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Changes in ecosystem service values in karst areas of China

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ABSTRACT

Karst ecosystem services (ESs), the key components of global terrestrial ESs, play a crucial role in human welfare and livelihood. However, the spatiotemporal changes of ecosystem service values (ESVs) in the karst areas of China remain unclear. In this paper, land use/land cover (LULC) data were used to estimate the ESVs changes during 1992–2015 by the benefit transfer method, to reveal its spatial heterogeneity and to explain the sensitivity of ESVs to land use change. The results indicated that the ESVs were increased by US$ 23.42 billion at 0.10%·yr^{-1} due to the LULC changes in over 15% of the total karst areas in China, while those in the non-karst areas were reduced by US$ 32.87 billion at 0.14%·yr^{-1}. In particular, the value of the regulation services contributed 69.05% to the total ESVs in the karst area, followed by support services (18.23%), provision services (8.54%), and cultural services (4.15%). The net change of ESVs showed a spatial heterogeneity, i.e. ESVs in the Northwest and North part of southwest increased, but that in the northeast and eastern part of southwest decreased. The ESVs were more sensitive to the bidirectional land conversion than the unidirectional conversion. These results provide an important scientific basis for ecological restoration and reconstruction of karst areas.

1. Introduction

Ecosystem services (ESs) science has long been considered as important ecological issues in the 21st century (Palmer et al., 2004). The ESs in karst areas received considerable attention because they are fragile systems with low environmental capacity and weak anti-interference ability. The karst ecosystems are characterized by poor ecological stability, great fluctuation in biological composition and productivity, sensitivity to ecological disturbance, and retrogressive succession in response to human utilization (Liu et al., 2016). Therefore, to reveal the spatiotemporal dynamic characteristics of ecosystem service values (ESVs) and to quantity the correlation of ESVs changes and geographical factors in karst areas are essential for an in-depth exploration of the impact of climate change and human activities on ESVs.

The studies concerning ES function assessment was started in the second half of the 19th century. The concept of ecosystem service function was initially defined by Holder and Ehrlich (1974). In 1997, the research results of Daily and Costanza further expanded the studies in the ecology area (Daily, 1997; Costanza et al., 1997). The first estimation of global ESVs was conducted by Costanza et al. (1997), and since then, ecological economics and ESVs both became hot topics wordwide. The Millennium Ecosystem Assessment Project organized by the United Nations in 2002 once again launched in-depth researches on ES function and started to assess the historical impact and possible changes of global ES function changes on human welfare, and made corresponding policy suggestions.

In China, the ESVs studies were started in the 1980s. Zhang (1982) estimated the ESVs of forest resources in Yunnan. Since the mid-to-late 1990s, more and more Chinese scholars started to conduct ESVs studies. For example, Ouyang et al. (1999) introduced ES functions and explained their methods for ESVs evaluation. Xie et al. (2003) conducted a questionnaire survey of among more than 200 ecologists in China, and proposed equivalent factors of ESVs per unit area of ecosystem in China. Since 2000, empirical studies on the ESVs, including large-scale studies on national ES (Li and Fang, 2014; Xie et al., 2015; Xing et al., 2018)

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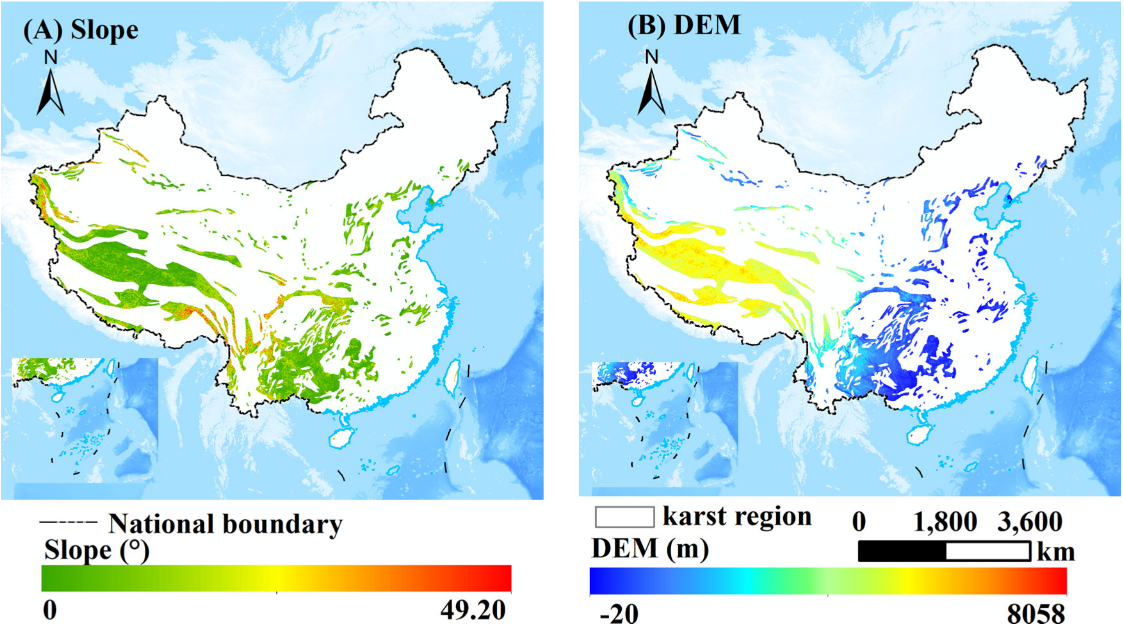

Fig. 1. Location, slope and elevation of the karst areas.

and small-scale studies on a specific ecosystem (Zhang et al., 2011; Song et al., 2015; Wang et al., 2018, 2019), have been kept increasing.

