Tropical Ecology **58**(2): 331–346, 2017 ISSN 0564-3295

www.tropecol.com

Assessing and mapping of multiple ecosystem services in Guizhou Province, China

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Abstract: Spatial explicit information related to ecosystem services is key in decision-making for attainment of sustainable development. Ecosystems in the Karst mountainous region of the southwest China subtropical zone contribute a substantial number of products and services. Based on the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, multiple ecosystem services including water supply, sediment retention, carbon storage and habitat quality in the Guizhou Province of southwest China were assessed and mapped at the watershed scale in this study. The correlation among multiple ecosystem services was investigated and effects of the ecological condition and human pressure on ecosystem services explored. Results indicated obvious spatial heterogeneity in multiple ecosystem services and ecosystem services bundling; 51.09% of the area was designated at a moderate-level for "hotspot" (high ecosystem services provision) area. Tradeoffs existed between water supply and sediment retention and also between carbon storage and sediment retention. The spatial pattern of water supply in Guizhou was heavily affected by precipitation, evaporation and root depth associated with each land use type, while the rainfall erosivity, topography, cover-management factor and support practice associated with land use types played important roles in spatial distribution of sediment retention. The area and proportion of forestland were considered to be dominant factors affecting carbon storage. Habitat suitability of natural land use and the weight and effect distance of human land use were key driving factors affecting the habitat quality score and its spatial pattern. A weak negative correlation was demonstrated between human pressure indicators including the urbanization rate, GDP per person and population density and ecosystem services.

Key words: Ecosystem services, Guizhou, influencing factors, InVEST model, land use, spatial heterogeneity.

Handling Editor: Sunil Kumar

Introduction

It is widely acknowledged that ecosystems provide multiple ecosystem services for human beings including provisioning (e.g., food, fresh water, fiber and bioenergy), regulating (e.g., climate, erosion, flood and water purification), cultural (e.g., recreation and education), and supporting (e.g., biogeochemical cycling and biodiversity) services (Bryan 2013; Mendoza-González *et al.* 2012). Previous research indicates that approximately 60% of ecosystem services studied have experienced notable degradation over the last 50 years (MA 2005).

Quantifying and mapping ecosystem services is vital for accurate interpretation of provisional

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service levels and for service locations (Crossman *et al.* 2012; Jackson *et al.* 2013; Pan *et al.* 2013). Past studies have quantified the provision level of multiple ecosystem services and identified hotspots for service provisions in mountainous areas (Bai *et al.* 2011; Egoh *et al.* 2009; Krishnaswamy *et al.* 2009). The ecosystem service supply levels in the Karst mountain areas, however, remain unquantified. In addition, provision level quantification is recognized as a factor of the physical environment and socioeconomic factors combined (De Groot *et al.* 2010; Dobbs *et al.* 2014), yet precise evaluation relating the extent of impact to ecosystem provisions has not been performed in the Karst mountain areas.

Limited analysis has been performed on the state and change of ecosystem services values in the Karst mountain areas (Wang *et al.* 2010; Zhou *et al.* 2011), yet a lack of analysis for the spatial distribution and correlation among multiple ecosystem services remains. The value coefficient approach of ecosystem services proposed by Costanza *et al.* (1997) and remote sensing monitoring, additionally, have been implemented to assess the provision of ecosystem services in the Karst mountain areas (Zhang *et al.* 2009; Zhao *et al.* 2014), yet ecosystem services models are rarely employed. A more detailed study for assessing and mapping the provision of multiple ecosystem services in the Karst mountain areas is thus essential for improving the management and protection of the terrestrial ecosystem.

Guizhou is one of three provinces in China encompassing this region of Karst landforms and covers more than 10 million ha of forestland serving crucial functions related to water supply, carbon sequestration, sediment retention, climate regulation and biodiversity (Li *et al.* 2010; Su & Zhu 2000). The economy has experienced a high growth rate over the past 20 years, resulting in significant land use/cover changes, inadvertently and substantially influencing the ecosystems, hence, a critical need to assess ecosystem services' status in this region is needed. A study for assessing and mapping multiple ecosystem service provisions including water supply, sediment retention, carbon storage and habitat quality utilizing the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model then was presented in this study with the Guizhou Province as the subject area. The correlation among multiple ecosystem services was investigated and the effects of ecological condition and human pressure on ecosystem services explored. Understanding spatial patterns and the correlation between ecosystem services and factors influencing the supply of ecosystem services in the area supports sustainable socio-economic development in the mountain areas.

The objectives of this study were to: (1) quantify and map multiple ecosystem services at watershed scale utilizing the InVEST model; (2) analyze spatial distribution of ecosystem services bundling and identify hotspots; (3) explore the correlation among ecosystem services; and (4) discuss impacts of ecological conditions and human pressure indicators on ecosystem services provision.

Following two hypotheses were tested in this study: (1) Significant spatial heterogeneity exists in ecosystem services; and (2) Ecological factors and human pressure exert significant effects on the spatial heterogeneity of ecosystem services.

Methods

Study area

The Guizhou Province (between 24°37′–29°13′N and 103°36′–109°35′E) features a total area of 1,76,132 km^2 and is located in southwest China in the upper reaches of the Yangtze River and the Pearl River (Fig. 1). The carbonatite distribution area (130,000 km^2) accounts for approximately 73% of the total area, qualifying the study area as an eco-fragile region under tremen-dous pressure from human activities (Xu *et al.* 2011; Zhang *et al.* 2012). Mountains and hills dominate the topography accounting for 92.5% of the total area. Altitude ranges from 154 m to 2859 m increasing from east to west with slopes declining from the south, east and north to the center and west. A subtropical monsoon climate is featured in the region with monthly average maximum and minimum temperatures of 25 °C and 4 °C in July and January, respectively, and average annual precipitation ranging from 850 mm to 1600 mm. Eight watersheds are also featured including Chishuihe, Wujiang, Niulanjiang-Hengjiang, Yuanjiang, Hongshuihe, Duliujiang, Beipanjiang, and Nanpanjiang. Population of the study area is approximately 34,740,000 with a population density of 164 persons km^{-2} as of 2010.

