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Trade-offs among ecosystem services in a typical Karst watershed, SW China

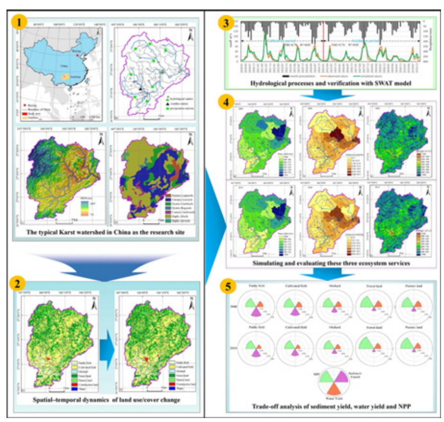
Yichao Tian [a,b,c], Shijie Wang [a,c], Xiaoyong Bai [a,c,*], Guangjie Luo [a,c], Yan Xu [a,c]

[a] State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Puding Karst Ecosystem Observation and Research Station, Anshun, Guizhou 561000, China

HIGHLIGHTS

- We developed an integrated model to quantify ecosystem services by coupling CASA and SWAT.
- Cultivated field shrinkage, pasture and forest land expansion were observed during 2000–2010.
- The sediment and water yields exhibited a decreasing trend, whereas NPP was reversely varied.
- We assessed the synergies and trade-offs relationships among ecosystem services.

GRAPHICAL ABSTRACT



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ABSTRACT

Nowadays, most research results on ecosystem services in Karst areas are limited to a single function of an ecosystem service. Few scholars conduct a comparative study on the mutual relationships among ecosystem services, let alone reveal the trade-off and synergic relationships in typical Karst watershed. This research aims to understand and quantitatively evaluate the relationships among ecosystem services in a typical Karst watershed, broaden the depth and width of trade-off and synergic relationships in ecosystem services and explore a set of technical processes involved in these relationships. With the Shibantang Karst watershed in China as the research site, we explore the trade-off and synergic relationships of net primary productivity (NPP), water yield, and sediment yield by coupling Soil and Water Assessment Tool (SWAT) and Carnegie–Ames–Stanford Approach (CASA), and simulating and evaluating these three ecosystem services between 2000 and 2010. Results of this study are as follows. (1) The annual average water yield decreased from 528 mm in 2000 to 513 mm in 2010, decreasing by 2.84%. (2) The annual average sediment yield decreased from 26.15 t/ha in 2000 to 23.81 t/ha in 2010, with an average annual reduction of 0.23 t/ha. (3) The annual average NPP increased from 739.38 g C m^{-2} a^{-1} in 2000 to 746.25 g C m^{-2} a^{-1} in 2010, increasing by 6.87 g C m^{-2} a^{-1}. (4) Water yield and sediment yield are in a synergic relationship. The increase of water yield can accumulate the soil erosion amount. NPP is in a trade-off relationship with water yield and sediment yield. The improvement of NPP is good for decreasing water yield

* Corresponding author at: State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, 46# Guanshui Road, Guiyang, Guizhou 550002, PR China.
E-mail address: baixiaoyong@126.com (X. Bai).

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and soil erosion amount and increasing soil conservation amount. This study provides policy makers and planners an approach to develop an integrated model, as well as design mapping and monitoring protocols for land use change and ecosystem service assessments.

1. Introduction

Ecosystem services refer to natural conditions and utilities provided by ecosystems and ecological processes that sustain human life (Daily, 1997). They mainly consist of provisioning, regulating, and cultural services that directly affect human well-being, as well as supporting services needed to maintain these three (Daily, 1997; Costanza et al., 1997; Ma, 2005). Ecosystem services are closely related to human well-being, and research on these services has attracted the attention of many scholars and organizations (Ma, 2005; Costanza et al., 2007; Turner and Daily, 2008; Whitehead and Crossman, 2012; Gibbons et al., 2014).

Land use and land cover change not only induces considerable change in surface structure but also greatly affects regional climate (Carlson and Arthur, 2000; Wu et al., 2014), hydrology and water resources (Langan et al., 1997; Gornitz et al., 1997; Weber et al., 2001; Sterling et al., 2012), soil (Islam and Weil, 2000), biodiversity (Crist et al., 2000), carbon cycle (Tian et al., 2012), and biogeochemical cycle of the region (Liu et al., 2009), which significantly influence the structure and functions of the entire ecosystem. Humans activities on land cause considerable changes to the land coverage of the surface and ultimately to the ability of the ecosystem service to provide (Vitousek et al., 1997; Foley et al., 2005; Ma, 2005). Among these activities, the Grain for Green Program (GGP) from 1999 is an important ecology project with the largest investment, strongest policy, widest range and highest public participation degree in China and the world (Uchida et al., 2005; Liu and Diamond, 2005; Liu et al., 2008). A total of 23,344 (1000 ha) of lands, including 8268 (1000 ha) of croplands and 15,076 (1000 ha) of barren lands, had been planted under the GGP from 1999 to 2010. The GGP directly involves 124 million people (32 million households) in 1897 counties in 25 provinces and the Xinjiang Production and Construction Corps (Mao et al., 2013). Households are given three kinds of subsidies, namely, cash, grain and seedlings, for converting their land. This project induces significant developments to the regional land use type. It affects water cycle, soil erosion, accumulation of ecosystem, and relationship between the ecosystem and the main ecological processes (Fu and Zhang, 2014). Studies reveal that by increasing vegetation coverage and decreasing runoff and soil erosion, the GGP can improve the ecosystem service ability of maintaining soil fertility (Ma and Fan, 2005; Li et al., 2006; Long et al., 2006; Xu et al., 2006).

Karst regions account for about 15% of land area globally (about 2.2 million km^2) and house approximately 1 billion people (17% of the world's population; Yuan and Cai, 1988). Over the past decades, Karst landscapes have confronted an increasing demand for their wide range of economic and cultural assets (e.g. minerals, oil and gas, geomorphologically remarkable phenomena), among which water resources are of the highest importance (Bakalowicz, 2005; Bai et al., 2013). Given their peculiar intrinsic characteristics of karst-specific processes, these areas have vulnerable ecological environment where water and soil loss is most serious. Changes in the ecosystem service functions, particularly changes in different land use patterns in Karst areas, affect soil conservation, carbon sink and water yield. Afforestation can increase carbon sink, regulate climatic law and enhance soil and water conservation in areas with serious soil erosion. However, afforestation increases water evapotranspiration and thus reduces runoff. Therefore, comparing carbon and water prices is necessary to determine an appropriate afforestation area in different regions. In Karst areas, grain production provides the most stable income to farmers. Economic backwardness directly or indirectly causes farmers to reclaim slopes to grow crops in Karst mountain areas and destroy considerable forest resources. An increase in grain yield is often at the cost of soil erosion intensification and runoff increase.

The geological structure of Karst watershed is complex and significant; however, research on Karst watershed ecosystem service trade-off and synergic relationships is relatively rare. Most research results are limited to a single service function of an ecosystem service. Only a few scholars have compared the mutual relationships among ecosystem services, let alone revealed the trade-off and synergic service in typical Karst watersheds. Among many hydrological models, Soil and Water Assessment Tool (SWAT) model proposed by Jeff Arnold is widely used in hydrological effects of land use/cover change, particularly in evaluating of the management of watershed runoff, sediment, non-point source pollution, water resource and global change response simulations of water resource to climate and land use (Arnold and Allen, 1996). Net primary productivity (NPP) is the remaining part of the organic substance amount produced by green plants in unit time and place with photosynthesis. NPP deducts autotrophic respiration, and it is a direct reflection of the carbon fixation capability of an ecosystem (Imhoff et al., 2004; Leith and Whittaker, 1975). Among many statistical models, parametric models, and process models based on remote sensing data, Carnegie–Ames–Stanford Approach (CASA) model (Monteith and Moss, 1977; Potter et al., 1993) is a process model to evaluate NPP based on the efficiency for solar energy utilization that is widely used in global and regional vegetation productivity. On this basis, this paper considers the Shibantang Karst watershed as the research site, combines SWAT and CASA, simulate and evaluate the NPP, water yield, and sediment yield (sediment yield is closely related to soil maintenance, such that sediment yield decreases with increasing soil conservation. This paper reflects soil conservation on ecosystem service in a limited sense by studying sediment yield), and considers wind rose map to explore the trade-off and synergic relationships of these three ecosystem services from 2000 to 2010. The following objectives were investigated: (1) spatial–temporal changes of water yield and sediment yield of the watershed, (2) spatial–temporal changes of NPP, and (3) trade-off relationships among water yield, sediment yield, and NPP.