With the rapid development of remote sensing technology, remote sensing data are increasingly used in ecosystem studies (Feng et al., 2010; Cabello et al., 2012; Leh et al., 2016; Assandri et al., 2018; Jiang et al., 2018). Currently, land use/land cover (LULC) data are important parameters widely utilized in ESVs estimation and in some important parts of global climate and environmental change because they represent the direct effects of human activities on eco-environment and the cross link between human socioeconomic activities, and processes of natural and ecological changes (Lambin et al., 2001; Zhao et al., 2016). The developmental trend and dynamics of LULC can reflect the change in ESVs and the security status of ecosystems. Li et al. (2016) estimated the spatiotemporal changes in ESVs in China and found hot- and cold-spot regions of ESVs changes. They also found that the hot-spot areas are concentrated in the west area of China, whereas the cold-spot areas are mostly located in coastal areas. Xing et al. (2018) constructed a comprehensive ESVs evaluation model to reflect the characteristics of natural geography and social economy based on land use data. Jiang et al. (2018b) studied the mechanism underlying landscape structure change in cultivated land area in China based on LULC data. The impacts of LULC change to ESVs (Li et al., 2010; Costanza et al., 2014; Song and Deng, 2017; Sannigrahia et al., 2018; Gashaw et al., 2018; Arowolo et al., 2018), the response of urban land change on ESVs (Martínez et al., 2009; Yoshida et al., 2010; Mendoza-González et al., 2012), and the relationship between ESV and LULC (Carreno et al., 2012) were also been widely studied.

Previous studies focused mainly on the overall change of ESVs in a study area and seldom addressed the specific geological conditions and landform features. China is one of the countries with the largest distribution of karst landform in the world. The karst area in China accounts for ca.15% of its land area (Jiang et al., 2014). Due to specific geological background and hydrology the karst areas are usually featured by a short of surface runoff (Wu et al., 2017), thin soil layer (Ouyang et al., 2011), serious soil erosion (Zeng et al., 2017), poor fertilizer efficiency (Xiong and Chi, 2015), and prominent spatio-temporal heterogeneity of hydrothermal factors. Zhang et al. (2002) indicated that low environmental capacity, high sensitivity, poor stability, weak anti-interference ability and ecological vulnerability are the primary characteristics of karst ecosystems. In this context, a diversity of ecosystems have been developed (Liu, 2009), which may provide a variety of ESs such as water conservation, biodiversity conservation, food production, water supply and recreation for the survival, production, life, and development of humans (Luo et al., 2014; Tian et al., 2016). With rapid economy development and expansion of human population, natural resources are being used unsustainably and being depleted, resulting in karst ecosystem degradation, and human deep poverty (Wang and Cai, 2010). In addition, these excessive and irrational activities have also endangered the ecosystem structure, leading to ecosystem imbalance and loss of various ecological services (Hou et al., 2016). Studies have shown that there is a significant positive correlation between incidence of poverty and ESVs in the karst areas (Gao et al. 2016). But relatively less attention has ever been paid to the karst areas.

At present, studies regarding the ES of karst areas were mainly focused on small-scale, single-phased and single ES (e.g., Li et al., 2010; Zhang et al., 2011; Cao et al., 2015; Tian et al., 2016; Wang et al., 2019; Oliver et al., 2020). To the best our knowledge, no estimates the of ESVs in the karst areas of China so far. In addition, the sensitivity of the impact of LULC changes on ESV remains currently uncertain. For this, the purpose of the study aims to (1) determine the characteristics of LULC changes during 1992-2015, (2) assess the ESVs in the karst areas of China, (3) reveal the spatial heterogeneity of ESVs, and (4) identify the sensitivity of ESVs to LULC.

2. Materials and methods

2.1. Overview of karst regions in China

A majority of the Karst regions in China was analyzed in the present paper (Fig. 1). The area of karst region in China has approximately 3.44 $\times$ 10^6 km^2 (including exposed, buried, and covered carbonate rocks regions), accounting for 36% of the total land area of China and 15.6% of the karst area in the world (Liu et al., 2016). Exposures of outcropping carbonate rocks are mainly distributed in Hu'nan, Yunnan, Guizhou, Hubei, Guangdong, Sichuan and Guangxi provinces and Chongqing, and the total area is approximately 5.1 $\times$ 10^5 km^2, accounting for 5.8% of the total area (Jiang et al., 2014). The karst areas are located at elevations of -20 m–8,058 m, with an average elevation of 2, 887 m. The angle of slopes ranges from 0°–45°, and the study area is dominated by plains, hills and plateaus in the study area. The landform conditions are relatively complex accompanized by severe soil erosion. This area features a mountainous climate, a subtropical-plateau mountain monsoon climate, and a monsoon climate. Influenced by local landforms, precipitation varies greatly across this area, and rainfall decreases gradually from southeast to northwest. Vegetation in the study area is dominated by subtropical and tropical evergreen broadleaved forests. The zonal soil is mainly red soil and yellow soil, and the non-zone soil is dominated by lime soil.

