northwest. In this region, small and medium-sized rolling mountainous lands dominate, and the karst physiography is widely distributed. The karst physiognomy gradually transitions from plateau peak cluster to hilly plain hoodoo physiognomy from southeast to northwest. The soil types are primarily limestone, latosolic red, red, and yellow soil; whereas cultivated land with thick soil layer, high

fertility, and good water conservation conditions account for a low proportion of the area. The climate ranges from subtropical moist monsoon climate to subtropical monsoon climate from north to south. Annual average temperatures range between 14 and 24 °C, gradually increasing from north to south. The regional water systems include the Sanchahe, Yachihe, Qingshuijiang, Nanpanjiang, Hongshuihe, Liujiang, Yujiang, and Qianjiang Rivers, and a large number of other tributaries. Annual average precipitation in this region varies between 900 and 1700 mm, gradually increasing from north to south.

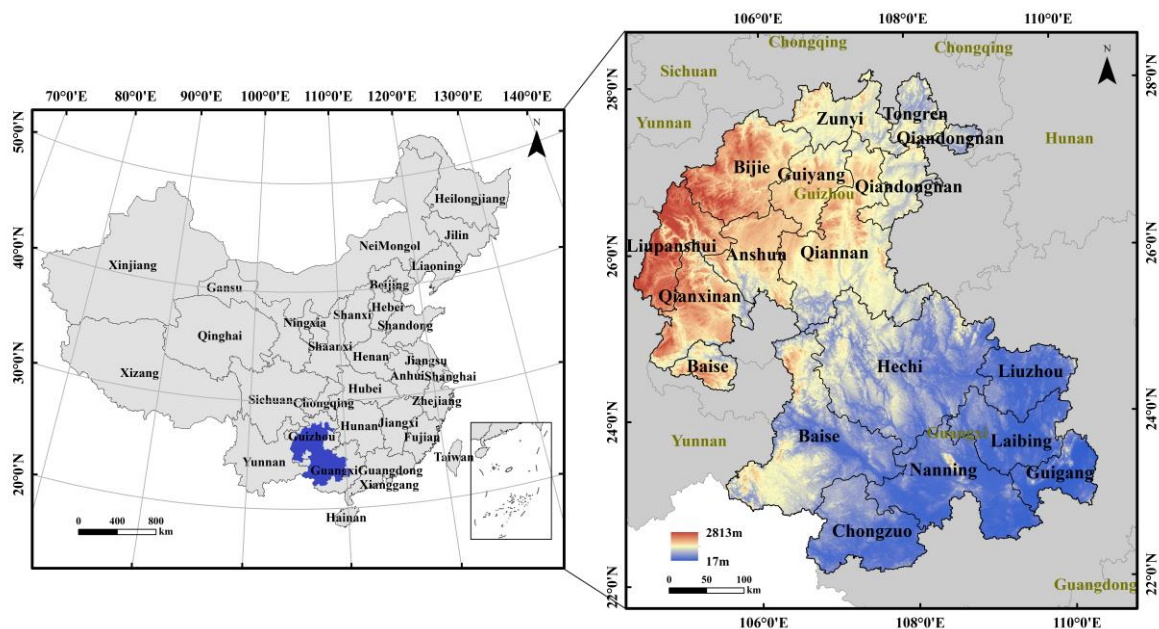


Figure 3. Geographic position of the study region.

The mountainous karst area of China has a population of about 46.16 million, with a relatively small corresponding economic aggregate that accounts for less than 3% of China's GDP (Gross Domestic Product). The ecological environment is complex and diverse, resulting in high biodiversity. However, the ecological environment is very fragile, and with intensifying human activities, the lack of water resources in this region is becoming more serious. Concurrently, ecological issues—such as drought and flood disasters, vegetation destruction, trends toward single ecosystem structure, soil erosion, and rocky desertification—have become concerns in this area.

4. Results

4.1. Temporal and Spatial Variation of Ecosystem Services in the Karst Mountainous Area

4.1.1. Temporal and Spatial Variation of Water Yield

Water yield is influenced by both land use change and climate change. Spatially, the distribution of water yield is generally consistent with the distribution of precipitation, and progressively increases from northwest to southeast (Figure 4). Quantitatively, the annual average water yield in the mountainous karst area fluctuates, but has a decreasing trend from 992.60 mm in 1990 to 968.10 mm in 2010, or 2.47%. Water yields have fluctuated, but generally have increased in the northwest and decreased to the southeast. The incremental increase in mean annual water yield in the southeast is the largest, exceeding 300 mm; in contrast, the southwest shows the largest decrease in annual average water yield. In some regions in the southwest, the decrease is even more than 400 mm.