2. Study site and materials

2.1. Study site

The Shibantang watershed (26°50′–27°26′ N, 105°50′–106°24′ E) is located west of Guizhou Province (Fig. 1a and 1b). The watershed is administratively divided into Jinsha, Dafang, and Qianxi counties, and it is an important part of Bijie experimental area. This watershed, which belongs to the Yangtze River system, is a main branch of Wujiang River. It covers an area of 2248.49 km^2, with an elevation range of 711–2097 m above sea level, and the mean elevation is 1292 m (Fig. 1c). The watershed's topography is mountainous. Elevation in the study area decreases from west to east, ranging in a large scope (Fig. 1c). The watershed belongs to humid subtropical monsoon climate, with an annual average temperature of 13.8 °C and average annual rainfall of 1300 mm/year based on the 10-year (2000 − 2010). The main soil types in the study area are Haplic Alisols and Chromic Luvisols (Fig. 1d). Large topographic gradient, thin soil, low vegetation cover, and abundant precipitation resulted in serious soil erosion in the watershed.

2.2. Materials

Remote sensing data and data obtained from other sources were used in this study. Remote sensing data (P127, R41), with a spatial resolution of 30 m, were selected for this work. These data include those extracted from Landsat 7-ETM+ on 09-01-2000 and Landsat 7-ETM+

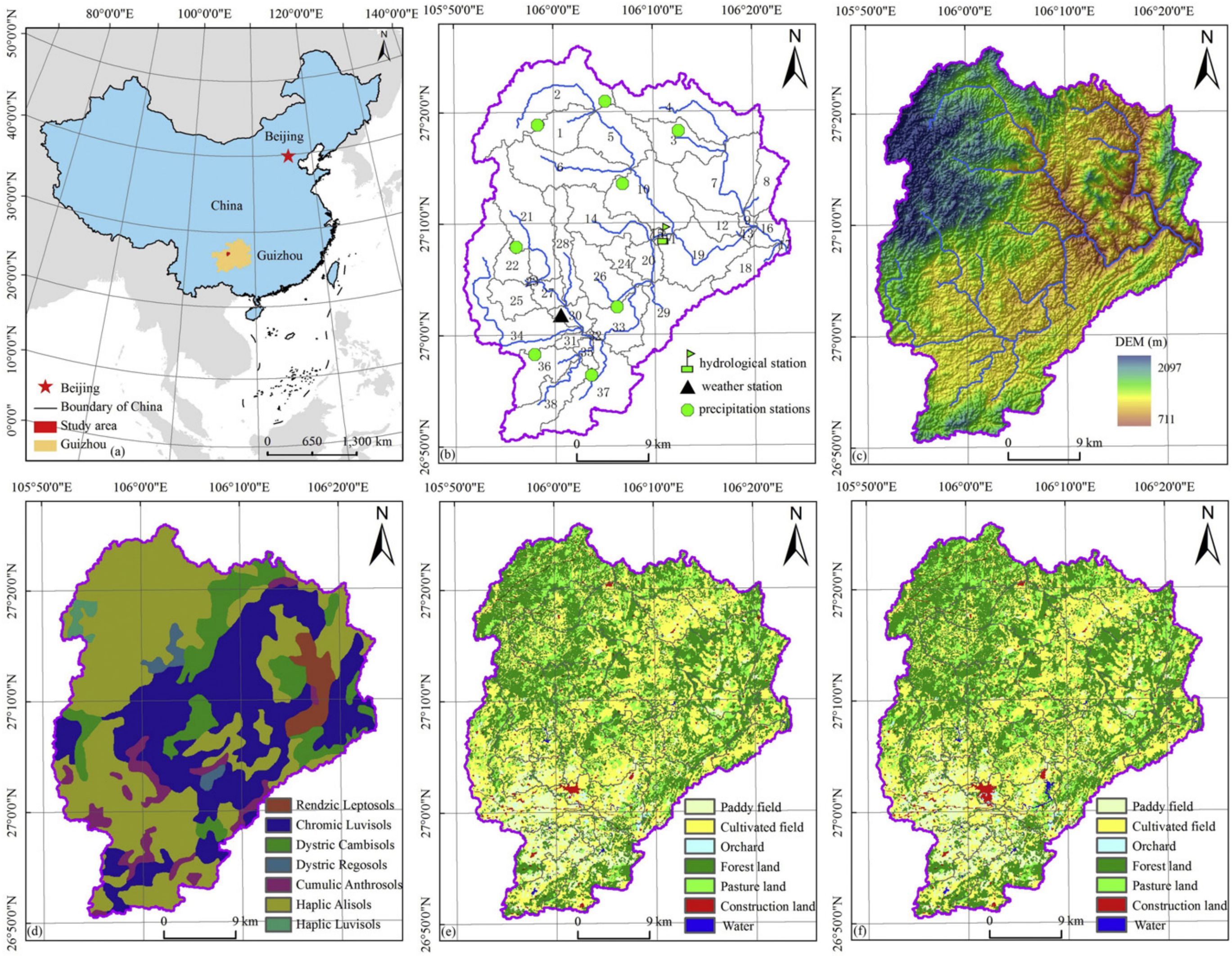

Fig. 1. Study area location in china (a), Shibantang watershed (b), topography (c), soil map (d), land use in 2000 (e) and 2010 (f).

on 11-04-2010, which were retrieved from the United States Geological Survey (USGS) website (http://earthexplorer.usgs.gov/). ArcGIS10.2 and eCognition9.1 were used to classify landscape types. Information on these landscape types was extracted from Landsat 7-ETM + with eCognition9.1 (DeFiniens, 2004; Wang et al., 2014a,b) using an object-oriented classification (based on decision trees). The different types of land use in the study area were classified as paddy field, cultivated field, orchard, forest land, pasture land, construction land, and water (Fig. 1e and 1f). Subsequently, manual correction was applied to ensure the accuracy of classification. In the field investigation, verification of landscape types identified in the polygons was performed by using the spatial join function in the program ArcMap10.2. The results of the manual interpretation and the original results of these selected samples were compared to produce confusion matrixes (Munroe and Müller, 2007). The overall accuracies for classification were 80.25 and 81.36% with Kappa coefficients of 0.79 and 0.80, respectively.

Data acquired through other sources mainly included digital elevation model (DEM) data, soil type, and hydrological and meteorological data. Among these data, DEM data, with a spatial resolution of 30 m, was provided by the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The soil data, including a soil map at a 1:50,000 sale and the information on related soil properties, were obtained from the State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences. Seven soil types were obtained in the watershed (Fig. 1d), of which Haplic Alisols and Chromic Luvisols were predominant and accounted for 47.06% and 31.80% of the total area, respectively. Hydrological data were mainly monthly runoff data of Shibantang watershed (log data from 01-1997 to 12-2010) from the Hydrology and Water Resources Bureau of Guizhou Province. Meteorological data mainly included daily precipitation, air temperature, humidity, wind speed and sunshine durations (1997–2013) in west Guizhou Province (http://www.gzswj.gov.cn/hydrology_gz_new/index.phtml). Daily rainfall data for the study area were also collected from eight stations from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/).

3. Methods

3.1. Simulation of NPP with CASA model

We calculated Net primary productivity (NPP) based on the process-based Carnegie-Ames-Stanford Approach (CASA) model. CASA ecosystem model, called the light-use efficiency (LUE) model, is one of the most widely used models which adequately addresses NPP spatial and temporal dynamics at regional to global scales (Potter et al., 1993; Mohamed et al., 2004). In the CASA model, NPP is the product of modulated absorbed photosynthetically active radiation (APAR) and a LUE factor (Xu et al., 2011). The model computes APAR as a function of solar radiation and the linear relationship that exists between fraction of APAR and reflectance properties expressed through a vegetation index (Mohamed et al., 2004). This model advocates that plant productivity is correlated with the amount of photosynthetically active radiation absorbed or intercepted by green foliage (Monteith and Moss, 1977; Potter et al., 1993). The CASA model is described as following:

$$NPP = \sum [APAR(t) \times \varepsilon(t)] \tag{1}$$

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

$$\varepsilon(t) = \varepsilon^* \times T_1(x,t) \times T_2(x,t) \times W(x,t) \tag{3}$$

where PAR is the total incident photosynthetically active radiation (MJ/m^2); FPAR is the fraction of PAR absorbed by the vegetation canopy; APAR is the canopy-absorbed incident solar radiation integrated over a time period (MJ m^{-2} mon^{-1}); $\varepsilon(t)$ refer to actual LUE (g/MJ) and ε^*-refer to maximum LUE (g/MJ); T_1(x,t) and T_2(x,t) refer to temperature stress coefficients and W(x,t) refers to water coefficient.