The InVEST model

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model (Sharp *et al.* 2014) is a suite of software models developed by

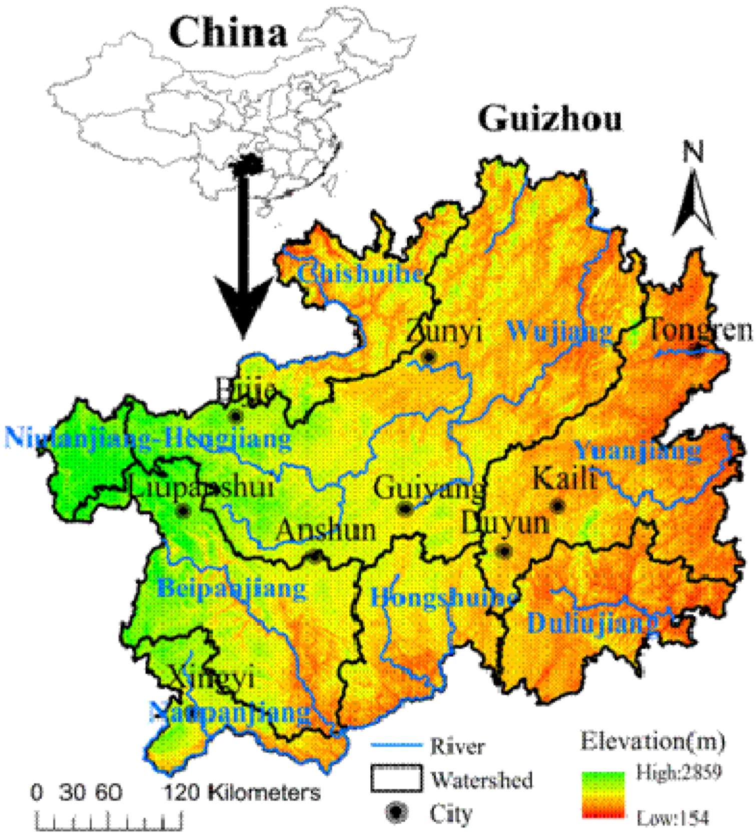

Fig. 1. Study area.

the Natural Capital Project (Stanford University, Stanford, CA, USA; www.naturalcapitalproject.org) employed to quantify and map land use change impact on ecosystem services. The model available in this software has been applied in different regions of the world (Delphin *et al.* 2013; Hoyer & Chang 2014; Marquès *et al.* 2013). The InVEST model was implemented in this study to assess the provision of multiple ecosystem services in the Guizhou Province at the watershed scale.

Local ecological constraints were considered in the selection of ecosystem services for the study area. Water supply, carbon storage, sediment retention and habitat quality were then modeled for this application as the decline of habitat quality, water shortage, soil erosion and the decrease of climate regulation function are the major ecological problems of the study area (Xiao 2000).

Landsat-5 satellite images of 30 m resolution were used to interpret a land use map of the region for 2010, and a 30 m resolution digital elevation model (DEM) for the Guizhou Province was derived from ASTER GDEM data of the National Aeronautics and Space Administration (NASA, Houston, TX, USA).

Water supply

The water yield module used the following parameters to calculate annual water yield: average annual precipitation, annual reference evapotranspiration and a correction factor for vegetation type, soil depth, plant available water content, land use and land cover, root depth, and elevation (Sánchez-Canales *et al.* 2012). The amounts of water supply in InVEST model was calculated based on equations developed by Zhang *et al.* (2001).

$$Y = (1 - \frac{AET}{P}) \cdot P \tag{1}$$

$$\frac{AET}{P} = \frac{1+\omega \cdot R}{1+\omega \cdot R + \frac{1}{R}} \tag{2}$$

$$R = \frac{k \cdot ETo}{P} \tag{3}$$

$$\omega = Z \cdot \frac{AWC}{P} \tag{4}$$

Table 1. Required data for water yield and sediment retention modules.

Land use types	k	Root depth (mm)	C	P
Woodland	1.00	7000	0.001	1.00
Grassland	0.65	1700	0.300	1.00
Farmland	0.70	600	0.800	0.50
Built-up land	0.30	10	0.000	0.00
Water body	1.00	10	0.000	0.00
Unused land	0.20	10	0.000	1.00

Where Y is the annual water supply, AET is the annual evapotranspiration, P is the annual precipitation, ω is the plant-available water coefficient, R is the Budyko dryness index (Budyko & Miller 1974), ET_0 is the reference evapotranspiration, k is the plant evapotranspiration coefficient, AWC is the plant available water content, Z denotes the Zhang coefficient. P was downloaded from the China Meteorological Data Sharing Service System and the ET_0 was calculated based on Hargreaves equation (Hargreaves *et al.* 2003) while AWC was calculated by referring to the method of Zhou *et al.* (2005). The k and root depth were derived from research findings of Allen *et al.* (1998) and Schenk & Jackson (2002) (Table 1).

Sediment retention

Sediment retention ability was quantified by the Universal Soil Loss Equation (USLE) in the sediment retention module, integrating information related to land cover patterns, soil properties, digital elevation and rainfall (Sharp *et al.* 2014; Wischmeier & Smith 1978). The USLE terms C (cover-management factor) and P (support practice factor) factors are adjustable and account for land cover types and effects of management practices on soil mobilization (Hoyer & Chang 2014).

$$\text{Sediment Retention} = \text{RKLS} - \text{USLE} = R \times K \times LS \times (1 - C \times P) \quad (5)$$

Where RKLS is the potential soil erosion, USLE is the actual soil erosion, R is the rainfall erosivity, K is the soil erodibility, LS is the topographic factor, C and P denote cover-management factor and support practice. Rainfall erosivity was estimated using the method of Zhang & Fu (2002). Soil erodibility was calculated based on soil texture derived from the China Soil Scientific Database while C and P were defined utilizing the reference value of Yang *et al.* (2013) (Table 1).

Carbon storage

The carbon module simplifies the carbon cycle to quantify the amount of carbon storage depending on the maps of land use types and data on stocks of four carbon pools, namely aboveground biomass, belowground biomass, soil and dead organic matter (Leh *et al.* 2013). Carbon storage was estimated by considering only three of these carbon pools (aboveground biomass, belowground biomass and soil organic matter) based on an average of the reported values (Table 2; Chuai *et al.* 2011; Li *et al.* 2013; Luo *et al.* 2008; Xi *et al.* 2008).

Table 2. Carbon density for each land use type.