2.2. Data sources

Data used in the study include administrative boundary data, topographic data, digital elevation model (DEM) data, socioeconomic statistics, and LULC data. The administrative boundary and topographic data were obtained from the Resource and Environment Science Data Center of the Chinese Academy of Sciences. The socioeconomic data were derived from the China Statistical Yearbook 2011 and the China Socioeconomic Statistical Yearbook. The LULC data sets from 1992 to 2015 were provided by the European Space Agency (ESA) and were reconstructed into a complete surface data set covering all land and oceans at a 300 m resolution by integrating several existing data sets. The data set has been widely used in global ESVs research, and its accuracy and applicability were also confirmed (Sannigrahia et al., 2018).

2.3. Calculation of the ESV

The method for ESV evaluation developed by Costanza et al. (1997), Xie et al. (2015), De Groot et al. (2012), Li et al. (2016), and Sannigrahia et al. (2018) was used in the study. The ESV coefficient for each element area of different ecosystem types was calculated in accordance with the respective circumstances,and the ESVs estimation coefficient per hectare of LULC was used (Table1). The ESV coefficients for urban land of Costanza et al. (2014) were adopted (Table1). In the karst areas, the ESVs of per unit area were calculated using the equivalent ESVs coefficient developed by Xie et al. (2015) as modified from Costanza et al (Costanza et al., 2014) to explain the environmental and social circumstances (Table 2). Therefore, the ESVs per unit area were decided for each LULC type. The ESVs of each LULC type and their service function as well as the total ESVs were calculated using the following formulas.

$$ESV_k = \sum_k A_k \times VC_k \tag{1}$$

$$ESV_f = \sum_f A_K \times VC_{kf} \tag{2}$$

$$ESV = \sum_k \sum_f A_k \times VC_{kf} \tag{3}$$

where ESV$_k$, ESV$_f$, and ESV represent the ESVs of LULC types ‘k’ (e.g., woodlands, grasslands and wetlands, etc.), the ESVs functions ‘f’ (e.g., regulation, supply, support and cultural services function), and the total ESVs, respectively; A$_k$ is the LULC type ‘k’; VC$_k$ is the value coefficient (billion US\$ ha^{-1} yr^{-1}) for LULC type ‘k’; and VC$_{kf}$ is the value coefficient (billion US\$ ha^{-1} yr^{-1}) for LULC type ‘k’ with ES function type ‘f’.

2.4. Coefficient of cross-sensitivity

Liu et al. (2018) developed the coefficient of cross-sensitivity (CCS) method to reveal the response mechanism of LULC change to ESVs. The formula is presented as follows.

$$CCS\,(j)_{kl} = \left| \frac{ESV_{(j-1,j)}}{\Delta CCL_{(k,I)}} \right| = \left| \frac{\frac{(ES_j - ES_{j-1})}{ES_{j-1}}}{\frac{(IR_{(k,I)} - TR_{(k,I)})}{\frac{(A_k + A_I)}{2}}} \right| \tag{4}$$

In this expression, J-1 means the base year of research, and CCS$_{(j)kl}$ represents the CCS of mutual conversion between ‘K’ and ‘I’ land use types in year ‘J’. ΔES$_{(J\text{-}1,J)}$ is the rate of change in ESVs from year ‘J-1’ to ‘J’. ΔCCL$_{(K,I)}$ is the net transformation rate between land use type ‘K’ and ‘I’. TR$_{(K,I)}$ means area change between land use type ‘I’ to ‘K’, and IR$_{(K,\ I)}$ means area change between land use type ‘K’ to’ I’. A$_k$ is the base area of land use type ‘K’, and A$_I$ is the base area of LULC category ‘I’. CCS$_{(j)kl}$ > 0 means that ESVs may change in the same direction to the net transformation of LULC. CCS$_{(j)kl}$ < 0 indicates that ESVs may change in a reverse direction to the net transformation of LULC. High absolute value of CCS$_{(j)kl}$ means high sensitivity of ESVs to the net conversion between the two LULC types, and vice versa.

3. Results

3.1. Variation of LULC during 1992–2015

3.1.1. Spatial distribution characteristics of LULC

In 1992, the woodland and grassland in the karst areas of China accounted for 59% of the total area, and the area of dry lands and bare lands accounted for 21.44% and 11.63%, respectively. The water bodies, shrub lands, and sparse woodlands accounted for 2.99% of the total area; the glacier snow cover accounted for 1.74%, and urban land accounted for 0.16%. The total area of woodland and grassland was increased by 1.09% higher in 2015 than in 1992. In particular, the area of grassland was increased by 1.07%, while that of woodland increased

Table 1

The equivalent coefficient per unit area of ES.

Sources: modified from Xie et al. (2015) and Costanza et al. (2014).