3.2. Hydrological processes with SWAT model

Soil Water and assessment Tool (SWAT) model is a distributed hydrological model that features a strong physical mechanism and long-term period. This model was developed for the Agricultural Research Center of the US Department of Agriculture in 1994 by Dr. Jeff Arnold using GREAMS, GLEAMS and EPIC as references (Arnold et al., 1998). The SWAT model mainly comprises three sub-models, namely, hydrological process, soil erosion, and pollution load sub-models. In the present study, SWAT model was used to simulate the runoffs and sediment yields of each month annually. In this model, watershed is divided into multiple sub-watersheds, which are then divided into unit of unique soil, land use and slope characteristics called Hydrologic Response Units (HRUs). In the SWAT, the runoff, sediment transformations and losses determined in each HRU are aggregated at the sub-basin and routed to the watershed outlet through the channel network (Arnold and Allen, 1996). The hydrological sub-model is based on the water balance equation in the soil profile, where simulated processes include precipitation, infiltration, surface runoff, evapotranspiration, lateral flow and percolation (Fan and Shibata, 2014). The water balance equation in the soil profile is described as follows:

$$SW_t = SW_0 + \sum_{i=0}^{t} (R_{day} - E_{surf} - W_{deep} - Q_{gw}) \tag{4}$$

where t is the time in days, SW_t and SW_0 are the final and initial soil water contents, respectively (mm), R_{day} is amount of precipitation on day i (mm), E_{surf} is the amount of surface runoff on day i (mm), W_{deep} is the amount of percolation and bypass flow exiting the soil profile bottom on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

Soil erosion is a hydrologically driven process on sediment being discharged with runoff (Kinnell, 2005). Overland soil erosion for each HRU is estimated using the Modified Universal Soil Loss Equation (Williams, 1995):

$$sed = 11.8\left(Q_{surf} \times q_{peak} \times area_{HRU}\right)^{0.56} \times K \times LS \times C \times P \tag{5}$$

where sed is the sediment load (metric tons day^{-1}); Q_{surf} is the surface runoff volume (mm day^{-1}); q_{peak} is the peak surface runoff rate (m^3 s^1); $area_{HRU}$ is the area of the hru (ha); K is the USLE soil erodibility factor, which is the erosion rate per unit of erosion index for specified soil; LS is the slope length and gradient factor; C is the cropping management factor defined as the ratio of soil loss from a field with a specified cropping and management to that from the fallow condition for which the factor K is evaluated; and P is the conservation support practice factor.

The major model inputs consist of topography, soil properties, land use, meteorological data (daily precipitation, daily temperature, daily solar radiation, daily wind speed, and daily relative humidity), and land management practices (Kushwaha and Jain, 2013). The watershed topography is defined by a DEM. It is used to calculate slope and define the stream network in sub-basin. The soil data (derived from the State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences) are required to define soil characteristics and attributes. The land use data during 2000–2010 provide vegetation information on ground and their ecological processes in lands and soils. Meteorological data based on daily historical monitoring data from eight stations during 1997–2010 are prepared according to SWAT input requirements.

SWAT model was employed to simulate the hydrological processes of different periods to quantitatively analyze the impacts of the change in land use on the runoff and sediment transport in the watershed. The model was first calibrated and verified when used in this watershed. The sequential uncertainty fitting algorithm (SUFI-2) method (Arnold and Allen, 1996) provided by SWAT-CUP was employed to calibrate and verify the parameters of the model, thereby confirming the accuracy of the results. The performance of SWAT was evaluated by some indicators, including coefficient of determination (R^2) and Nash–Sutcliffe efficiency (NSE) (Niraula et al., 2012). When NSE > 0.5 and R^2 > 0.6, the simulation results are satisfactory. In the present study, monthly data of runoffs of Shibantang hydrological station from 1997 to 2010 were selected to calibrate and verify the parameters of the SWAT model. The measured runoff data of Shibantang watershed from 1997 to 2010 were classified into three parts. The first (1997–1999), second (2000–2004) and third (2005–2010) parts were used for preheating, calibrating and verifying of the model, respectively. Subsequently, the land use maps and meteorological data in 2000 and 2010 were adopted for the simulation of runoff and sediment in 2000 and 2010, respectively.

4. Results

4.1. Land cover changes between 2000 and 2010

The cultivated field and forest land are the two main land use types in Shibantang watershed, followed by pasture land and paddy field in second and third ranks, respectively; on the contrary, construction land, orchard land and water area account for a small percentage (Fig. 2). According to the land use change between 2000 and 2010, forest land, pasture land, construction land, and water area clearly increased. However, cultivated field, paddy field, and garden land decreased. The proportion of forest land increased from 37.41% in 2000 to 43.36% in 2010, with an amplification of 5.95% and increment of 13,381.53 ha. The proportion of pasture land increased from 11.01% in 2000 to 14.59% in 2010, with an amplification of 3.57% and increment of 8028.35 ha. The proportion of cultivated field decreased from 40.42% in 2000 to 31.18% in 2010, with a damping of 9.25% and decrement of

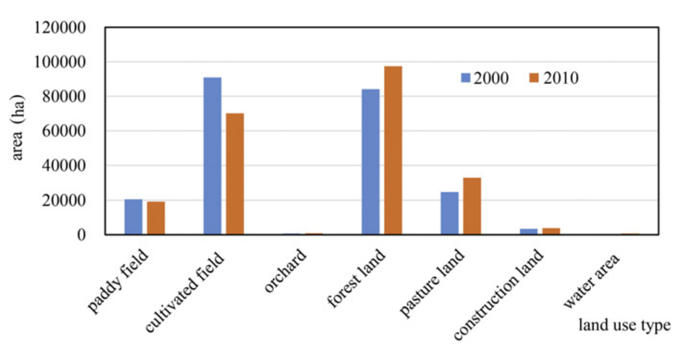

Fig. 2. Area of each land use type in study area in 2000 and 2010.

20,787.34 ha. Thus, the transformation proportion between cultivated field, pasture land and forest land is almost a balanced over the past 10 years. Significant changes have occurred on the land coverage because of the performance of ecological projects, such as GGP and forest plantation from 1999. The GGP in the watershed has also obtained a good effect.

4.2. Verification of SWAT model

The efficacy of simulation and evaluation index (Fig. 3) of the monthly runoff processes during calibration and verification were obtained. The value range of the parameters was continuously adjusted based on the relative sensitivity of runoff parameters to obtain a set of appropriate parameters to achieve better simulation results. The distribution of the measured monthly runoffs in the calibration period from 2000 to 2004 was close to the simulated values, and the two distributions had high degree of correlation, that is, correlation coefficient $R^2 = 0.85$ and NSE = 0.78. Hence, the result was credible. The efficacy of simulation during the verification period was favorable, because the correlation and relative errors compared with the measured data were acceptable, that is, $R^2 = 0.82$ and NSE = 0.76, which indicated close correlation between the measured and simulated data. The higher simulation accuracy resulted in more credible simulation results. By contrast, the efficacy of the simulation of monthly runoffs during the verification period was inferior to that during the calibration period. This characteristic could be attributed to the higher variability and more complex variation in the factors that determined the monthly runoffs during the verification period compared with that during the calibration period. In summary, the simulation of monthly runoffs in the watershed using the SWAT model demonstrated excellent results. The effect of calibration period was better than that of the verification period, which indicated that the SWAT model had outstanding applicability in Shibantang watershed.