Land use types	Carbon density (t ha^{-1})		
	aboveground	belowground	Soil
Farmland	6.06	1.87	222.58
Forestland	26.57	4.31	325.78
Grassland	0.82	0.87	246.22
Built-up land	0.10	0.02	233.38
Water body	0.60	0.12	213.01
Unused land	0.74	0.13	231.55

Habitat quality

Habitat quality is recognized as a proxy for biodiversity and is estimated by analyzing the land use map in conjunction with threats (Leh *et al.* 2013; Sharp *et al.* 2014). The land use types in this module were classified into natural land uses (e.g., forestland, grassland) and human land uses (e.g., farmland, built-up land). Relative habitat suitability values ranging from 0 to 1 were assigned to each land use type (Terrado *et al.* 2016). Human land use types were regarded as threat factors. Built-up land was classified into city, rural settlement and industrial land categories to improve the estimation accuracy. Influence weight, distance of threat factors, and relative sensitivity of habitat types to threats were elicited from expert knowledge (Table 3 and 4). Habitat quality scores ranged from 0 to 1, where 1 denoted high habitat quality (Terrado *et al.* 2016).

$$Q_{xj} = H_j \left(1 - \left(\frac{D_{xj}^z}{D_{xj}^z + k^z} \right) \right) \tag{6}$$

$$D_{xj} = \sum_{r=1}^{R} \sum_{y=1}^{Y} \left(\frac{w_r}{\sum_{r=1}^{R} w_r} \right) r_y i_{rxy} \beta_x S_{jr} \tag{7}$$

Table 3. Influence distance and weights of threat factors.

	Maximum influence distance (km)	Weights
Farmland	1.00	0.30
City	10.00	0.90
Rural settlement	1.00	0.40
Industrial land	5.00	0.60

Where Q_{xj} is the habitat quality value, H_j is the habitat suitability, D_{xj} is the habitat degradation, Z is equal to 2.5, k is equal to half of grid resolution, W_r is the weights of threat factors, r_y is the number of threat factors, β_x is the protective degree of natural land use type, S_{jr} is the sensitivity of habitat types to threats.

Ecosystem services bundling

Ecosystem services bundling was calculated according to Eq. (8) by overlapping individual ecosystem services results utilizing the ArcGIS ver10.1 software. Estimation of individual ecosystem services was normalized from 0 to 1.

According to expert estimation and based on individual ecosystem services priority, sediment retention was assigned 35 percent of weight based on the Analytic Hierarchy Process (AHP) model. Carbon storage, water supply and habitat quality were assigned 15, 25, 25 percent, respectively.

$$V_t = \sum_{i=1}^{n} W_i \bullet X_i \tag{8}$$

Where V_t is the ecosystem services bundling (sum of ecosystem services), W_i is the weight of individual ecosystem services of type i, X_i is the normalized value of individual ecosystem services.

Data analysis

Hotspot regions analysis for ecosystem services bundling

The G_i^* proposed by Getis & Ord (1992) was utilized to analyze hotspot regions based on results of ecosystem services bundling. Value of G_i^* could identify clusters of the region with the value (QDSs) in magnitude (Santora *et al.* 2010). Hotspots were then mapped based on the value of G_i^* and categorized as low level ($G_i^* < -1.67$), moderate level ($-1.68 < G_i^* < 1.26$) and high level ($G_i^* > 1.27$).

Analysis of correlation among ecosystem services

Pearson correlation coefficient (r) was applied to analyze the correlation among ecosystem services. The correlation was then categorized as strong tradeoffs ($-1 < r < -0.6$), moderate tradeoffs ($-0.6 < r < -0.2$), weak tradeoffs ($-0.2 < r < 0$), weak synergy ($0 < r < 0.2$), moderate synergy ($0.2 < r < 0.6$), and strong synergy ($0.6 < r < 1$).

Regression analysis between human pressure indicators and ecosystem services

The urbanization rate, GDP (Gross Domestic Product) per person, and population density may be reflective of human activity intensity, thus were selected as human pressure indicators. Regression modeling was used to quantify the correlation between ecosystem services and human pressure indicators. SPSS software (IBM Chicago, IL, USA) was then employed to test the regression coefficients.

Results

Spatial pattern of individual ecosystem services

Assessment results for the individual ecosystem services revealed that average values of water supply, sediment retention, carbon storage and habitat quality in the entire study area were 545.16 mm, 585.43 t ha^{-1}, 310.08 t ha^{-1} and 0.72, respectively (Table 5). The average values of water supply in Beipanjiang, Hongshuihe, Yuanjiang and Wujiang watersheds were greater than other watersheds. The average values of sediment retention in Chishuihe, Beipanjiang, Duliujiang, Nanpanjiang watersheds were greater than other watersheds, and average values of carbon storage and habitat quality were higher in Duliujiang, Yuanjiang, Hongshuihe and Chishuihe watersheds (Table 5).

Table 4. Relative sensitivity of habitat types to threat factors.

	Habitat suitability	Farmland	City	Rural settlement	Industrial land
Farmland	0.10	0.30	0.80	0.40	0.60
Forestland	0.90	0.50	0.40	0.10	0.30
Grassland	0.60	0.70	0.10	0.10	0.20
Built-up land	0.00	0.00	0.00	0.00	0.00
Water body	1.00	0.80	0.90	0.10	0.90
Unused land	0.10	0.20	0.10	0.00	0.10

Table 5. Average value of ecosystem services at watershed scale.

	Water supply (mm yr^{-1})	Sediment retention (t ha^{-1} yr^{-1})	Carbon storage (t ha^{-1})	Habitat quality	Ecosystem services bundling
Whole study area	545.16	585.43	310.08	0.72	0.43
Wujiang	544.64	430.46	305.28	0.67	0.35
Yuanjiang	574.27	485.49	326.55	0.84	0.53
Nanpanjiang	423.49	699.49	309.52	0.73	0.38
Niulanjiang-Hengjiang	320.52	513.01	280.78	0.55	0.12
Hongshuihe	578.38	504.83	318.84	0.81	0.50
Duliujiang	507.40	722.50	333.93	0.87	0.57
Chishuihe	486.69	877.51	318.14	0.77	0.49
Beipanjiang	607.04	846.27	295.07	0.68	0.44

Low-value (263–433 mm) water supply regions were typically distributed in the Niulanjiang-Hengjiang watershed, southern portions of Chishuihe and Nanpanjiang watersheds, western portion of the Wujiang watershed, and the southeast portion of the Duliujiang watershed (Fig. 2a). High-value (646–810 mm) regions were typically located in the southern portion of the Wujiang watershed, northeast portion of the Beipanjiang watershed, western portion of the Yuanjiang watershed, and throughout the Hongshuihe watershed (Fig. 2a). Low-value (187–379 t ha^{-1}) regions of sediment retention were typically located in southern and central portions of the Wujiang watershed, northern portion of the Hongshuihe watershed, and the central portion of the Yuanjiang watershed, while high-value (1090–1818 t ha^{-1}) regions were in the Beipanjiang watershed western portion and Chishuihe watershed northern area (Fig. 2c). A similar spatial distribution was observed between carbon storage and habitat quality with high-value (328–343 t ha^{-1} and 0.83–0.91) regions mainly located in the Duliujiang watershed, the southern portion of the Yuanjiang watershed, and the northern portion of the Chishuihe watershed. Low-value (278–291 t ha^{-1} and 0.50–0.60) regions were located in the Niulanjiang-Hengjiang watershed and the southern portion of the Wujiang watershed (Figs. 2b and d). Carbon storage in the central and northern areas of the Beipanjiang watershed also ranged from 278 to 291 t ha^{-1} (Fig. 2b).