Type	Sub-Type	Dry land	Paddy field	Woodland	Shrub land	Grassland	Sparse woodland	Wetland	Bare land	Water bodies	Glacier snow	Urban land	Total
Provision	FP	0.85	1.36	0.27	0.19	0.16	0.38	0.51	0.01	0.80	0.00	0.00	4.53
	RM	0.40	0.09	0.63	0.43	0.24	0.56	0.50	0.03	0.23	0.00	0.00	3.11
	WS	0.02	−2.63	0.33	0.22	0.13	0.31	2.59	0.02	8.29	2.16	0.00	11.44
Regulate	GR	0.67	1.11	2.07	1.41	0.83	1.97	1.90	0.11	0.77	0.18	0.00	11.02
	CR	0.36	0.57	6.20	4.23	2.18	5.21	3.60	0.10	2.29	0.54	4.89	30.17
	PE	0.10	0.17	1.36	1.28	0.72	1.72	3.60	0.31	5.55	0.16	0.00	14.97
	WR	0.27	2.72	3.66	3.35	1.60	3.82	24.23	0.21	102.24	7.13	0.00	149.22
Support	SFR	1.03	0.01	1.84	1.72	1.01	2.40	2.31	0.13	0.93	0.00	0.09	11.47
	MNC	0.12	0.19	0.20	0.13	0.08	0.18	0.18	0.01	0.07	0.00	0.00	1.16
	BD	0.13	0.21	1.74	1.57	0.92	2.18	7.87	0.12	2.55	0.01	0.00	17.30
Culture	RCT	0.06	0.09	0.76	0.69	0.41	0.96	4.73	0.05	1.89	0.09	31.07	40.80
Total		4.01	3.89	19.07	15.22	8.25	19.69	52.02	1.10	125.61	10.27	36.05	

Abbreviations: FP: food production; WS: water supply; RM: raw material production; CR: climate regulation; GR: gas regulation; PE: purification of the environment; SFR: soil formation and retention; WR: water regulation; BD: biodiversity; MNC: maintenance of nutrient circulation; RCT: recreation, culture, tourism.

Table 2
The equivalent ESV (US\$ ha yr^{-1}) per unit of area (ha) for eleven LULC categories.

Type	Sub-Type	Dry land	Paddy field	Woodland	Shrub land	Grassland	Sparse woodland	Wetland	Bare land	Waterbodies	Glacier snow	Urban land	Total
Provision	FP	71.47	114.35	22.98	15.98	13.45	31.95	42.88	0.84	67.27	0.00	0.00	381.18
	RM	33.63	7.57	52.97	36.16	19.76	47.09	42.04	2.52	19.34	0.00	0.00	261.08
	WS	1.68	−221.14	27.47	18.50	10.93	26.07	217.78	1.68	697.06	181.62	0.00	961.64
Regulate	GR	56.34	93.33	174.33	118.56	69.37	165.65	159.76	9.25	64.74	15.14	0.00	926.47
	CR	30.27	47.93	521.32	355.68	183.30	438.08	302.70	8.41	192.55	45.41	411.17	2536.82
	PE	8.41	14.29	114.63	107.63	60.54	144.62	302.70	26.07	466.67	13.45	0.00	1259.02
	WR	22.70	228.71	307.47	281.68	134.11	321.20	2037.36	17.66	8596.76	599.52	0.00	12547.17
Support	SFR	86.61	0.84	154.71	144.62	84.50	201.80	194.23	10.93	78.20	0.00	7.57	964.02
	MNC	10.09	15.98	17.10	10.93	6.73	15.14	15.14	0.84	5.89	0.00	0.00	97.82
	BD	10.93	17.66	146.31	132.01	76.94	183.30	661.74	10.09	214.41	0.84	0.00	1454.24
Culture	RCT	5.05	7.57	64.18	58.02	34.05	80.72	397.72	4.20	158.92	7.57	2612.49	3430.49
Total		337.18	327.09	1603.48	1279.76	693.69	1655.62	4374.06	92.49	10561.8	863.54	3031.23	24819.95

Abbreviations: FP: food production; WS: water supply; RM: raw material production; CR: climate regulation; GR: gas regulation; PE: purification of the environment; SFR: soil formation and retention; WR: water regulation; BD: biodiversity; MNC: maintenance of nutrient circulation; RCT: recreation, culture, tourism.

by 0.02%. Although the area of most land use types increased during the study period, that of shrub lands and bare lands decreased by 0.36% and 0.25%, respectively. From 1992 to 2015, the LULC in more than 15% of the karst areas changed. In particular, the areas of the urban lands, woodlands, grasslands, sparse woodlands and water bodies increased, while those of wetlands, shrub lands and bare lands decreased. In contrast, the area of the glacier snow cover remained unchanged.

The LULC showed a significant spatial heterogeneity. In particular, woodlands and grasslands were widely distributed throughout the entire area, whereas other LULC categories were sparsely distributed (Fig. 2). Over 76% of the woodlands, dry lands, and paddy lands were distributed in the ecological areas of southwestern China, i.e., Guizhou, Yunnan, Chongqing, and Sichuan. Over 75% of the grasslands were concentrated in Tibet and Xinjiang. Over 85% of the glacier snow land was concentrated in Xinjiang, and other land use types were scattered sparsely throughout the karst areas.