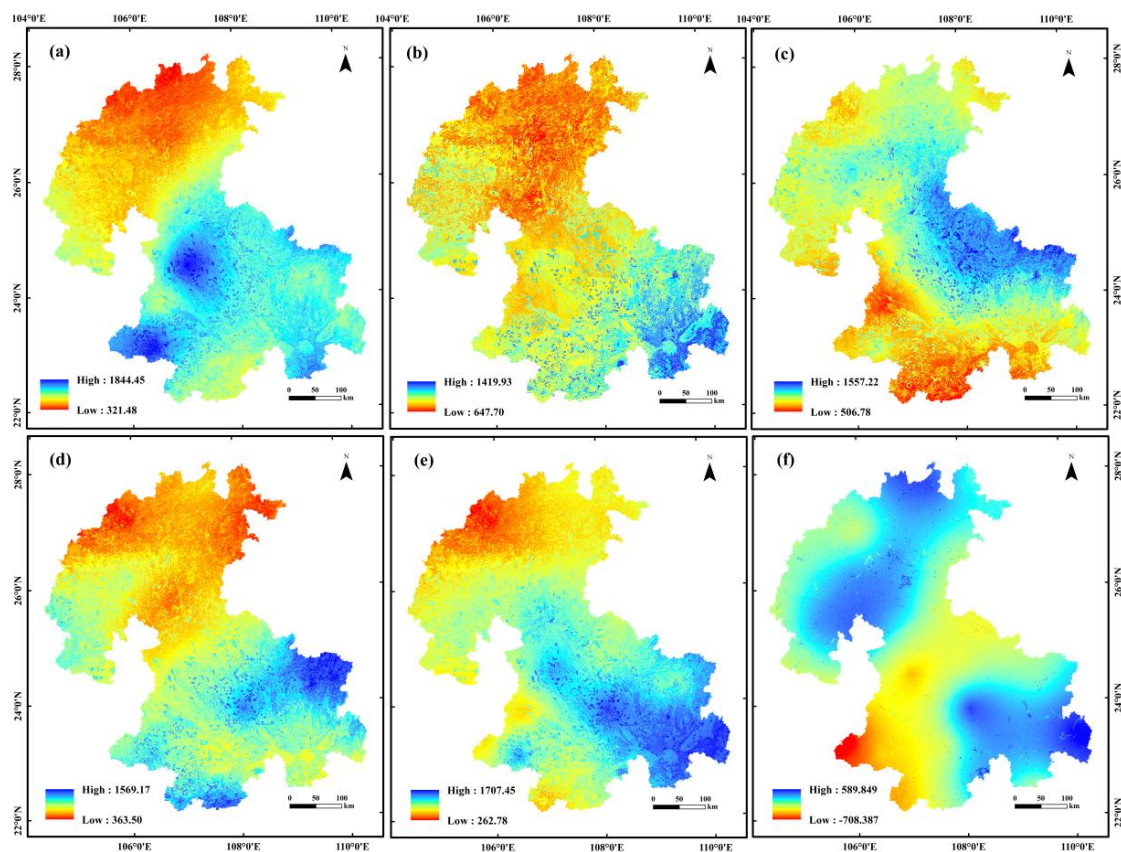


Figure 4. Water yields from 1990 to 2010, (a) 1990, (b) 1995, (c) 2000, (d) 2005, and (e) 2010, and (f) water yield variation from 1990 to 2000 (all units are in mm).

4.1.2. Temporal–Spatial Variation in Soil Conservation

From 1990 to 2010, the regions with a relatively high slope in the northwestern, central, and southwestern regions had a high soil conservation value, while those with a relatively flat terrain in the northern, the southern, and the southeastern parts had a low soil conservation value (Figure 5). Regional soil conservation is influenced by a variety of factors, such as climate, topography, land use, and human activities. Soil conservation showed large differences between 1990 and 2010 in the mountainous karst area. Annual average soil conservation increased by 29,295.05 t/km² (39.43%), from 74,294.70 t/km² in 1990 to 103,590.19 t/km² in 2010. Spatially, the annual average soil conservation for most regions had an increasing trend. Areas with a relatively high slope in the middle and the southeast parts had the largest incremental increase in soil conservation, exceeding 40,000 t/km²; only a few regions in the northwest and southwest had a decreasing trend, exceeding 2000 t/km².