Spatial pattern of ecosystem services bundling and hotspots

Calculated results for the ecosystem services bundling revealed that values ranged from 0.09 to 0.69. Low-value (0.09–0.25) regions of ecosystem services bundling were distributed in the Niulanjiang-Hengjiang watershed and in the Wujiang watershed central area while high-value (0.56–0.69) regions were typically in the northwest portion of the Duliujiang watershed, northern and southern portions of the Yuanjiang watershed, eastern portion of the Hongshuihe watershed, and in the northern area of the Chishuihe watershed (Fig. 3a). The average value of ecosystem services bundling in the whole study area was 0.43 with

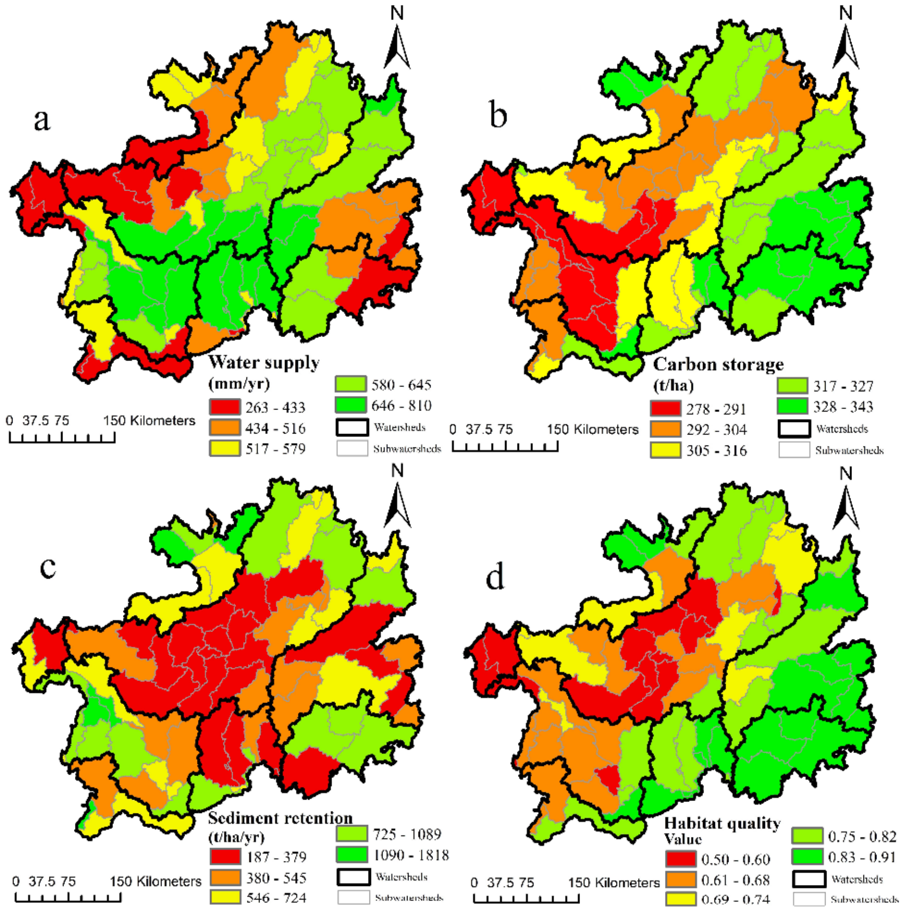

Fig. 2. Spatial distribution of water supply (a), carbon storage (b), sediment retention (c), and habitat quality (d) at watershed scale.

average values in Duliujiang, Yuanjiang, Hongshuihe and Chishuihe watersheds relatively large compared to other watersheds (Table 5).

High-level hotspot regions were typically in the Chishuihe watershed northern area, southern and northern portions of the Yuanjiang watershed, northern area of the Duliujiang watershed, and the eastern area of the Hongshuihe watershed. Moderate-level regions were located in the entire region of the Nanpanjiang watershed, most of the Beipanjiang watershed, the Wujiang watershed eastern area, the Yuanjiang watershed central portion. Low-level regions were in the Wujiang watershed's western and southern areas, the entire region of the Niulanjiang-Hengjiang watershed, and the southern portion of the Chishuihe watershed (Fig. 3b). Moderate-levels in the entire study area accounted for 51.09% of total areas while proportions of low-levels in the Niulanjiang-Hengjiang watershed and the Wujiang watershed were greater than other watersheds. The moderate-level was the dominate hotspot category in Nanpanjiang, Beipanjiang, Yuanjiang and Hongshuihe watersheds, while high-level dominated in the Duliujiang and Chishuihe watersheds (Table 6).

Correlation among ecosystem services

Weak tradeoffs ($-0.2<r<0$) existed between water supply and sediment retention services and between carbon storage and sediment retention services for the entire study area. The relationship among other ecosystem services, with the exception between water supply and sediment retention services and between carbon storage and sediment retention services, were synergistic ($r>0$). The ecosystem services bundling demonstrated strong synergy ($r>0.6$) with habitat quality and carbon storage and the correlation between carbon storage and habitat quality exhibited moderate synergism ($0.2<r<0.6$) at watershed scale. A weak tradeoff or synergy ($-0.2<r<0.2$) was