To further reveal the spatial heterogeneity of the different LULC types, we analyzed their spatial distribution patterns in the karst areas according to slopes and elevation gradients (Fig. 3). Based on the National Land Plan of China, the slopes are divided into six grades (Fig. 3A). The elevation in a given region is obtained at a 100 m scale (Fig. 3B). As the slope increases, dry lands, paddy fields, and water bodies decrease, suggesting a negative correlation between land types and slope, especially in the areas between 0°-2°. In contrast, woodlands and glacier snow cover increase as the slope increases, suggesting a positive correlation. Grasslands are mainly distributed in the ecological regions with slopes of 5°–8° and 8°–15°. In contrast, other land use types are distributed sporadically in areas with various slopes. Regarding elevation, dry lands and woodlands gradually decrease as the altitude increases. The dry lands are concentrated in areas below 3,300 m, and woodlands are concentrated below 4,600 m. Grasslands are mainly distributed between 2,000 and 6,100 m above sea level. Glacial snow cover is concentrated at elevations between 5,800 and 8,100 m, but gradually decreases above 7,200 m. Paddy fields are concentrated at elevations between 100 and 400 m and gradually decrease with increasing elevation. Urban lands are centered below 2,300 m elevation. Bare lands are concentrated between 3,100 and 7,100 m. However, the water bodies are distributed between 100 m and 400 m and between 4,300 m and 5,100 m elevation. In summary, different LULC types had vertical spatial distribution patterns.

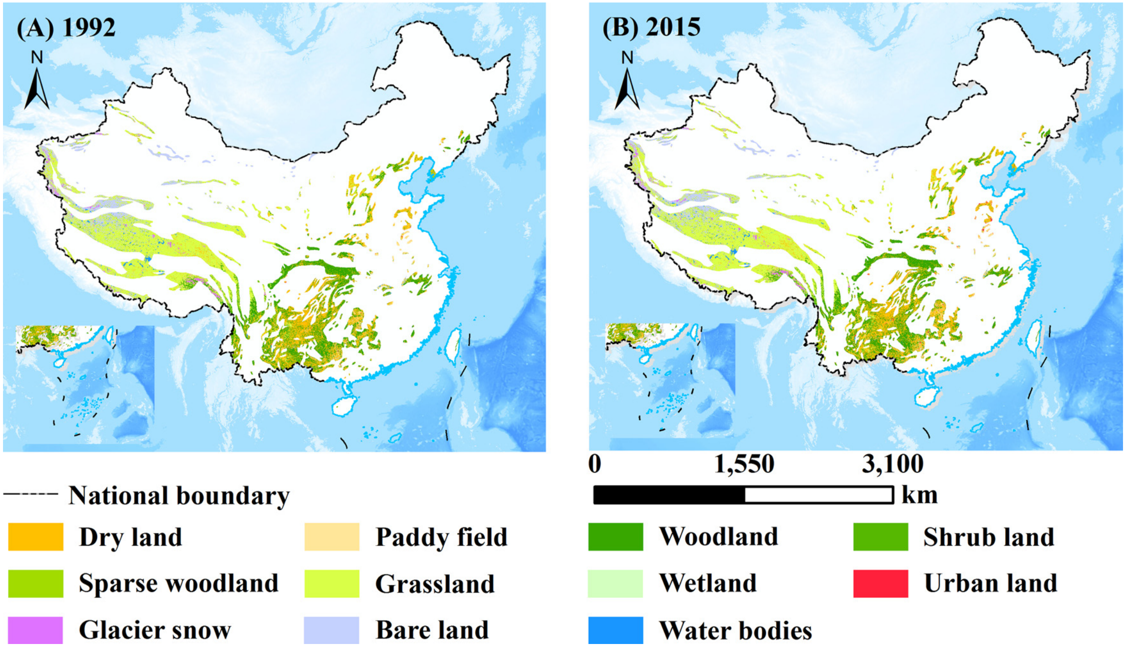

Fig. 2. Changes in the spatial distribution pattern of LULC from 1992 to 2015.