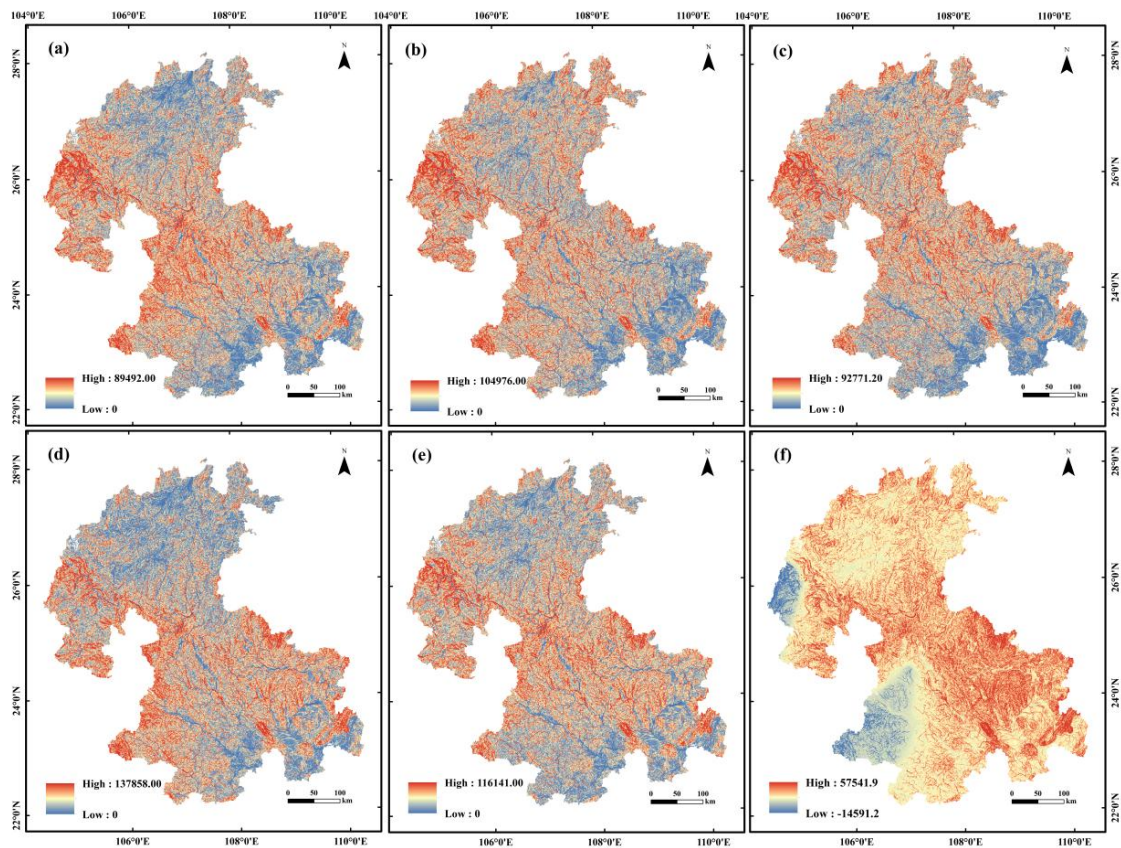


Figure 5. Soil conservation quantities from 1990 to 2010, (a) 1990, (b) 1995, (c) 2000, (d) 2005, and (e) 2010, and (f) soil conservation variations from 1990 to 2010 (all units are in t/km^2).

4.1.3. Temporal–Spatial Variation of Carbon Storage

From 1990 to 2010, the spatial distribution of carbon storage in this mountainous karst area indicated lower values at either the beginning or end of the period, but higher values toward the middle. Temporally, changes in land use corresponded to changes in annual average carbon storage, fluctuating but generally decreasing from $3080.96 \text{ kg}/km^2$ in 1990 to $3073.62 \text{ kg}/km^2$ in 2010, a total of $10.34 \text{ kg}/km^2$ (0.34%); the change was relatively small. Spatially, carbon storage change corresponded to regions with land use change, primarily distributed in the Qiannan region and the cities of Hechi (central) and Baise (southwest), which showed the largest variation in carbon storage. In contrast, Zunyi City in the north, Tongren City in the northeast, and Liuzhou City in the southeast showed relatively small carbon storage variations. Therefore, we suggest that regional carbon storage is closely related to land use change (Figure 6).