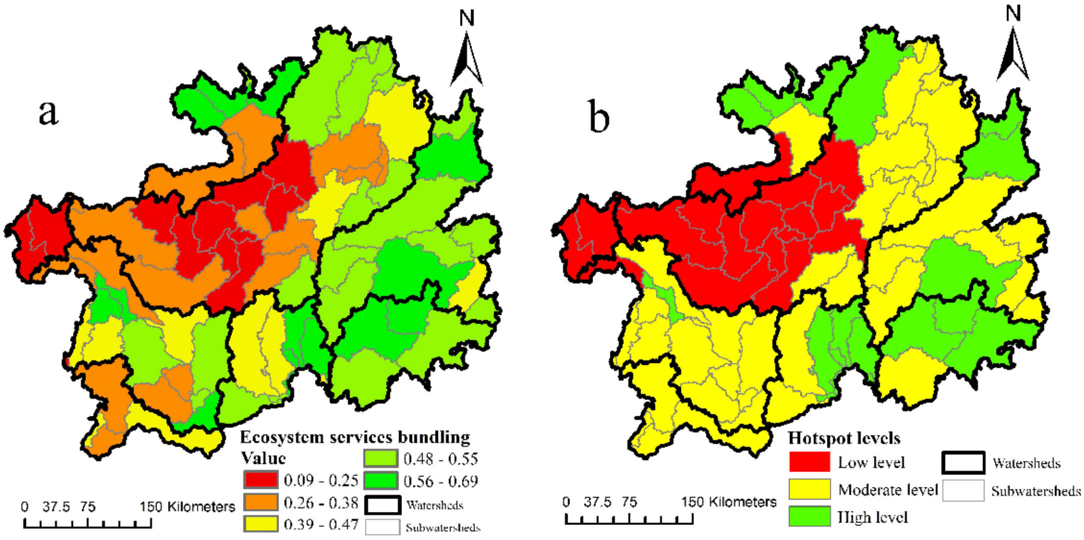

Fig. 3. Spatial distribution of the ecosystem services bundling (a) and hotspots (b) at watershed scale.

Table 6. Area (km²) and proportion (%) for hotspot levels at watershed scale.

	Low level		Moderate level		High level	
	Area	Proportion	Area	Proportion	Area	Proportion
Whole study area	42689.23	24.23	89978.53	51.09	43464.24	24.68
Wujiang	32156.87	49.60	25661.08	39.58	7012.12	10.82
Yuanjiang	0.00	0.00	19460.27	62.96	11446.83	37.04
Nanpanjiang	0.00	0.00	7809.98	100.00	0.00	0.00
Niulanjiang-Hengjiang	4690.99	100.00	0.00	0.00	0.00	0.00
Hongshuihe	0.00	0.00	6843.05	50.42	6727.71	49.58
Duliujiang	0.00	0.00	4153.84	26.51	11513.10	73.49
Chishuihe	4530.70	32.75	3350.32	24.21	5954.82	43.04
Beipanjiang	1310.67	5.28	22699.99	91.46	809.66	3.26

reflected among other ecosystem services, however, at watershed scale (Table 7).

Impacts of ecological conditions and human indicators on ecosystem services

Water supply demonstrated a strong positive correlation with precipitation while exhibiting a negative correlation with evaporation (Sánchez-Canales *et al.* 2012). Estimates of water supply in the northeastern Beipanjiang watershed area, for example, were greater than estimates in other watersheds due to greater precipitation and lesser evaporation (Figs. 2a and 4). A negative correlation also appeared between root depth for land use classes and water supply (Hoyer & Chang 2014). Deep root depth for land use classes (e.g. forestland) was adverse to water yield while shallow root depth (e.g. farmland) was conducive to water yield. The effect of land use types on water supply could be reflected in the provision level of ecosystem services for each land use type (Fig. 5). Despite the high value of precipitation (1117–1200 mm) in Duliujiang watershed western area, the non-high value of water supply was not only correlated with relatively large evaporation but also with high forestland proportion (Figs. 2a, 4 and 6).

Sediment retention demonstrated a positive correlation with rainfall erosivity, DEM and slope while representing a negative correlation with the cover-management factor and support practice for land use types (Hoyer & Chang 2014; Sánchez-Canales *et al.* 2015). High value of sediment retention in the Beipanjiang watershed western area and in the northern portion of the Duliujiang watershed was closely associated with the high

Table 7. Correlations among ecosystem services at watershed scale.

		Water supply	Sediment retention	Carbon storage	Habitat quality	Ecosystem services bundling
Whole study area	Water supply	1.000	-	-	-	-
	Sediment retention	–0.009	1.000	-	-	-
	Carbon storage	0.028	–0.001	1.000	-	-
	Habitat quality	0.044	0.004	0.230	1.000	-
	Ecosystem services bundling	0.133	0.03	0.674	0.907	1.000
Wujiang	Water supply	1.000	-	-	-	-
	Sediment retention	0.020	1.000	-	-	-
	Carbon storage	–0.008	0.034	1.000	-	-
	Habitat quality	–0.005	0.040	0.311	1.000	-
	Ecosystem services bundling	0.060	0.093	0.666	0.912	1.000
Yuanjiang	Water supply	1.000	-	-	-	-
	Sediment retention	–0.020	1.000	-	-	-
	Carbon storage	–0.147	0.020	1.000	-	-
	Habitat quality	–0.076	0.009	0.271	1.000	
	Ecosystem services bundling	0.052	0.069	0.660	0.897	1.000
Nanpanjiang	Water supply	1.000	-	-	-	-
	Sediment retention	0.001	1.000	-	-	-
	Carbon storage	0.071	–0.022	1.000	-	-
	Habitat quality	0.034	0.004	0.291	1.000	-
	Ecosystem services bundling	0.127	0.051	0.662	0.904	1.000
Niulanjiang-Hengjiang	Water supply	1.000	-	-	-	-
	Sediment retention	–0.004	1.000	-	-	-
	Carbon storage	0.023	–0.016	1.000	-	-
	Habitat quality	–0.004	0.038	0.245	1.000	-
	Ecosystem services bundling	0.040	0.077	0.607	0.917	1.000
Hongshuihe	Water supply	1.000	-	-	-	-
	Sediment retention	–0.084	1.000	-	-	-
	Carbon storage	0.086	0.010	1.000	-	-
	Habitat quality	0.038	0.016	0.230	1.000	-
	Ecosystem services bundling	0.131	0.069	0.649	0.886	1.000
Duliujiang	Water supply	1.000	-	-	-	-
	Sediment retention	–0.024	1.000	-	-	-
	Carbon storage	–0.115	0.012	1.000	-	-
	Habitat quality	0.041	–0.004	0.262	1.000	-
	Ecosystem services bundling	0.068	0.079	0.646	0.897	1.000
Chishuihe	Water supply	1.000	-	-	-	-
	Sediment retention	0.079	1.000	-	-	-
	Carbon storage	0.087	0.017	1.000	-	-
	Habitat quality	0.098	0.034	0.362	1.000	
	Ecosystem services bundling	0.160	0.119	0.701	0.913	1.000
Beipanjiang	Water supply	1.000	-	-	-	-
	Sediment retention	0.006	1.000	-	-	-
	Carbon storage	–0.003	–0.017	1.000	-	-
	Habitat quality	0.054	0.009	0.252	1.000	-
	Ecosystem services bundling	0.116	0.091	0.625	0.904	1.000