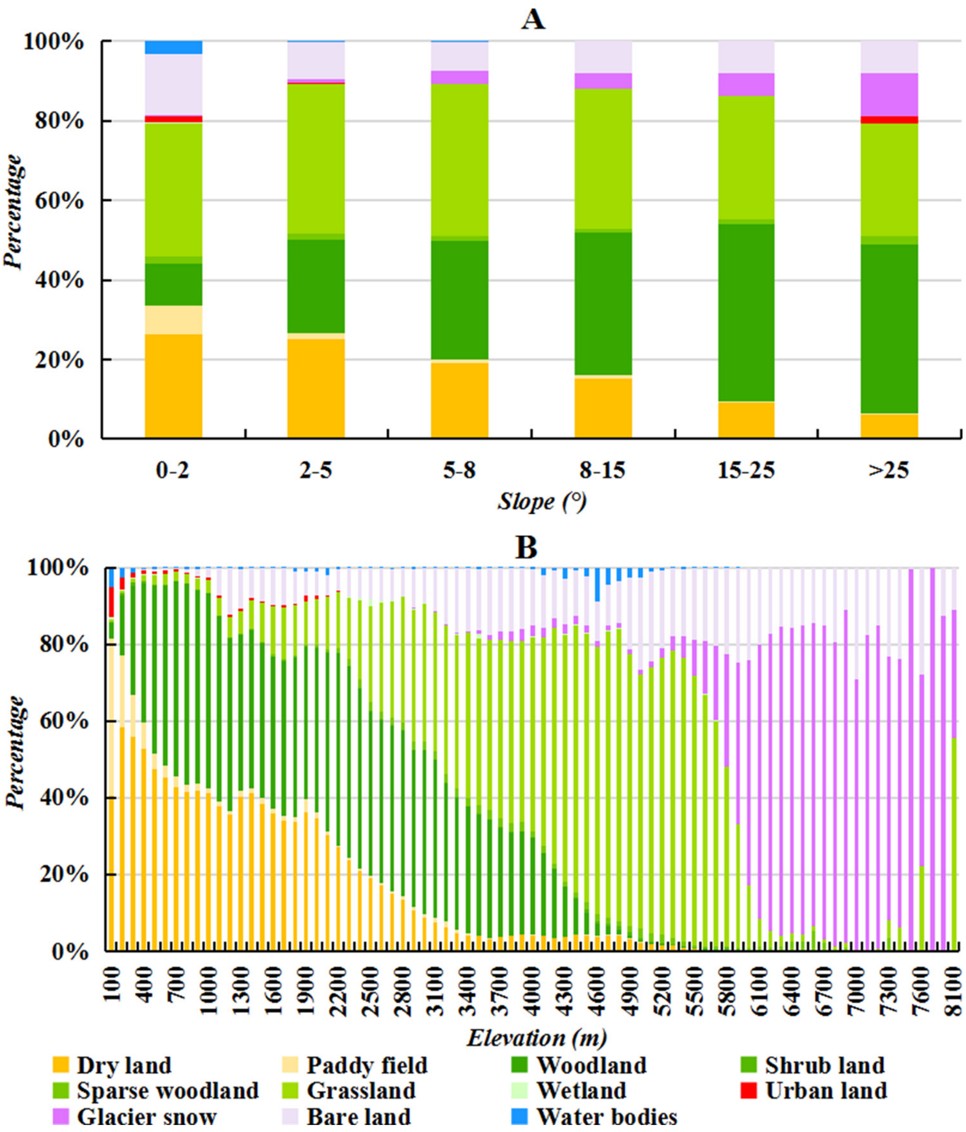

Fig. 3. Spatial heterogeneity of LULC change in the karst areas of China.

3.1.2. Temporal variation in LULC during 1992–2015

As shown in Fig. 4 and Table 3, land use transfer differed significantly over time. From 1992 to 2015, the area of glacier snow cover remained almost unchanged. The area of shrub lands and bare lands decreased, at rates of −0.33% to −0.48% and 0.12% to −0.14%, respectively. This was mainly caused by the conversion of shrub lands into woodlands and dry lands and the conversion of bare lands into grasslands. The areas of sparse woodlands and urban lands increased at

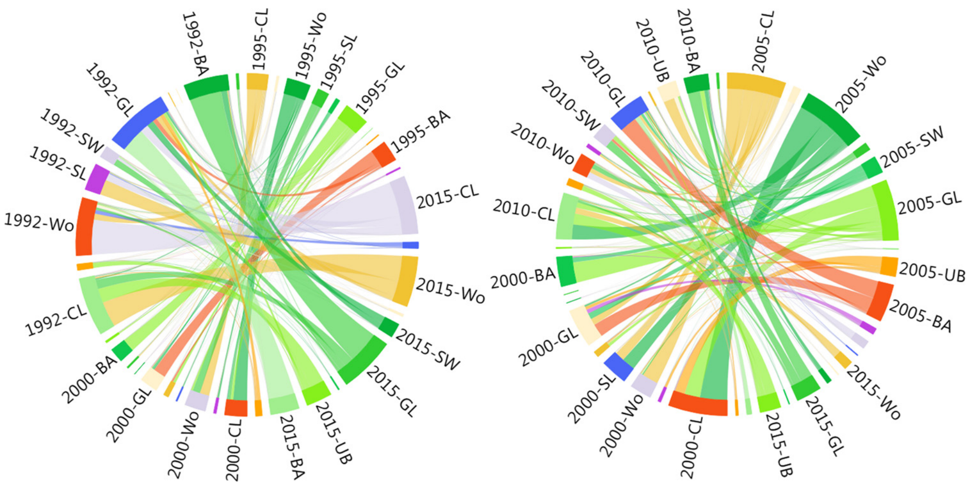

Fig. 4. Transformation of LULC from (a) 1992–1995, 1995–2000 and 1992–2015, with (b) 2000–2005, 2005–2010 and 2010–2015 in karst areas in China. DL: dry land; PF: paddy field; Wo: woodland, SL: shrub land, GL: grassland, SW: sparse woodland, WL: wetland, UB: urban land, WB: water bodies, BL: bare land, GS: glacier snow.

Table 3
LULC change rate in Karst areas of China in different periods (unit: %).