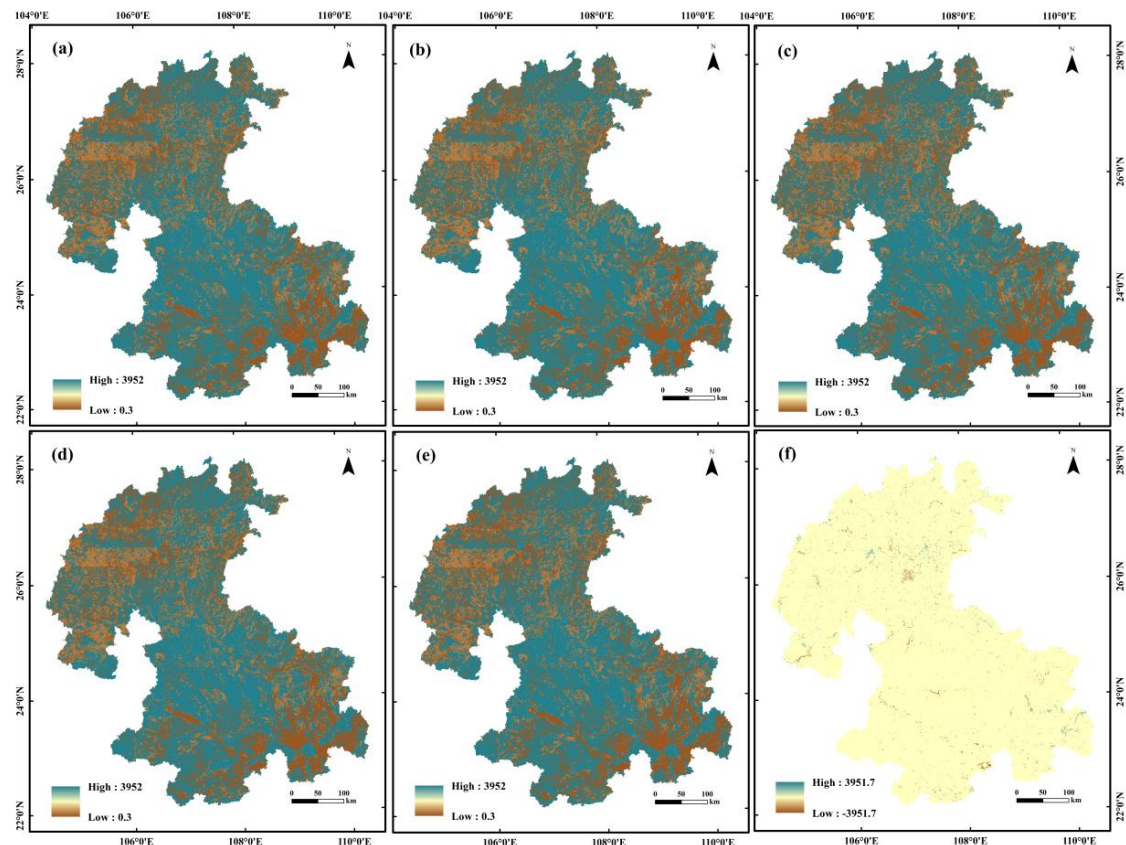


Figure 6. Carbon storage from 1990 to 2010, (a) 1990, (b) 1995, (c) 2000, (d) 2005, and (e) 2010, and (f) carbon storage variations from 1990 to 2010 (all units are in t/km^2).

4.1.4. Temporal–Spatial Variation of Nutrient Retention

Here, nutrient retention refers to N (nitrogen) and P (phosphorus). The entry of excessive nutrients and toxic substances into water areas can cause eutrophication, which directly affects the growth of aquatic organisms, including fish, and negatively impacts humans consuming these fish. These nutrients and contaminants can be partially retained by the ecosystem, for example, plants can store and convert contaminants, thereby reducing the discharge of contaminants into water. Higher nutrient retention of the ecosystem results in fewer nutrients entering water, which improves water quality functions.

The nutrient retention of most regions in the mountainous karst area was less than $1000 \text{ kg}/\text{km}^2$ (Figure 7), and only a few regions had a nutrient retention greater than $1000 \text{ kg}/\text{km}^2$, which were scattered along the rivers across the whole area. Due to the combined impacts of land use and climate change, the nutrient retention varied temporally, but generally decreased. The average nutrient retention decreased slightly, $7.12 \text{ kg}/\text{km}^2$ (1.16%), from $613.01 \text{ kg}/\text{km}^2$ in 1990 to $605.90 \text{ kg}/\text{km}^2$ in 2010.

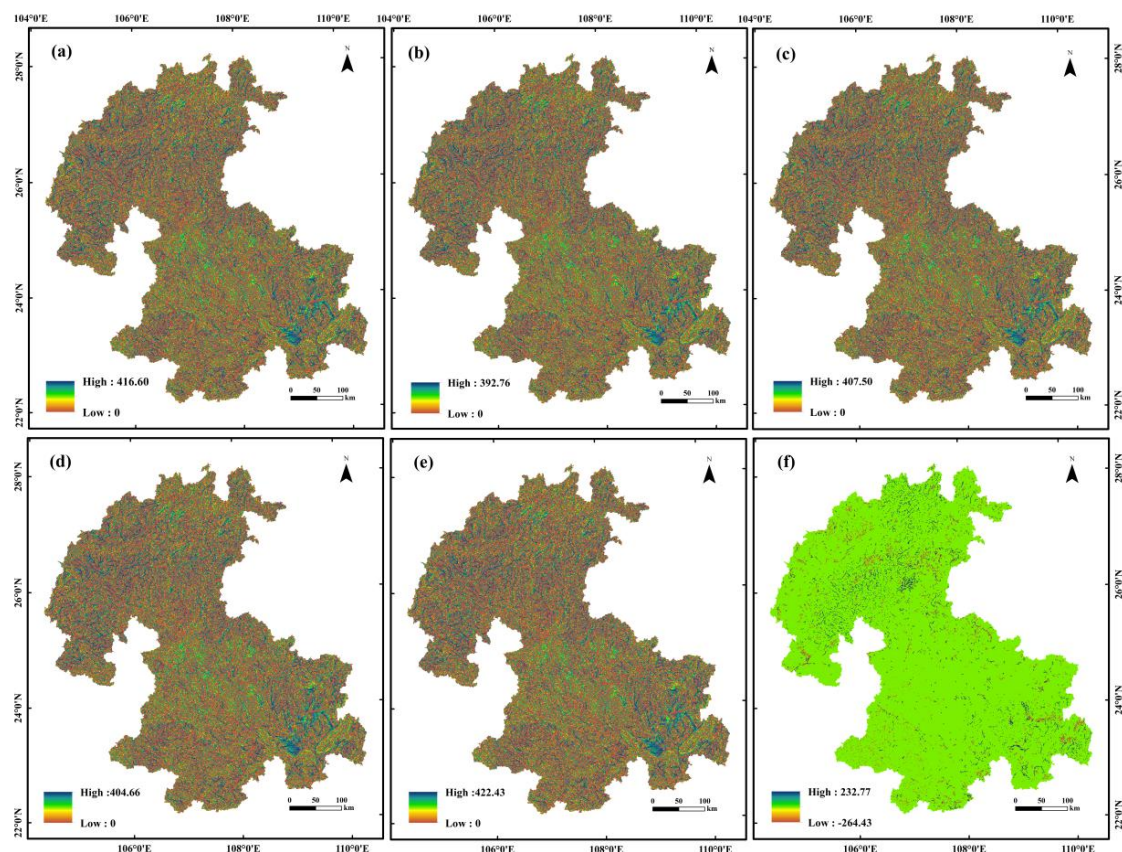


Figure 7. Nutrient retention from 1990 to 2010, (a) 1990, (b) 1995, (c) 2000, (d) 2005, and (e) 2010, and (f) variation in nutrient retention from 1990 to 2010 (all units are in t/km^2).