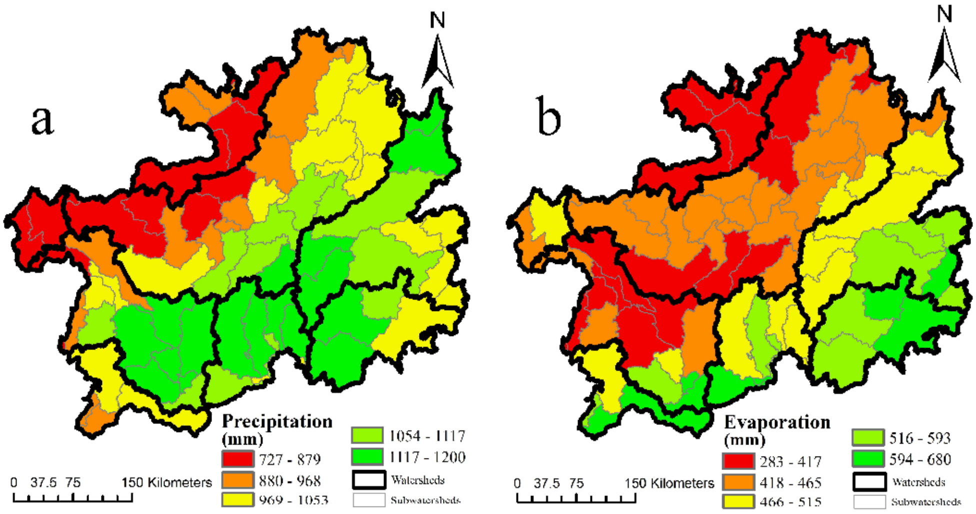

Fig. 4. Spatial distribution of precipitation (a) and evaporation (b) at watershed scale.

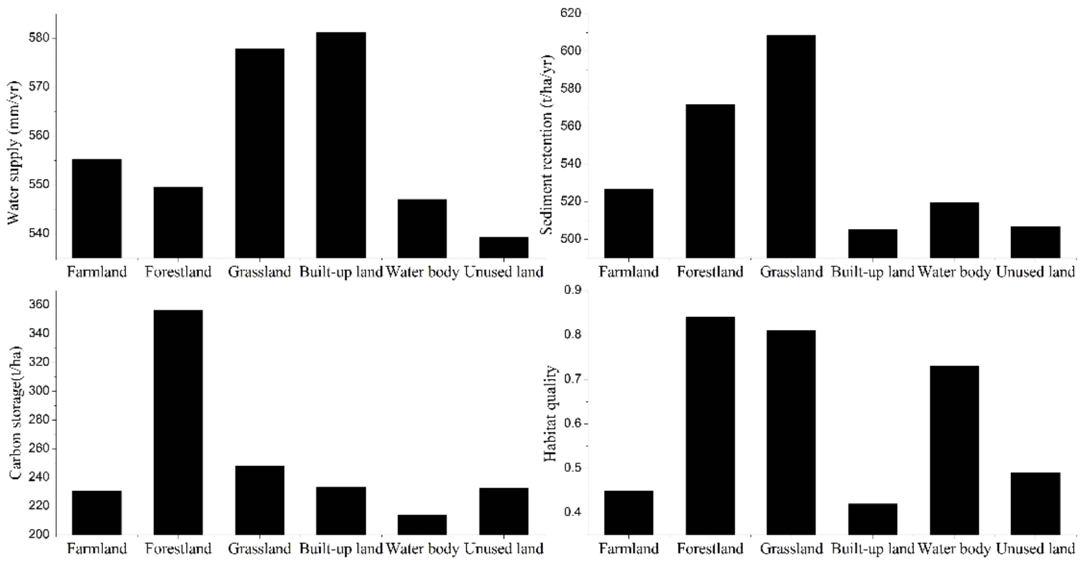

Fig. 5. Multiple ecosystem services for each land use type.

rainfall erosivity and rugged topography. Rainfall erosivity in these regions (>2927 MJ mm ha^{-1} h yr^{-1}) was greater than other regions while topographies consisted of primarily moderate and high elevation mountains (900–1900 m and >1900 m) with slopes greater than 21.62° (Ma and An, 2012) (Figs. 1, 2c and 7). According to the proportion and relative location of land use type, cover-management factors and support practice exert influences on sediment retention. Dominant land use type contributed significantly to sediment retention (Fig. 5). For example, despite low rainfall erosivity (2363–2651 MJ mm ha^{-1} h yr^{-1}), the high value of sediment retention (725–1818 t ha^{-1}) in the northern Chishuihe watershed area related to a high proportion of forestland. Conversely, the smooth terrain, relatively low rainfall erosivity and high proportion of farmland resulted in a low value of sediment retention (187–379 t ha^{-1}) in the central and southern portions of the Wujiang watershed (Figs. 2c, 6 and 7a).

Carbon density and proportion for each land use type were considered to be dominant factors affecting carbon storage. Forestland significantly affected carbon storage due to high proportion in total area and high carbon density while farmland and grassland with high proportion exhibited relatively slight effects on carbon storage resulting

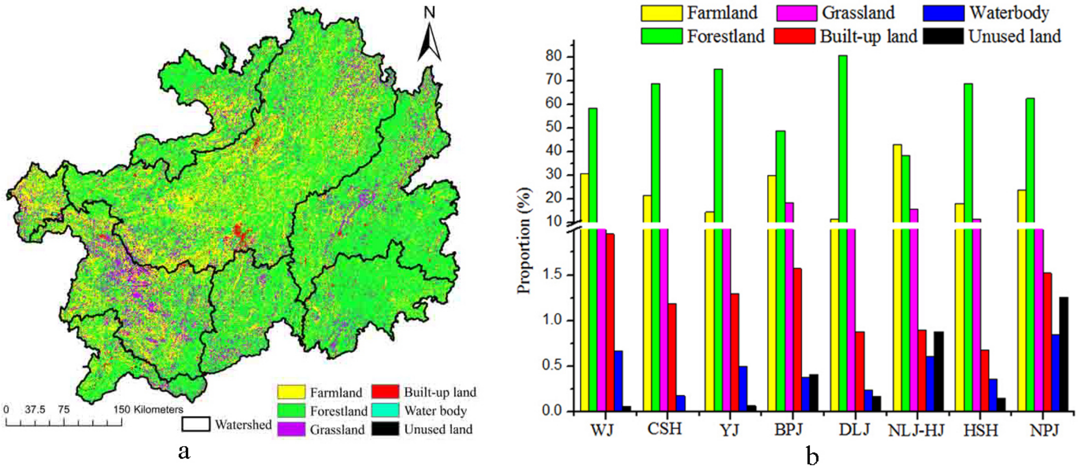

Fig. 6. Spatial pattern (a) and proportion (b) for each land use type in Guizhou. WJ–Wujiang; CSH–Chishuihe; YJ–Yuanjiang; BPJ–Beipanjiang; DLJ–Duliujiang; NLJ-HJ–Niulanjiang-Hengjiang; HSH–Hongshuihe; NPJ–Nanpanjiang.