4.3. Spatial–temporal dynamics of water yield, sediment yield and NPP

4.3.1. Water yield

We analyzed the annual average water yield features of the sub-watershed based on the SWAT simulation result. The spatial distribution characteristics of water yield in the two phases are nearly the same (Fig. 4). The annual average water yield decreased from 528 mm in 2000 to 513 mm in 2010, decreasing by 2.84%. Regions of high water yield were mainly distributed in Nos. 7, 9 and 12 sub-watersheds of the northeast and No. 5 in the northwest. Regions of low water yield were distributed mainly in Nos. 27, 31, 33, 35, 36 and 38 sub-watersheds in the south. Compared with those in 2000, regions with fewer water yields in 2010 were mainly Nos. 5, 20, 33 and 38 sub-watersheds. The water yield of other sub-watersheds also decreased, although the decrease was not evident. Three sub-watersheds were used as examples in this study to analyze the change of two phases of Nos. 5, 33 and 38. In comparison with Table 1, the forest land and pasture land proportions of the three sub-watersheds all increased, whereas those of the paddy field and cultivated field decreased. Moreover, the garden land slightly changed, thereby contributing minimally to the reduction of water yield. In summary, the main factors of the decreasing water yield in sub-watersheds are related to the increase of forest land and pasture land and the decrease of agricultural land area (e.g. cultivated field and paddy field).

4.3.2. Sediment yield

SWAT model was employed to simulate the hydrological processes of different periods to analyze the impacts of the change in land use on sediment transport in the watershed quantitatively. Calibration and verification of the model was were initially conducted. Afterwards, the data of land use in 2000 and 2010 were adopted for the simulation. The spatial distribution of sediment yields under different years were obtained and expressed in diagrams (Fig. 5). The sediment yield of the watershed exhibited a decreasing trend, that is, reduction by 8.95% from 26.15 t/ha in 2000 to 23.81 t/ha in 2010 during 10 years after the implementation of the conversion of farmland to forest and grassland. This phenomenon indicated that the conversion from farmland to forest had achieved significant results in the recent 10 years and effectively curbed regional water loss and soil erosion. Low sediment yields were observed in the northwestern and southeastern sides of the watershed, whereas higher sediment yields were observed in the middle and lower reaches of the watershed. Intense changes in sediment yields were mainly concentrated at the middle reaches of the watershed, namely, sub-basins 10, 11, 13, 14, 15, 16 and 17. The sediment yields of sub-basins in the region also demonstrated a decreasing trend in spatial distribution over time.

4.3.3. Temporal and spatial variations of NPP

4.3.3.1. NPP changes in different land use types. We use CASA model to evaluate the NPP of 2000 and 2010 and then carry out the statistical analysis of the average value and the total amount of NPP in the watershed (Table 2). Fig. 6 illustrates the spatial distribution of NPP in the research region in 2000 and 2010. The NPP values of Nos. 1, 2, 5, 6 and 7 sub-watersheds were high, and the maximum value can reach as high as 900 g C m^{-2} a^{-1} (Fig. 6). As a mountainous and hilly land, the vegetation form is mostly forest land and grass land with high vegetation coverage and strong photosynthesis; thus, NPP was high. On the contrary, the lowest NPP appeared in the downtown of Qianxi County and its residence area, and the lowest value was 200 g C m^{-2} a^{-1}. The vegetation coverage of the residence is relatively low, and the land is mainly used for mining and industry or housing estate. The NPP increased in the area centers on the northwest part of the watershed (Fig. 6b). Therefore, the GGP was evident. The regions where NPP decreased are located at the No. 30 sub-watershed of the south area, which is influenced by construction for land expansion.

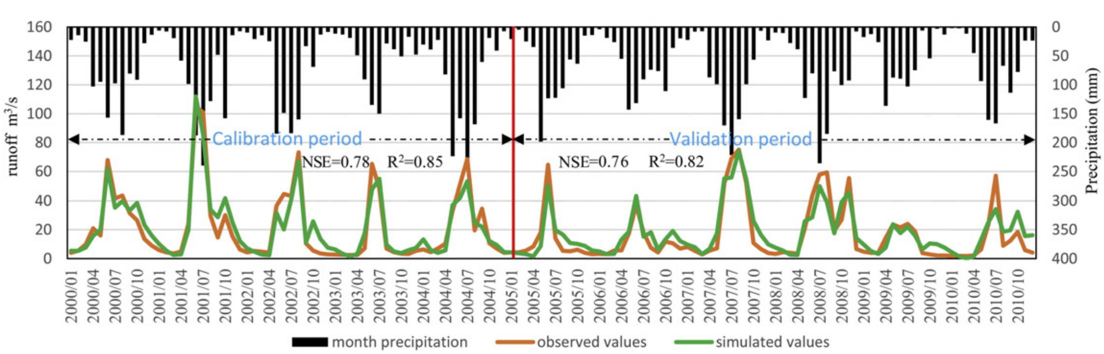

Fig. 3. Simulated and observed monthly runoff in calibration and validation periods.

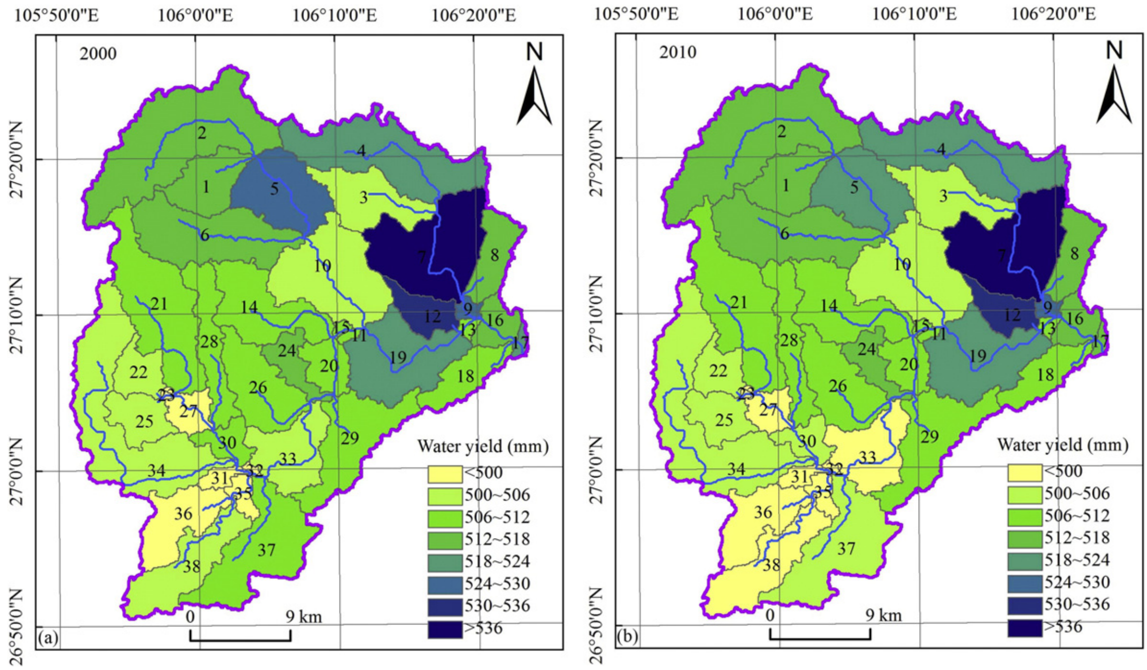

Fig. 4. Spatial distribution of annual water yield in 2000 and 2010.

Based on the changes of NPP in different land use types, the NPP of different land use types also differed considerably (Table 2). The annual average value of NPP in research region increased from 739.38 g C m^{-2} a^{-1} in 2000 to 746.25 g C m^{-2} a^{-1} in 2010, increasing by 6.87 g C m^{-2} a^{-1}. The total amount of NPP increased from 1655.54 Gg C a^{-1} in 2000 to 1670.93 Gg C a^{-1} in 2010, which showed an increase of 15.39 Gg C a^{-1}. According to the average value of NPP change in different land use types, the average value of NPP of forest land, pasture land, and paddy field was increasing, whereas that of cultivated field, garden land, and construction land was decreasing. The average value of NPP of forest land was the highest because the vegetation coverage is high, trees are distributed vertically, and trees can efficiently use the light energy with strong photosynthesis. The average value of NPP of construction land was the lowest because the vegetation coverage of the residence region was low, and the land is mainly used for mining and industry or housing estate. According to the total amount of NPP of different land use types, the NPP of forest land increased the most from 660.50 Gg C a^{-1} in 2000 to 723.89 Gg C a^{-1} in 2010, thus the increase of 63.39 Gg C a^{-1}. By contrast, the amount of NPP of cultivated field decreased the most from 640.27 Gg C a^{-1} in 2000 to 583.25 Gg C a^{-1} in 2010, which decreased by 57.01 Gg C a^{-1}.