4.2. Variation in Ecosystem Services between Land Use Types

Ecosystem services showed clear differences between land use types. From 1990 to 2010, construction land had the largest water yield, averaging 1220.64 mm; idle land had the second largest annual average water yield of 1059.56 mm, followed by grass land and cultivated land, which had annual average water yields of 1010.98 and 992.84 mm, respectively. Water areas and forest land had the smallest water yields, 922.18 and 912.64 mm, respectively. The water yield of these land use types were ranked in the following order: construction land > idle land > grass land > cultivated land > water areas > forest land.

From 1990 to 2010, grass land and forest land had the largest annual average soil conservation of 91,404.87 and 31,387.63 t/km^2 , respectively, followed by cultivated land and water areas (76,292.20 and 68,563.46 t/km^2 , respectively), and construction land and idle land (52,373.37 and 34,306.74 t/km^2 , respectively). Soil conservation followed the order: grass land > forest land > cultivated land > water areas > construction land > idle land.

Forest land had the largest carbon storage, with an annual average carbon storage of 3952.00 kg/km^2 , followed by cultivated land and grass land with carbon storage of 1948.00 and 2217.00 kg/km^2 , respectively. Construction land, water areas, and idle land had relatively small annual average carbon storage of 0.3, 0.9, and 1.1 kg/km^2 , respectively. Carbon storage values were ranked in the following order: forest land > grass land > cultivated land > idle land > water areas > construction land.

Forest land, grass land, and cultivated land had relatively large annual average nutrient retention, >600 kg/km^2 ; grass land had the largest of 650.12 kg/km^2 ; forest land had the second largest of 617.91 kg/km^2 ; and cultivated land had the smallest of 610.82 kg/km^2 . In contrast, water areas, construction land, and idle land all had annual average nutrient retention, <200 kg/km^2 , 160.27, 166.91,

and 90.90 kg/km², respectively. Nutrient retention were ranked in the following order: grass land > forest land > cultivated land > construction land > water areas > idle land.

In the same ecosystem, ecosystem services differed significantly, therefore, an average normalization was performed for each ecosystem service (Figure 8). The ecosystem services for cultivated land and grass land were relatively balanced, while the nutrient retention and carbon storage were slightly larger than those for water yield and soil conservation. Forest land had relatively large ecosystem services, with the exception of water yield; the four ecosystem services for water areas were all relatively small. Construction land and idle land had relatively large water yield, while soil conservation, carbon storage, and nutrient retention were comparatively small.



Figure 8. Variation in ecosystem services between different ecosystems. Notes: the normalization formula is $S_{ij} = A_{ij}/T_i$, where S_{ij} is the normalized value of the i -th ecosystem service for j -th land use type, A_{ij} is the average of the i -th ecosystem service for j -th land use type, and T_i is the average of i -th ecosystem service in the mountainous karst area.

4.3. Analysis of Spatial Ecosystem Service Trade-Offs

Variations in natural and socioeconomic conditions can affect regional ecosystem services with different relationships. They interact and have trade-offs or synergistic relationships. This study investigated the spatial trade-off and synergistic relationships of pairwise ecosystem services for water yield, soil conservation, carbon storage, and nutrient retention using the production possibility frontier analysis method. We further quantitatively analyzed the spatially reciprocal relationships of ecosystem services.

As shown in the production possibility frontier curves, the existing trade-off relationships include:

- (1) Water yield and soil conservation: When water yield increases, the soil conservation decreases; According to the production possibility frontier concept, water yield can be regarded as an opportunity cost of soil conservation. As shown in Figure 9a, from point a to point b, a 0.066 m decrease in water yield represents an increase of one million tons of soil conservation; while from point c to point d, a 0.114 m decrease in water yield represents an increase of 1 million tons of soil conservation. Thus, the required opportunity cost investment to achieve a certain soil conservation is quite different at different stages. To increase soil conservation, opportunity cost will need to gradually increase.
- (2) Nutrient retention and water yield: Increases in water yield lead to gradual decreases in nutrient retention. Water yield is the opportunity cost for nutrient retention. As shown in Figure 9b, from point a to point b, a 0.1 m decrease in water yield can result in an increase of 100×10^2 kg in nutrient retention; from point b to point c, the variation amplitude consistently varies; from point c to point d, a 0.22 m decrease in water yield results in an increase of 100×10^2 kg in nutrient retention. To obtain a certain nutrient retention, only a slight opportunity cost is required at the initial stage; as investments are made in opportunity cost, the nutrient retention gradually decreases.
- (3) Carbon storage and water yield: Increases in water yield result in gradual decreases in carbon storage; water yield can therefore be regarded as an opportunity cost of carbon storage. As shown in Figure 9c, from point a to point b, a 115.22 m decrease in water yield results in an increase of 100×10^3 tons of carbon storage; while from point c to point d, a 216.82 m decrease in water yield is required to achieve an increase of 100×10^3 tons of carbon storage. To obtain a certain carbon storage, the opportunity costs at different stages vary and the water yield pay-out gradually increases.
- (4) Nutrient retention and soil conservation: Soil conservation can be conceptualized as the opportunity cost of nutrient retention. As shown in Figure 9d, from point a to point b, a 2.83 million tons decrease in soil conservation can result in a 100×10^2 kg increase in nutrient retention; while from point c to point d, a 2.57 million tons decrease in soil conservation results in a 100×10^2 kg increase in nutrient retention; therefore, as soil conservation decreases, nutrient retention gradually increases.