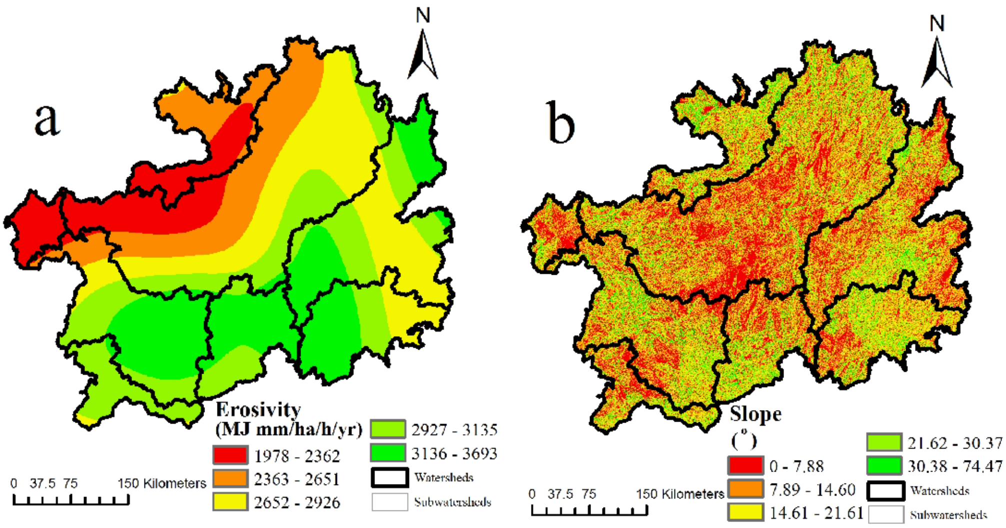

Fig. 7. Rainfall erosivity (a) and slope (b) at watershed scale.

from low carbon density for these land use types. Contribution on carbon storage from built-up land, water body, and unused land was only slight due to small proportions (Table 2, Figs. 5 and 6). High value carbon storage (328–343 t ha^{-1}) was observed in the Duliujiang and Yuanjiang watersheds due to high carbon density and a large forest proportion. Low value carbon storage (278–291 t ha^{-1}) in the Niulanjiang-Hengjiang watershed western portion, western portion of the Beipanjiang watershed, and the Wujiang watershed southern and central portions resulted from low density farmland and grassland (Table 2, Figs. 2b, 5 and 6).

Habitat suitability of natural land uses, weight, and effect distance of threat factors (e.g. farmland and built-up land) were key driving factors affecting habitat quality levels. The low habitat quality (0.50–0.60) in the southern Wujiang watershed area resulted from significant amounts of farmland and built-up land, while habitat quality levels in the Niulanjiang-Hengjiang watershed (0.50–0.60) was low as a result of significant farmland area. A high habitat quality level in the Duliujiang watershed and the Yuanjiang watershed (0.83–0.91) manifested as a result of satisfactory habitat suitability and forestland area combined with a relatively small proportion of built-up land (Figs. 2d, 5 and 6).

High value (50.68–96.98%, 3422–5678 USD

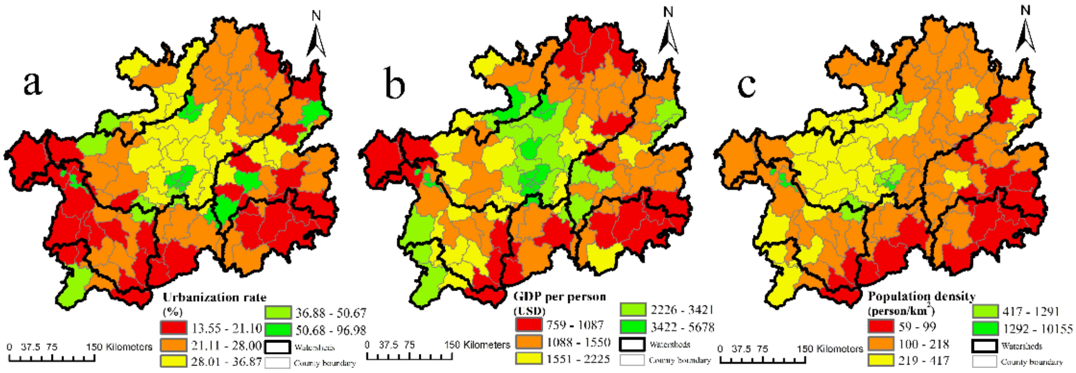

Fig. 8. Spatial pattern of urbanization rate (a), GDP per person (b) and population density (c) at watershed scale.

Table 8. Correlations between urbanization rate, GDP per person, population density and ecosystem services at watershed scale.