4.3.3.2. Influence of land use change on NPP. According to the transfer matrix of different land use types during 2000–2010 (Fig. 7a), the transfer of cultivated field to forest land accounted the most (13.28%), which was mainly located at the west part of the research area. The transfer of cultivated field to construction land followed next, accounting for 3.13%, which is mainly located at the downtown of Qianxi County. The other land use types only accounted for a small percentage, that is, less than 5%. From the different maps of NPP during 2000–2010 (Fig. 7b), the increased areas of NPP were mainly distributed in Nos. 4, 8, 34, 36 and 38 sub-watersheds, and the decreased area was mainly located at No. 30. The most profitable transfer method of the annual average NPP within the decade was the transfer between cultivated field to pasture land, which increased by 47.03 g C m^{-2} a^{-1}, followed by the transfer between 'cultivated field–garden land' and 'cultivated field–forest land' (Table 3). The least profitable transfer method of the annual NPP was paddy field to construction land, which decreased by −170.89 g C $m^{-2}a^{-1}$. Among the total amount of NPP change, the NPP losses of cultivated field transferring to construction land and paddy field transferring to construction land were evidently more than that of other transfer methods. The cultivated field transfer to construction land causes the most losses of NPP, that is, 437.01 Gg C a^{-1}. The NPP profits of cultivated field transferring to forest land, cultivated field transferring to garden land and cultivated field transferring to pasture land were more than those of other transfer methods. Among them, the NPP profit of cultivated field transferring to forest land was the largest, that is, 2259.92 Gg C a^{-1}.

Table 1
The proportion statistics of land use types in sub basin.

Land use type	No. 5			No. 33			No. 38		
	2000 (%)	2010 (%)	Change ratio (%)	2000 (%)	2010 (%)	Change ratio (%)	2000 (%)	2010 (%)	Change ratio (%)
Paddy field	2.35	2.33	−0.02	19.87	16.39	−3.48	101.20	97.66	−3.54
Cultivated field	39.25	36.61	−2.65	48.33	44.00	−4.33	130.76	117.13	−13.63
Orchard	0.00	0.00	0.00	1.29	1.38	0.09	0.00	0.00	0.00
Forest land	43.40	45.73	2.33	17.69	20.61	2.92	88.53	104.92	16.39
Pasture land	13.62	13.94	0.32	9.09	10.09	1.01	5.56	6.27	0.71
Construction land	1.33	1.34	0.01	2.57	3.40	0.83	5.49	5.52	0.04
Water area	0.05	0.06	0.01	1.16	4.13	2.97	2.83	2.87	0.04

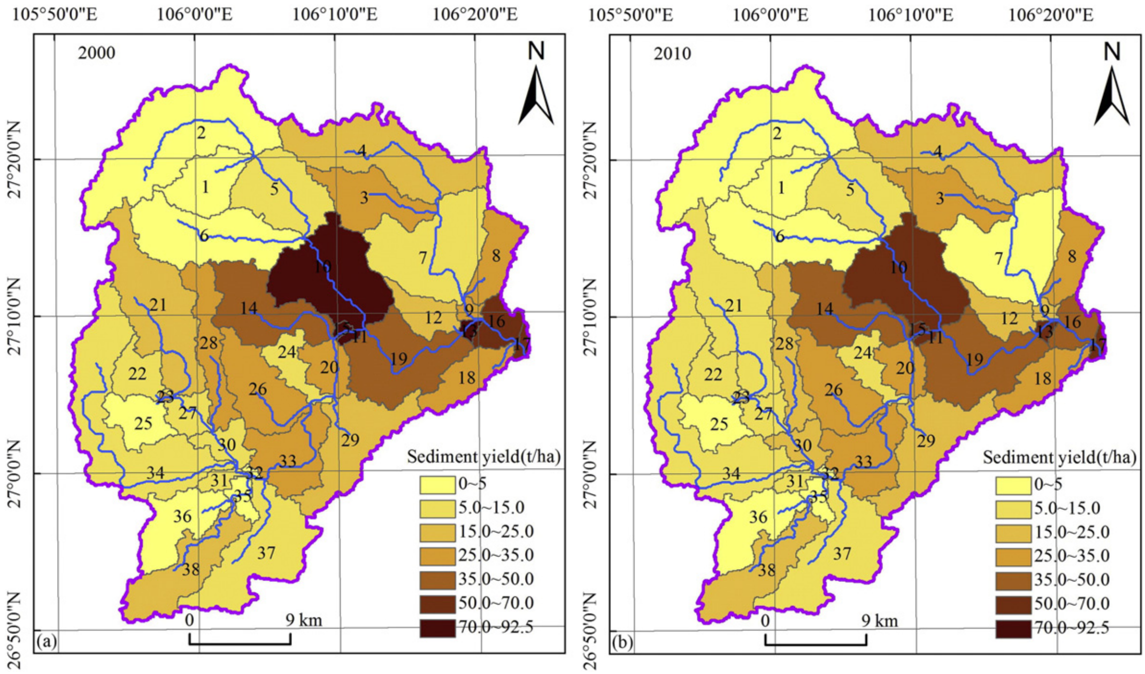

Fig. 5. Spatial distribution of sediment yield in 2000 and 2010.

4.4. Trade-off analysis of sediment yield, water yield and NPP

4.4.1. Correlation of sediment yield, water yield and NPP

Spearman correlation analysis was performed on the sediment yield, water yield and NPP of different years through SPSS. Consequently, the correlation index (Table 4) of different ecosystem service functions was obtained. The sediment yield of 2000, 2010 and 2010–2000 showed negative correlation with NPP. NPP and sediment yield presented a good reverse relationship in 2000 and 2010, and the correlation indexes were −0.637 and −0.682, respectively. They also passed the test at 0.01 significant level. However, the correlation index between NPP and sediment yield in 2010–2000 did not pass the test of 0.01 significant level. Sediment yield and water yield showed significant positive correlation in 2000, 2010 and 2010–2000. Particularly, the correlation index between sediment yield and water yield was 0.713 in 2010. NPP and water yield also showed significant negative relationship in 2000, 2010 and 2010–2000. In 2000 and 2010, the correlation indexes were high at 0.682 and 0.821, respectively, and they all passed the test at 0.01 significant level. In terms of changes on the three largest ecosystem service functions, NPP showed a negative correlation with sediment yield and water yield, and water yield and sediment yield presented a positive correlation.

4.4.2. Trade-off relationship of sediment yield, water yield and NPP in different land use types

In the same land use type, the existence modes of different ecosystem services are in different forms. The same ecosystem service also varies at different land use types. With the regional statistics of the three ecosystem services in the watershed, we obtained the average value of five land use ecosystem services: paddy field, cultivated field, garden land, forest land, and pasture land. Given that the three ecosystem services differ in magnitude orders, this paper uses the relationship among the different ecosystem services as the key research point to make the result real, analyzable, and visible. Thus, according to the land use types, the paper normalizes NPP, sediment yield and water yield to 0–1. Python language was adopted to deal with the data and make it visible. Subsequently, a polar diagram, which is also known as rose map, was created. The NPP of forest land was the highest, and its sediment yield and water yield were the lowest (Fig. 8). The NPP of paddy field was the lowest, and its sediment yield and water yield were the highest. For different years, the NPP of pasture land and forest land increased from 2000 to 2010, whereas the sediment yield and water yield decreased. The NPP of paddy field, cultivated field, and garden land decreased within the decade, but the sediment yield and water yield increased. In different land uses, water yield and sediment yield

Table 2
Mean and total NPP in different land use types in 2000 and 2010 in study area.