Synergistic relationships include:

- (1) Carbon storage and nutrient retention: As shown in Figure 10a, from point a to point b, a 0.1×10^3 ton increase in carbon storage can result in an increase of 3656.29×10^2 kg in nutrient retention; from point b to point c, the variation amplitude consistently varies; from point c to point d, a 0.1×10^3 ton increase in carbon storage results in a $10,304.29 \times 10^2$ kg increase in nutrient retention. Therefore, continuously increasing carbon storage results in continually increasing nutrient retention.
- (2) Carbon storage and soil conservation: As shown in Figure 10b, from point a to point b, carbon storage increase 100×10^3 tons, with a corresponding soil conservation increase of 181.238 million tons; from point b to point c, the variation amplitude consistently varies; from point c to point d, carbon storage increase 100×10^3 tons with a corresponding increase in soil conservation

of 26.867 million tons. Therefore, increases in carbon storage result in consistent decreases in soil conservation.

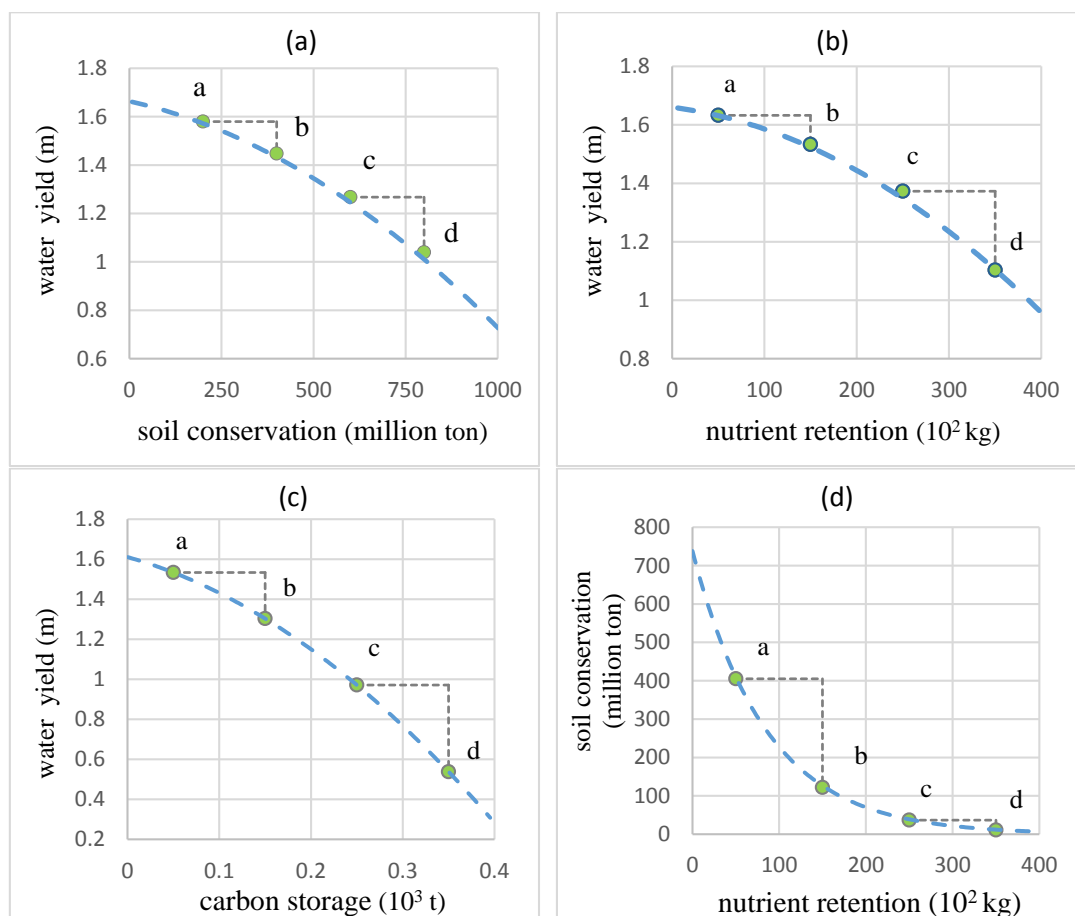


Figure 9. Production possibility frontier curve for soil conservation and water yield (a); production possibility frontier curve for nutrient retention and water yield (b); production possibility frontier curve for carbon storage and water yield (c); production possibility frontier curve for nutrient retention and soil conservation (d).