		Water supply	Sediment retention	Carbon storage	Habitat quality	Ecosystem services bundling
Whole study area	Urbanization rate	–0.014	–0.037	–0.037	–0.041	–0.075
	GDP per person	–0.286	–0.009	–0.136	–0.078	–0.194
	Population density	–0.080	–0.015	–0.075	–0.044	–0.105
Wujiang	Urbanization rate	0.082	–0.092	–0.060	–0.082	–0.088
	GDP per person	0.093	–0.118	–0.080	–0.090	–0.104
	Population density	0.047	–0.040	–0.059	–0.058	–0.069
Yuanjiang	Urbanization rate	0.281	–0.044	–0.097	–0.084	–0.091
	GDP per person	0.351	–0.063	–1.080	–0.110	–0.112
	Population density	0.437	–0.054	–0.136	–0.112	–0.120
Nanpanjiang	Urbanization rate	–0.118	–0.002	–0.020	–0.055	–0.060
	GDP per person	0.049	0.028	0.096	0.170	0.179
	Population density	–0.002	–0.038	–0.098	–0.165	–0.173
Niulanjiang-Hengjiang	Urbanization rate	0.017	–0.056	–0.108	–0.032	–0.066
	GDP per person	–0.017	–0.056	–0.108	–0.032	–0.066
	Population density	0.017	–0.056	–0.108	–0.032	–0.066
Hongshuihe	Urbanization rate	0.313	–0.056	–0.020	–0.006	–0.022
	GDP per person	0.157	–0.061	–0.029	–0.034	–0.033
	Population density	0.236	–0.064	–0.044	–0.045	–0.043
Duliujiang	Urbanization rate	0.310	–0.051	–0.076	–0.047	–0.047
	GDP per person	0.281	–0.090	–0.101	–0.036	–0.056
	Population density	0.298	–0.050	–0.002	–0.045	–0.003
Chishuihe	Urbanization rate	–0.051	–0.017	–0.043	–0.029	–0.036
	GDP per person	–0.040	–0.047	–0.141	–0.155	–0.178
	Population density	–0.397	–0.104	–0.091	–0.102	–0.138
Beipanjiang	Urbanization rate	–0.097	–0.072	–0.055	–0.068	–0.077
	GDP per person	–0.117	–0.012	–0.062	–0.083	–0.102
	Population density	–0.126	–0.039	–0.072	–0.083	–0.109

and 1292–10155 person km^{-2}) of urbanization rate, GDP per person and population density were typically located in the southern and central areas of the Wujiang watershed, while low value (13.55–21.10%, 759–1087 USD and 59–99 person km^{-2}) were mainly situated in the Niulanjiang-Hengjiang, Duliujiang and Hongshuihe watersheds (Fig. 8). Spatial distribution of ecosystem services was approximately contrary to that of human pressure indicators (Figs. 2 and 8), thus a weak negative correlation between human pressure indicators and ecosystem services was present in the entire study area. The human pressure indicators in most watersheds exhibited a negative correlation with sediment retention, carbon storage, habitat quality and ecosystem services bundling. Both positive and negative correlations appeared between human pressure indicators and water supply (Table 8). Correlation between human pressure indicators and individual ecosystem services was dependent on spatial consistence at the watershed scale. The high value of water supply (646–810 mm) and human pressure indicators (50.68–96.98%, 3422–5678 USD and 1292–10155 person km^{-2}), for example, were located in the southern Wujiang watershed area. Spatial patterns between water supply and human pressure indicators were approximately consistent, thus a positive correlation between human pressure indicators and water supply in the Wujiang watershed was exhibited (Figs. 2a and 8).

Discussion

Comparison of the results with other studies

Results of this study were compared with previous studies with the average value of water yield results in the study (545.16 mm) slightly less than Hao & Chen (2012) and mainly related to varying precipitations in the 1980s and 2010. The average amount of sediment retention (585.43 t ha^{-1}) was slightly less than Rao *et al.* (2014) estimate as a result of different settings for the cover-management factor. The estimation of average carbon density was greater than Zhang *et al.* (2015) research due to the higher forestland proportion in this study. Habitat quality score was consistent with similar research by Wang *et al.* (2014) with a similar habitat quality spatial pattern.

Informing decision for environmental management

Environmental management benefits goals for providing high-value ecosystem services areas expansion, reduction of low-value ecosystem services areas, and focusing on factors with substantial potential for impacting provisions from ecosystem services (Chan *et al.* 2006; Dickie *et al.* 2011). Factors including the mapping of ecosystem service hotspots as conservation goals may be explicitly addressed through identification of priority areas for maintaining key ecosystem services for the benefit of humans (Fürst *et al.* 2013; García-Nieto *et al.* 2013). Our results demonstrated that the entire Niulanjiang-Hengjiang watershed area and the western Wujiang and Chishuihe watershed area should be considered as a priority conservation region. Analysis of the spatial heterogeneity of the ecosystem services also explicitly provides spatial information to implement specific environmental policies in different regions (Burkhard *et al.* 2013; Klain & Chan 2012; Kroll *et al.* 2012). The Niulanjiang-Hengjiang watershed, for example, is priority afforestation area as a result of the low carbon storage value, while human activity (e.g. rapid urban expansion) in the southern Wujiang watershed area should be restricted to minimize human interference with biodiversity. Understanding tradeoffs and synergies among ecosystem services may assist managers in the formation of a more comprehensive decision-making process with management policies adjusted according to varying objectives (Bennett *et al.* 2014; Chan *et al.* 2007; Chettri *et al.* 2012; Jia *et al.* 2014; Rodríguez *et al.* 2006). Land use optimization and the market place are then vital to tradeoffs management.

Limitations and uncertainties

The InVEST model features limitations due to the simplification of ecological processes. Specifically, to reduce the number of input parameters of the model, the carbon storage module oversimplifies the carbon cycle. The module assumes linear change in carbon storage over time and unchanged carbon density corresponding to each land use type. Flux information between different carbon pools can not be obtained. Subsurface flow and surface water–ground water interactions in the water supply model are also not considered (Leh *et al.* 2013; Sharp *et al.* 2014).

Conclusions

The goal of this study was to assess and map multiple ecosystem services in the Karst mountain area of the Guizhou Provision in the southwest China area. Conclusions are as follows:

(1) Average values of water supply, sediment retention, carbon storage, habitat quality and ecosystem services bundling were 545.16 mm, 585.43 t ha^{-1}, 310.08 t ha^{-1}, 0.72 and 0.43, respectively. Obvious spatial differences in the supply of multiple ecosystem services existed. The low-level, moderate-level and high-level hotspot regions account for 24.23%, 51.09% and 24.68% of total area, respectively.

(2) Tradeoffs were exhibited between water supply and sediment retention and also between carbon storage and sediment retention while synergies were observed among other ecosystem services except for with relationships between water supply and sediment retention and between the carbon storage and sediment retention. Significant differences for the relationship among ecosystem services were observed in different watersheds.

(3) Precipitation, evaporation and root depth for each land use type were dominant factors affecting the spatial pattern of water supply, while the spatial heterogeneity of sediment retention resulted from the rainfall erosivity, topography, cover-management factor and support practice for land use types. Carbon storage was substantially influenced by the forestland proportionate area, while habitat quality was significantly influenced by habitat suitability of natural land use and the weight and effective distance for human land use. A weak negative correlation was demonstrated between the urbanization rate, GDP per person, population density and ecosystem services.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 41361091).

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(Received on 19.05.2015 and accepted after revisions, on 11.05.2016)