Land use type	1992–1995	1995–2000	2000–2005	2005–2010	2010–2015
Dry land	0.08	0.14	−0.13	0.02	−0.08
Paddy field	0.18	0.24	0.02	−0.16	−0.22
Woodland	−0.08	0.01	0.14	−0.05	0.01
Shrub land	−0.33	−4.26	−5.72	−1.54	−0.48
Grassland	0.18	0.52	0.86	0.10	−0.76
Sparse woodland	−0.06	−0.05	0.02	0.03	0.06
Wetland	0.02	0.23	0.44	0.80	0.31
Water bodies	1.68	2.94	12.11	7.81	5.58
Glacier Snow	0.00	0.00	0.00	0.00	0.00
Bare land	0.12	−0.04	−0.17	−0.20	−0.14
Urban and	0.01	0.32	0.50	0.12	0.21

rates of −0.06% to 0.06% and 0.01% to 0.21%, respectively. A main reason for this changes was the conversion of grasslands and bare land into sparse woodlands, and the conversion of dry lands into urban lands due to expanding urbanization. The change rate of dry lands and paddy fields was increased from 0.08% (0.18%) to 0.14% (0.24%) before 2000, and it fluctuated after that. The paddy fields were converted into water bodies, and the dry lands were converted into woodlands, shrub lands, grasslands and urban lands, which were mainly driven by the conversion of farmland into forest land/grass land projects and expanding urbanization. The change rate of grassland was increased from 0.18% to 0.86% before 2005 but it increased significantly during 2000-2005. This was mainly driven by the project of returning farmlands to grasslands. However, the area of grasslands began to decrease after 2005 due mainly to urban expansion. The area of water bodies and wetlands increased before 2005 but began to decrease after that. The water bodies were converted into wetlands and bare lands due mainly to the decline of lake and river water levels (Li et al., 2019). There was conversion between wetlands and water bodies, and of which the conversion of water bodies into wetlands is more than that of wetlands into water bodies. This leads to an increase of water bodies and a decrease of wetlands. The area of dry lands, woodlands, grasslands, sparse woodlands, urban lands and water bodies increased significantly, and of which the most increase was attributed to that of urban lands and water bodies. The area of shrub lands and bare lands decreased significantly, and the most reduction was attributed to bare lands. The area of glaciers snow cover remained almost unchanged. In addition, the conversion of land use type was a bidirectional phenomenon instead of a unidirectional one.

3.2. *Dynamics of ESVs during 1992-2015*

3.2.1. *Temporal variation of ESVs*

From 1992 to 2015, the ESV decreased initially and then increased. In particular, it decreased during 1992-2000 and increased during 2000-2015. In karst areas, the ESVs was US$ 1330.86 billion, with woodland contributing 50.72%, followed by grasslands (22.05%) and dry lands (10.29%) in 1992. However, the ESVs amounted to US$ 1354.28 billion, with woodlands contributing the greatest portion (US$ 678.19 billion, 50.08%) in 2015. The contribution of grasslands to the total ESVs was US$ 293.56 billion, ca. 21.68%, followed by dry lands, paddy fields, shrub lands, sparse woodlands, wetlands, bare lands, and glacier snow cover. Among all of these types of ESs, the ESVs of dry lands and paddy fields increased initially and then decreased. However, the ESVs of woodlands, wetlands, bare lands, and glacier snow cover decreased. In contrast, the ESVs of grasslands, urban lands, and water bodies increased.

From 1992 to 1995, the ESVs of the karst areas decreased by US$ 1.15 billion, an annual reduction 0.03%. In terms of LULC types, the greatest decrease was in the ESVs of woodlands (decreasing by US$ 1.76billion), followed by shrub lands, grasslands, and wetlands, which were the main factors in the decrease in the ESVs. In contrast, the ESVs of urban lands, dry lands, and paddy fields increased. The ESVs of urban lands significantly increased, ca. US$ 0.78 billion. During the same period, the ESVs were increased by US$ 1.00 billion at an annual rate of 0.02%. In comparison, the increase rate in 1995-2000 was 0.02% yr^{-1} and that in 1992–1995 was 0.03% yr^{-1}. From 2000 to 2005, the ESVs were increased by US$ 10.18 billion, indicating an annual increase of 0.15%. The ESVs also increased in 1995–2000, but this rate of increase was 0.02% yr^{-1}, much less than the 0.15% yr^{-1} in 2000–2005. During this period, the ESVs of the urban lands and water bodies were increased significantly by US$ 7.00 billion and US$ 2.20 billion, respectively. From 2005 to 2010, the ESVs continued to increase, with a total increase of US$ 7.26 billion. The ESVs were US$ 1330.86 billion in 1992, and they were increased to US$ 1354.28 billion in 2015, indicating an annual increase rate of US$ 0.10 billion (Fig. 5). From 1992 to 2015, the greatest increases in ESVs occurred in urban lands and water bodies, increasing by US$ 23.77 billion and US$ 5.10 billion, respectively, followed by dry lands, woodlands, sparse woodlands, and grasslands, indicating that the increase in the ESVs of the karst areas was driven by returning farmland to forest/grassland projects and urbanization.

3.2.2. *Spatial distribution dynamics of ESVs in the karst areas*

The results indicated that the changes of ESVs in the kart areas are region specific (Fig. 6). As shown in Fig. 6A, the low ESVs (US$ 8.92–17.91 billion) in 1992 were mainly distributed in the eastern and southwestern parts of the karst areas, such as southern part of Jiangsu, eastern part of Henan, northern part of Anhui, eastern part of Hunan, and southeastern part of Guangxi. In addition, the high ESVs (US$ 137.05–678.19 billion) were mainly distributed in the southwest China (e.g., Sichuan, Guangxi, Guizhou, Chongqing). In 2015, the ESVs varied considerably compared with that in the previous period. The ESVs in most regions, including regions in the north and southwest parts of the karst areas (e.g., Xinjiang, northwestern of Tibet, Inner Mongolia, southeastern of Guangxi, and northeastern of Hunan) (Fig. 6B), were significantly reduced, suggesting intense anthropogenic activities in these regions.