	Paddy field	Cultivated field	Orchard	Forest land	Pasture land	Construction land	Total area
Mean NPP (g C m^{-2} a^{-1})							
2000	660.24	706.79	677.64	789.62	768.46	662.04	739.38
2010	682.51	704.01	630.10	795.62	782.66	629.87	746.25
Change in NPP	22.27	−2.79	−47.54	6.00	14.20	−32.17	6.87
Percent change (%)	3.37	−0.39	−7.02	0.76	1.85	−4.86	0.93
Total NPP (Gg C a^{-1})							
2000	134.84	640.27	5.24	660.50	189.62	23.80	1655.54
2010	137.24	583.25	5.13	723.89	193.34	22.34	1670.93
Change in NPP	2.40	−57.01	−0.11	63.39	3.73	−1.46	15.39
Percent change (%)	1.78	−8.90	−2.14	9.60	1.97	−6.54	0.93

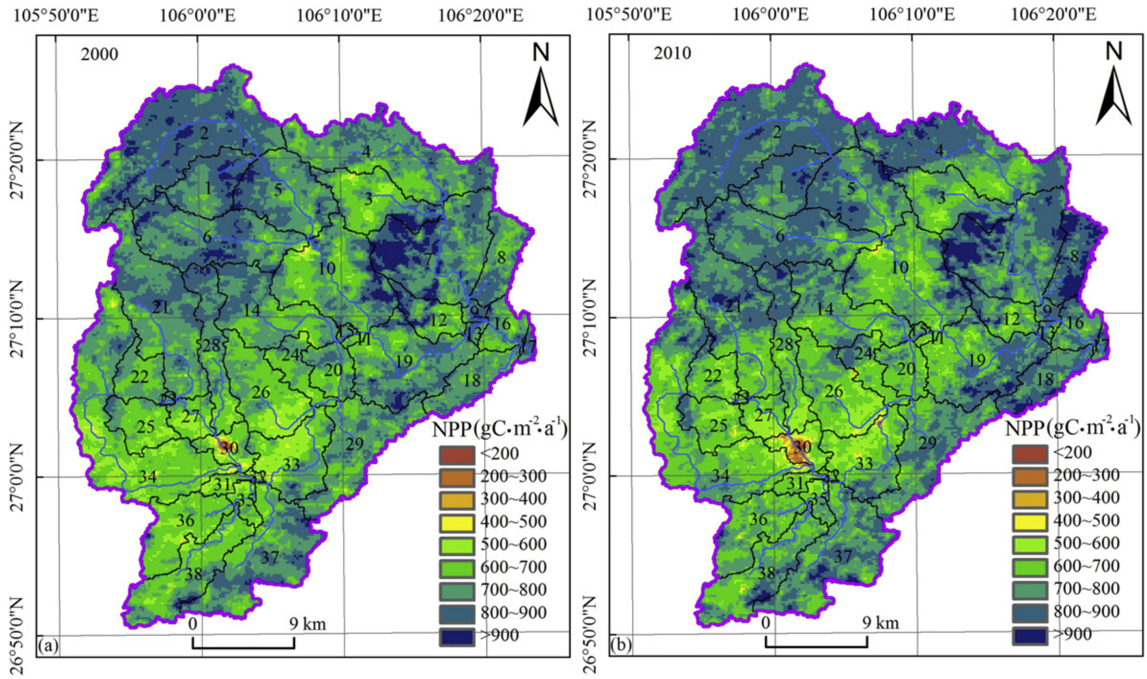

Fig. 6. Spatial pattern of NPP in 2000 and 2010.

increased and decreased simultaneously, but NPP was negatively related to water yield and sediment yield. From the above analysis, sediment yield and water yield were in a synergic relationship, and an increment of water yield can improve soil erosion. NPP was in a trade-off relationship with water yield and sediment yield. An increment of NPP is good for decreasing water yield and soil erosion and good for increasing soil conservation amount.

5. Discussion

5.1. Land coverage changes and the changing climate

Ma (2005) divided the main factors affecting the watershed ecosystem service into climatic factors and change on land use patterns. Rainfall and temperature are the main climatic factors that affect water yield,

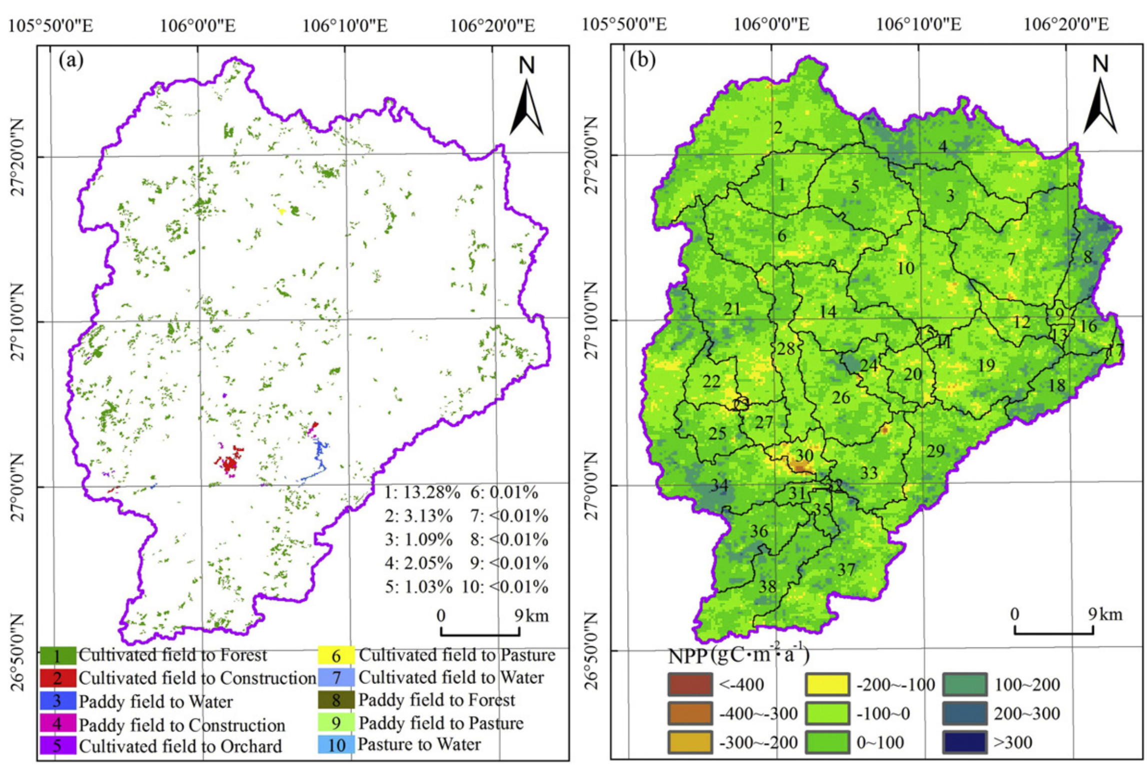

Fig. 7. Land use change and NPP changes.

Table 3
Gain and loss of NPP in different land use types during 2000–2010.

		Mean NPP ($g\ C\ m^{-2}\ a^{-1}$)	Total NPP ($t\ a^{-1}$)
1	Cultivated field–forest land	30.81	2259.92
2	Cultivated field–construction land	−146.21	−437.01
3	Paddy field–water area	−35.79	−74.50
4	Paddy field–construction land	−170.89	−179.95
5	Cultivated field–orchard	38.76	28.89
6	Cultivated field–pasture land	47.03	13.33
7	Cultivated field–water area	31.18	0.83
8	Paddy field–forest land	−42.27	−0.34
9	Paddy field–pasture land	4.46	0.04
10	Pasture land–water area	−49.62	−0.40

sediment yield and NPP. The rainfall and temperature of Shibantang watershed from 2000 to 2010 were analyzed (Fig. 9), and the temperature slowly increased during the decade with an increase rate of 0.185 °C/10 a, whereas the rainfall decreased with a rate of 1.69 mm/10 a. In the recent decade, the climatic factor does not change excessively, which implies that the changes on water yield, sediment yield, and NPP are mainly caused by land use changes. The change in land use type affects main ecological processes, such as energy interchange, water cycle, soil erosion and accumulation, and biogeochemical cycle of ecosystem. Thus, land use type changes the provision of ecosystem service (Fu et al., 2013; Ma, 2005; Vitousek et al., 1997). At the end of the 20th century, a series of ecological environmental problems occurred (e.g. land deterioration, water and soil loss, and vegetation deterioration) because of unreasonable land utilization. To protect and restore the impaired ecosystem, the Chinese government performed many vegetable restoration plans, including the GGP, Natural Forest Protection Project, and the Sloping Land Conversion Project (Bennett, 2008; Uchida et al., 2005; Yin et al., 2010). GGP, which started in 1999, is an ecological project with the strongest policy, highest investment amount, widest coverage area and highest public participation (Liu and Diamond, 2008; FAO, 2010; Yin and Yin, 2010; Yin and Zhao, 2012). The investment has reached 431.8 billion yuan (SFA, 1999–2010), concerning 23,344 (1000 ha) of Grain for Green area (SFA, 1999–2010). The performance of these projects directly affects the NPP, water yield and sediment yield of the watershed. Zuo et al. (2014) pointed out that the vegetation coverage rate of Bijie experimental area during 2000–2005 increased from 29.54% to 33.92%. Since 2005, the vegetation coverage rate has rapidly increased at an annual average rate of more than 1.2%, and it reaches 40.03% in 2010. The result of the present study also verifies the viewpoint of Zuo. The forest land proportion reaches 43.36% in 2010 (Fig. 2), which is slightly higher than that of the Bijie experimental area. From the increasing and

Table 4
Correlation of sediment yield, water yield and NPP.