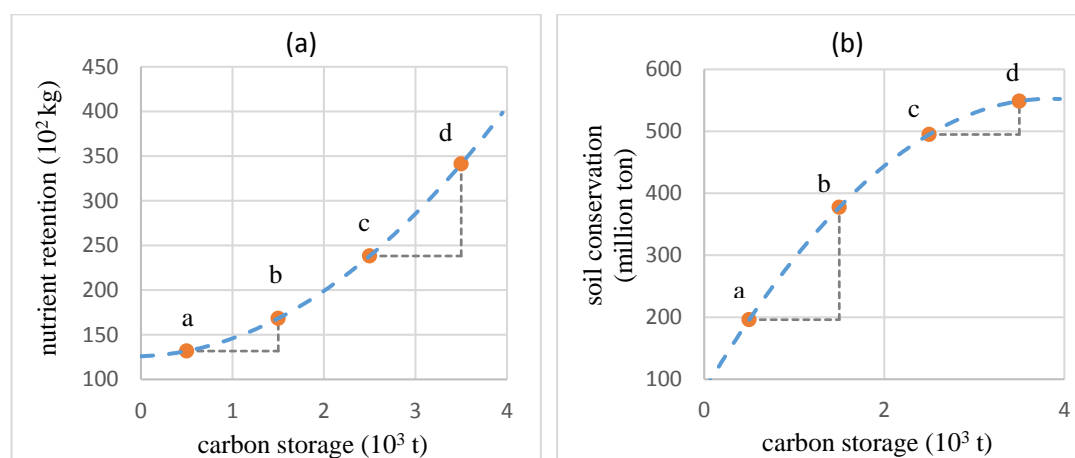


Figure 10. Production possibility frontier curve for nutrient retention and carbon storage (a); production possibility frontier curve for soil conservation and carbon storage (b).

5. Discussion

5.1. Trade-Offs Analysis and Main Findings of This Paper

According to the definition of trade-off [17], trade-off of ecosystem services refers to the provision of one kind of ecosystem service usually decrease due to the utilization increase of other kinds of ecosystem service. The trade-off includes the trade-off between ecosystem services, and the trade-offs between different ecosystems. Moreover, the relationships between ecosystem services are not simple correlations. As we have discussed in Figure 2, six kinds of trade-off lines can be drawn. Although the shape of the six trade-off lines are different, they all describe the substantive characteristics of ecosystem service trade-off, i.e., the increase of one kind of ecosystem service is usually the cost of the decrease of the other kind of ecosystem service. In general, trade-offs can be classified into two types, i.e., spatial trade-off and temporal trade-off. Spatial scale trade-off refers to the trade-off relationship of different ecosystem services were presented in spatial due to the changes in locations. For example, from the foot to the peak of the mountain areas, the grain production function would decrease while the carbon storage could increase due to the changes in land use types. Temporal scale trade-off refers to trade-off relationship presented in temporal according to time variation [19,59,60]. For example, along with grow of trees, the carbon storage could increase while the water yield could decrease.

The research presented in this paper belongs to spatial trade-offs. In this paper, water yield has trade-off relationships with soil conservation, carbon storage, and nutrient retention; soil conservation also has a trade-off relationship with nutrient retention, while carbon storage has synergistic relationships with soil conservation or nutrient retention (Table 1). Our findings are different from some previous researches such as Bai et al. [61] and Han et al. [62]. The former research analyzed the trade-offs in ecosystem services according to five alternative land use and land cover scenarios. It was found that there are important potential trade-offs among ecosystem services of agricultural production, hydropower production, and water quality. The latter research conducted a trade-off analysis of ecosystem services using a double mass curve (DMC) approach. It was found that the synergistic relationships instead of trade-off relationships were observed among net primary productivity (NPP), water yield, and soil conservation. Our results were slightly different.

Table 1. Main findings of this paper.

Major Findings	Limitations	Geographic Scale and Regions
The production possibility frontier method can be adopted to quantify the ecosystem service trade-off relationships.	This method is can only describe the trade-off relationship between two ecosystem services.	All regions
Water yield has trade-off relationships with soil conservation, nutrient retention, and carbon storage.	There are uncertainties in the assessments because InVEST model rarely adopts socioeconomic data and survey data.	Karst mountainous area
Carbon storage has synergistic relationships with nutrient retention and soil conservation.	There are uncertainties in the assessments because InVEST model rarely adopts socioeconomic data and survey data.	Karst mountainous area
Land use change is the most intuitive, regular, and systematic factor can explain the differences in ecosystem services.	The actual differences are more complicate, and each grid has its own characteristics.	Varies from place to place

The method applicability of production possibility frontier is another main finding of our paper. In the previous researches [7–9,34–36,61,62], the trade-off analysis of ecosystem services is usually qualitative. In limited quantitative researches, method of linear regression, land use change scenario analysis and DMC curve were usually adopted to perform trade-off analysis. However, these methods are not developed based on the definition of a ‘trade-off’. In fact, the concept of a ‘trade-off’ came from economics. The production possibility frontier is in fact a production concept which was utilized to

describe the input and output of production. A production–possibility frontier is the possible trade-off of producing combinations of goods with constant technology and resources per unit time. Therefore, the production possibility frontier can better describe the trade-off relationships in ecosystem services than the previous methods.

In addition, we also found that, spatially, except for slightly varying factors (such as geomorphology, altitude, and geological conditions) and unpredictable factors (such as climate change), land use change is the most intuitive, regular, and systematic factor. It is accompanied by changes in landscape structure and patterns, physical and chemical soil properties, and vegetation cover. Moreover, ecosystem services for different land use types vary significantly.