		NPP		
		2000	2010	2010–2000
Sediment yield	2000	−0.637**		
	2010		−0.682**	
	2010–2000			−0.263*
	Water yield			
		2000	2010	2010–2000
Sediment yield	2000	0.568**		
	2010		0.713**	
	2010–2000			0.451*
	Water yield			
		2000	2010	2010–2000
NPP	2000	−0.682**		
	2010		−0.821**	
	2010–2000			−0.563**

* at 0.05 level.
** at 0.01 level.

decreasing figures of different land use areas (Fig. 10), the decreased area of paddy field and cultivated field within the decade is in accordance with the increment area of forest land and pasture land in spatial scale. The increment of forest land is the largest, which further illustrates that the NPP profit of cultivated field transferring to forest land is the largest (2259.92 Gg C a^{-1}).

5.2. Trade-off and synergic relationship of ecosystem service

Ecosystem service functions are not linearly dependent (Farley et al., 2005; Van Jaarsveld et al., 2005). Bennett et al. (2009) proposed a classification system based on drive force and mutual function of different ecosystem service functions, which aims to improve the understanding on the connection between multiple ecosystem services and mechanism of connection. Several independent features can affect multiple service transmission simultaneously, but a single service is dependent on multiple features; thus, the features and gathering of services are relevant (Bennett and Balvanera, 2007; Bennett et al., 2009). Relationships among water yield, sediment yield and NPP can be summed up as the interchange and synergy of ecosystem services on spatial and temporal scale. Chang et al. (2012) speculated that a high soil conservation amount indicates minimal free water flow, good water conservation, and high vegetation carbon fixation. They also speculated that a high seepage amount leads to minimal water conservation and low NPP. In the present research, water yield and sediment yield show a significant positive correlation, which is concerned with their common hydrological process. In addition, they are in direct relationship with the driving factors of shared land use/vegetation coverage.

5.3. Uncertainty of model evaluation and future research direction

In many studies applying SWAT, several domestic and foreign scholars have reported uncertainty and adaptation problems existing in the model stimulation. For example, the application of Schmalz et al. (2008) in northern Germany showed that a considerable uncertainty in SWAT when it is used to stimulate the hydrological process of a lake peat-type region with flat and shallow ground water level. The research of Hattermann et al. (2008) showed that SWAT is insufficient in stimulating a wetland process. When Cheng et al. (2009) applied SWAT to sediment and coarse sediment in typical watersheds of dry and semi-arid regions in the midstream of the Yellow River, the SWAT mechanisms of runoff generation could not effectively stimulate the interflow, base flow and spring flood flow process of the dry and semi-arid regions. Given the objective existence of a hydrological model, good model uncertainty is an important indicator for model analysis and verification precision of the results (Mansour et al., 2010). In future model calibration, we can lower model uncertainty and improve model calibration and test result precision through enlarging iterations of runoff stations appropriately. The research chooses runoff data of the Shibantang hydrological station from 1997 to 2010 to calibrate and test the SWAT parameters. Subsequently, the SWAT obtains that the annual average sediment yield is lowered from 26.15 t/ha in 2000 to 23.81 t/ha in 2010. The result is in accordance with that of Wang et al. (2014a) and the water and soil conservation report of Guizhou Province (Department of Water Resources of Guizhou Province, 2005), which signifies the reliability of the result of this paper.

Furthermore, the present study uses CASA model to simulate NPP from 2000 to 2010. When selecting the data, error in land use interpretation, resolution ratio of remote sensing image, different precisions of auxiliary data and cut of pixel by vector data can cause data uncertainty. Currently, the simulation of NPP is being perfected continuously, but the application of each model needs further discussion. The evaluation of different factors in one model may cause the result to lose comparability. Studies using this model to stimulate vegetation NPP in Southwest Karst region are few. Wang et al. (2008) used LUE model of MODIS data to evaluate the average NPP of Guizhou Province, which is

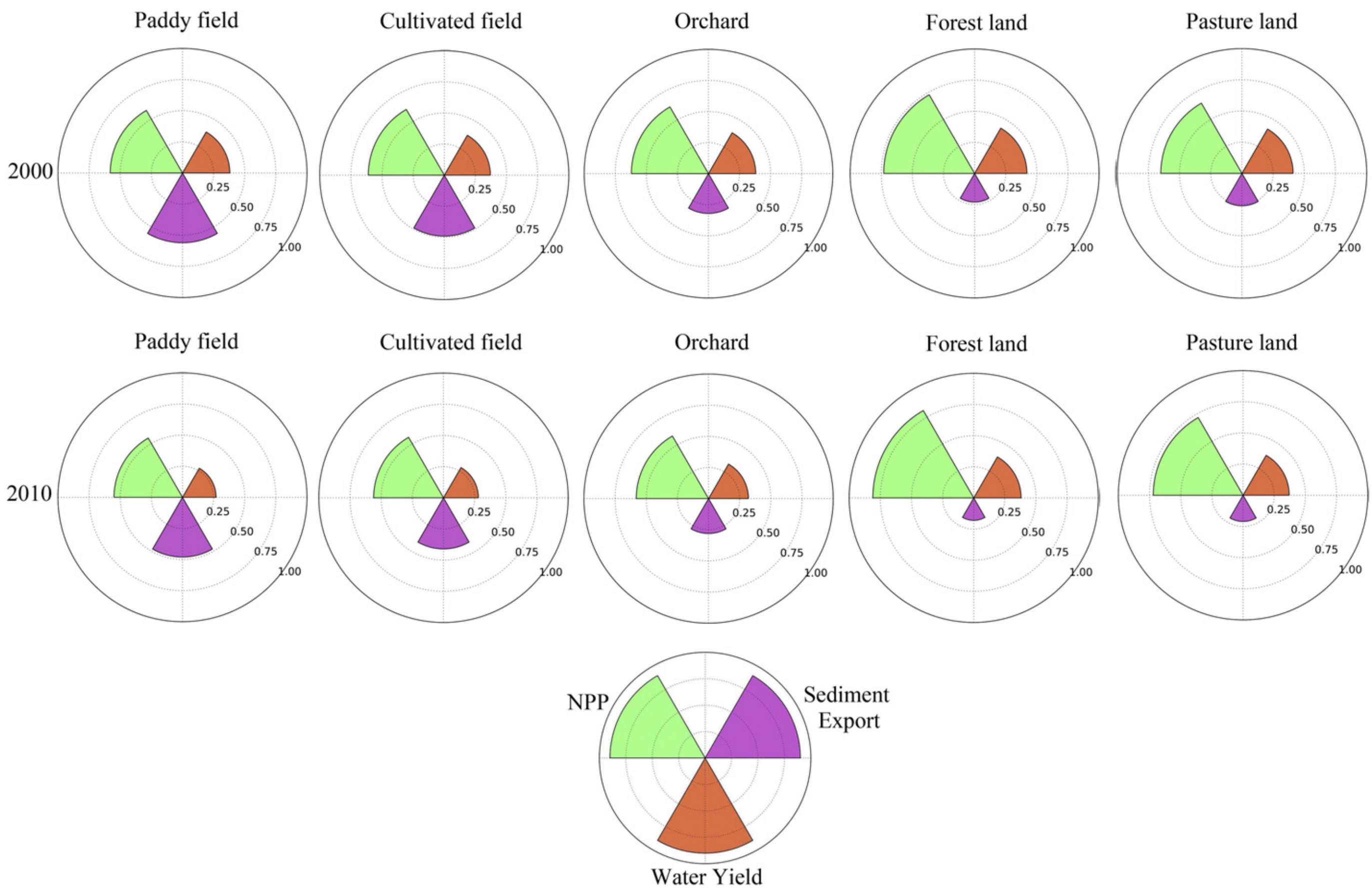

Fig. 8. The rose map of ecosystem services in different land use types in study area from 2000 to 2010.

461.53 g C m^{-2} a^{-1}. The value is lower than that of the present study, which is 739.38 g C m^{-2} a^{-1}. Dong and Ni (2011) used SPOT-VEGETATION data during 1999–2003 to obtain the added value of annual average NPP of SW Karst region, which is 15.77 g C m^{-2} a^{-1}. The value is higher than the 6.87 g C m^{-2} a^{-1} of the current study. In addition to the difference in the model and driven data, the difference in vegetation regions is another reason for the varying values. Thus, in the precondition of ensuring accessible data and finding an optimal procedure of NPP evaluation or exclusive procedure of Karst watershed, many aspects must be explored.

The GGP on the watershed scale changes ecosystem services (NPP, water yield and sediment yield). Vegetation growth can improve carbon fixation amount, change hydrological environment, decrease water supply and diminish water yield. Forestation contributes to climate adjustment and water and soil conservation, but it is not good for runoff formation. Quantitative research on trade-off relationships among NPP water yield and sediment yield of the ecosystem has important practical significance and can guide ecological restoration effectively. Future research may include single service to multiple services, blending of different ecosystem services into the research area, comprehensively analyzing land use type, guidance on regional land use and implementation of scientific rectification.

5.4. The policy recommendations

The specific policy implications based on our research are as follows:

(1) Relatively high soil conservation service and carbon storage service are obtained by returning farmland to forest/grassland at less food supply service loss, thereby contributing to the sustainable utilization of ecosystem services. Through spatial-temporal trade-off analysis, we suggest that the protection and restoration of forest and grassland should be taken seriously, and that the population size and the expansion of construction land should

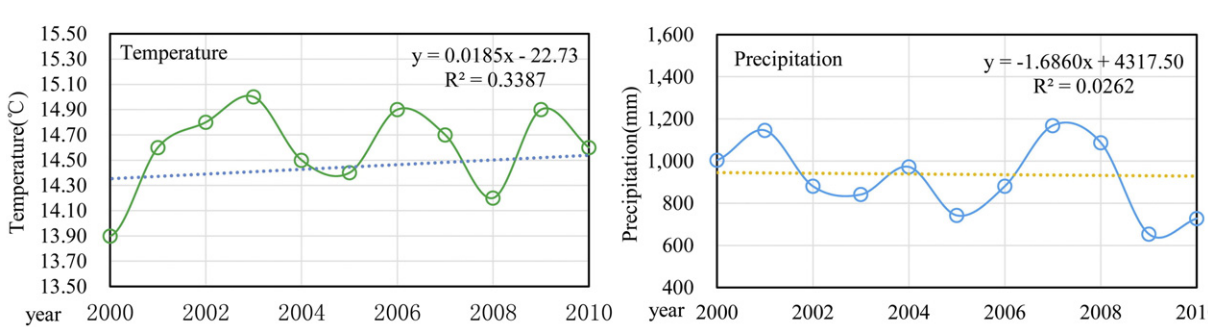

Fig. 9. The trend towards a warmer climate in study area.

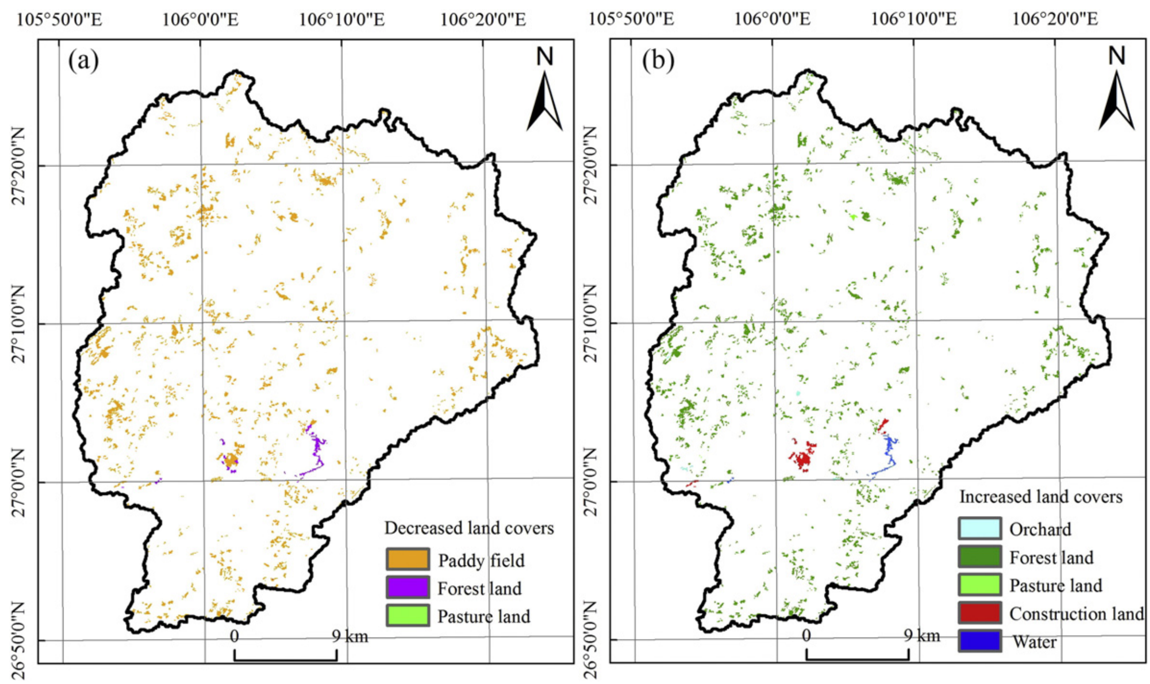

Fig. 10. Decreased and increased land covers from 2000 to 2010.

be properly controlled in Karst regions.

(2) The area of afforestation or returning farmland to forest/grassland should be mainly based on amount of watershed runoff and soil erosion. We should not blindly pursue increasing the forest coverage rate, and we should deal with the trade-off among ecosystem services.

(3) The ecosystem service method and model should be integrated to establish a comprehensive database of various service capabilities for the ecosystem in Karst areas to provide better adaptive management services for Karst drainage basins.

6. Conclusions

This paper takes Shibantang watershed as the research site, calculates the NPP, water yield and sediment yield of the ecosystem between 2000 and 2010 based on SWAT and CASA, and analyzes the correlation among these three ecosystem services. The main conclusions are as follows:

(1) Forest land, pasture land, construction land and water area in the watershed increased, whereas cultivated field, paddy field and garden land decreased. The transformation proportion between cultivated field, pasture land and forest land is almost balanced in the past 10 years. Considerable changes have occurred on the land coverage because of the performance of ecological projects, such as GGP and forest plantation from 1999. The GGP in the watershed has also obtained a good effect.

(2) Calibration and verification of SWAT model (during calibration period, $R^2 = 0.85$ and NSE = 0.78; during verification period, $R^2 = 0.82$ and NSE = 0.76) proved that the model can be applied in Shibantang watershed.

(3) The annual average sediment yield of the watershed exhibited a decreasing trend from 26.15 t/ha in 2000 to 23.81 t/ha in 2010. The annual average water yield decreased from 528 mm in 2000 to 513 mm in 2010. NPP increased during this period from 739.38 $g\,C\,m^{-2}\,a^{-1}$ in 2000 to 746.25 $g\,C\,m^{-2}\,a^{-1}$ in 2010.

(4) The water yield and sediment yield are in a synergic relationship. The increment of water yield can promote the improvement of soil erosion amount. A trade-off relationship exists between NPP, sediment yield and water yield. An increment of NPP is good for decreasing water yield and soil erosion amount and increasing soil conservation amount.

Acknowledgments

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