There are some limitations in our study. First, the InVEST model is based on natural data and rarely uses socioeconomic data and survey data. However, ecosystem services are closely related to the socioeconomic developments and human activities. Therefore, there are some uncertainty in the results of assessment. Second, the production possibility frontier method is still immature. The curve only represents the optimal combination of random two ecosystem services. Nevertheless, there are still other complicated relationships that were not mentioned in this paper.

5.2. Necessary of Trade-Off Assessment and Its Potential Contribution for Policy Making

Trade-off analysis is very necessary for sustainable development. In the past several decades, the human beings have a rapid development in their capacities to transform the natural environment. To feed the continuously increasing population worldwide, human beings have paid much attention to the increase of ecosystem provision functions such as the grain production and timber production. However, the increase of provision function has inevitably lead to decreasing of regulation, culture, and biodiversity [63]. To achieve the goal of sustainable development, it is necessary to comprehensively consider multiple ecosystem service functions instead of focusing on pursuing a single ecosystem function. Nowadays, researchers have come to understand some causal relationships between human activities and ecosystem service changes such as deforestation and soil conservation. However, the nonlinearity features between deforestation and soil conservation are still not clear [63]. In particular, the nonlinearity features could change along with the changes in geographical locations. In addition, a lot of relationships between human activities and ecosystem service changes in different regions are still not clear. Trade-off analysis provides an effective tool to solve this problem.

Trade-offs are very important to understand in order to help with policy making. First, the trade-off analysis can provide scientific basis for region land use planning, biodiversity protection, and eco-compensation. For example, reclaiming forestry land to cultivated land can increase the function of grain production while decrease the function of biodiversity and climate regulation [63]. On the basis of trade-off analysis in a spatial context, we can design several different land use change scenarios and select the optimal one. In addition, in the management practice, regulating services were usually underestimated due to the slow process of the formation regulating services. Trade-off analysis can help to identify the relationship between regulating services and other ecosystem services that result from human activities. This would help enacting effective policies to conserve the regulating services in ecosystems.

In this paper, evaluating ecosystem services, clarifying their variations and conducting trade-off analysis of ecosystem services can provide the foundation for sustainable economic development and establishing an ecological balance in the mountainous karst area. Our study shows that from 1990 to 2010, among the four ecosystem services in the karst mountainous area, only soil conservation increased, whereas water yield, carbon storage, and nutrient retention all decreased. For different ecosystems, the dominant ecosystem services also varied. The increase in construction land is conducive to increases in water yield, increases in forest land are conducive to increases in carbon storage and soil conservation, while vegetation restoration has positive influences on nutrient retention. From an economic perspective, decreasing opportunity costs are due to transformations in land use [64]. In trade-off relationships between ecosystem services, improvements in any ecosystem service occur

at the cost of another ecosystem service, namely through land use change. It is impossible to infinitely increase one certain land use type. For economic development, it is necessary to expand cultivated land and construction land areas, which will inevitably lead to increases in regional water yield; however, this necessarily occurs at the cost of sacrificing forest land and grass land. Decreasing forest land area will result in decreasing soil conservation, nutrient retention, and carbon storage, which inhibits regional ecological protection [65,66]. Therefore, we should pay equal attention to economic development and ecological protection, and guarantee a balanced development of ecosystem services when searching for maximum benefits.

6. Conclusions

Under the combined influences of natural and socioeconomic conditions, each ecosystem service in the mountainous karst area shows different degrees of variation, both temporally and spatially. From 1990 to 2010, water yield had a generally increasing trend from the northwest to the southeast; the annual average water yield decreased 24.50 mm (2.47%). The regions with higher slopes in the northwest, middle, and southwest had higher soil conservation, while those with relatively flat terrain in the north, south, and southeast had lower soil conservation, annual average soil conservation had a generally increasing trend, and increased by 29,295.05 t/km² (39.43%). Carbon storage variations were more complex, with low values at the beginning and end of the study period, and high values in the middle, the annual average carbon storage decreased by 10.34 kg/km² (0.34%). For most regions in the mountainous karst area, nutrient retention was below 1000 kg/km², only a few regions with a nutrient retention of more than 1000 kg/km² were scattered throughout the area. The annual average nutrient retention generally decreased, with some fluctuations, and decreased by 7.12 kg/km² (1.16%).

In our study, cultivated land and grass land had relatively balanced ecosystem services, while forest land had three ecosystem services that were high. The four ecosystem services for water areas were all relatively low. The water yield for construction land and idle land were relatively high, while the other three services were low. Spatially, water yield has trade-off relationships with soil conservation, nutrient retention, and carbon storage. With increasing water yield, soil conservation, nutrient retention, and carbon storage all show accelerated decreases. Meanwhile, soil conservation also has a trade-off relationship with nutrient retention, with decreasing soil conservation, nutrient retention gradually increases.

In previous studies, trade-offs in ecosystem services were usually analyzed using simple linear or nonlinear curves. In this paper, we introduced the production possibility frontier into the analysis of trade-off. This method analyzed the trade-off in ecosystems from an economic perspective. Therefore, the result of the paper could be more reasonable than previous studies.

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