During 1995-2000 and 2000-2005, the area with net ESVs loss was greater than the area with net gain, whereas in the other periods, the area with net ESVs loss was less than the area with net gain (Fig. 7). As shown in Fig. 8, the ESVs in the karst areas of China were region specific, and these regions were unevenly distributed. The central karst ecological region was distributed sporadically, and the areas with ESVs losses were concentrated in the northern and southwestern of the karst areas (e.g., Liaoning, Hunan, Guangdong, northeastern Guangxi, and the southern part of Guizhou). In conclusion, the areas with increased ESVs were concentrated in the southwestern and western karst areas, and this distribution is attributed to implementation of various ecological projects, such as the Grain for Green Program (GFGP) and recovery planning and ecological engineering in 2000 (Jia et al., 2014; Zhao et al., 2017; Zhang et al., 2018).

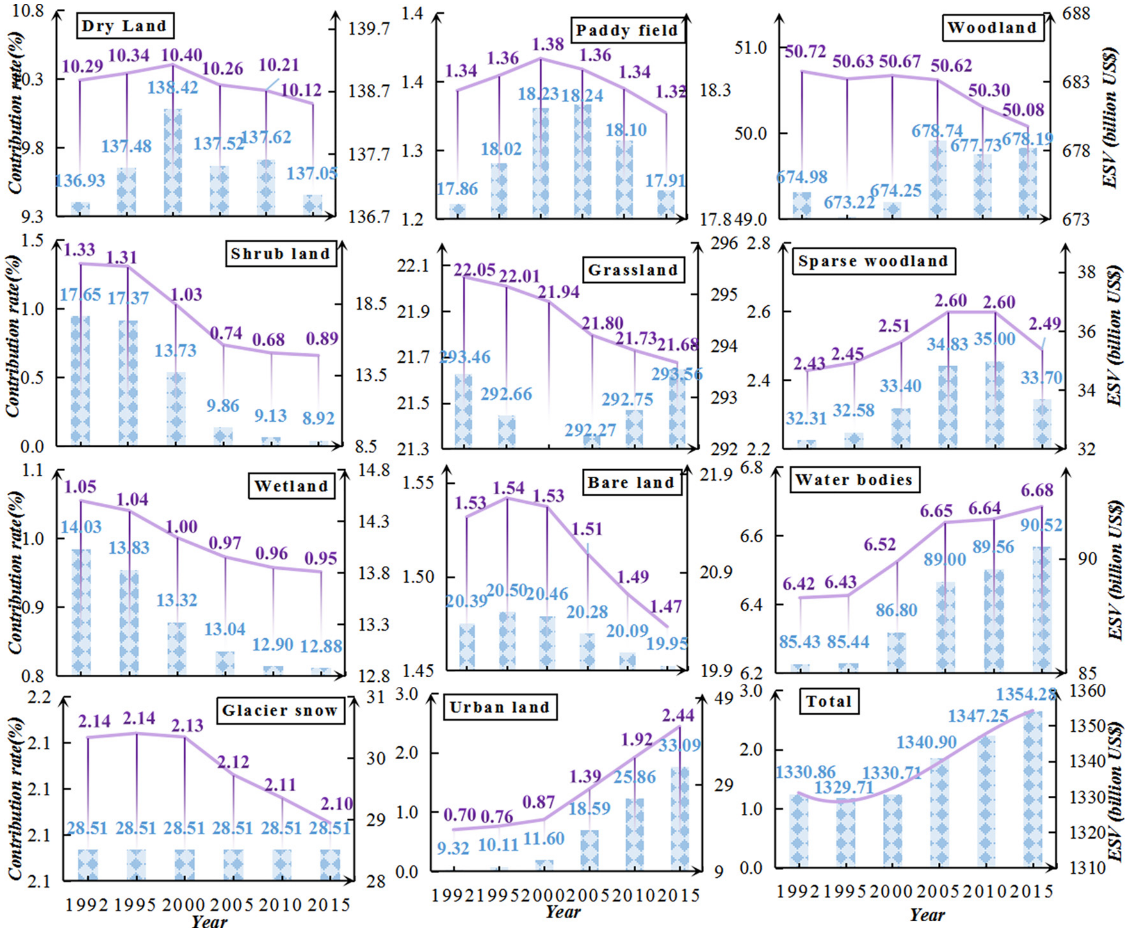

Fig. 5. The ESVs of different ecological regions for six reference years with percentages (%) (The horizontal axis represents the year, the vertical axis represent the value; the columns represent the ESVs, the dashed line represents the ESVs percentage of different LULC (%)).

3.3. Value changes of ecosystem service function

The value of ES function differed significantly. The contribution of the regulation services to the ESVs was relatively large (approximately 69%), and hydrological regulation and climate regulation services contributed the greatest proportions, ca. 44% and 32%, respectively. The contributions of the support services, cultural and entertainment services, and the provision services were 18.2%, 4% and 8.5%, respectively. From 1992 to 1995, the ESVs of the regulation services in the karst areas were decreased more rapidly than those of other ESs, with a decrease rate of 0.04% and a total reduction of US$ 1.37 billion. Although most of the values of ES functions decreased, those of culture

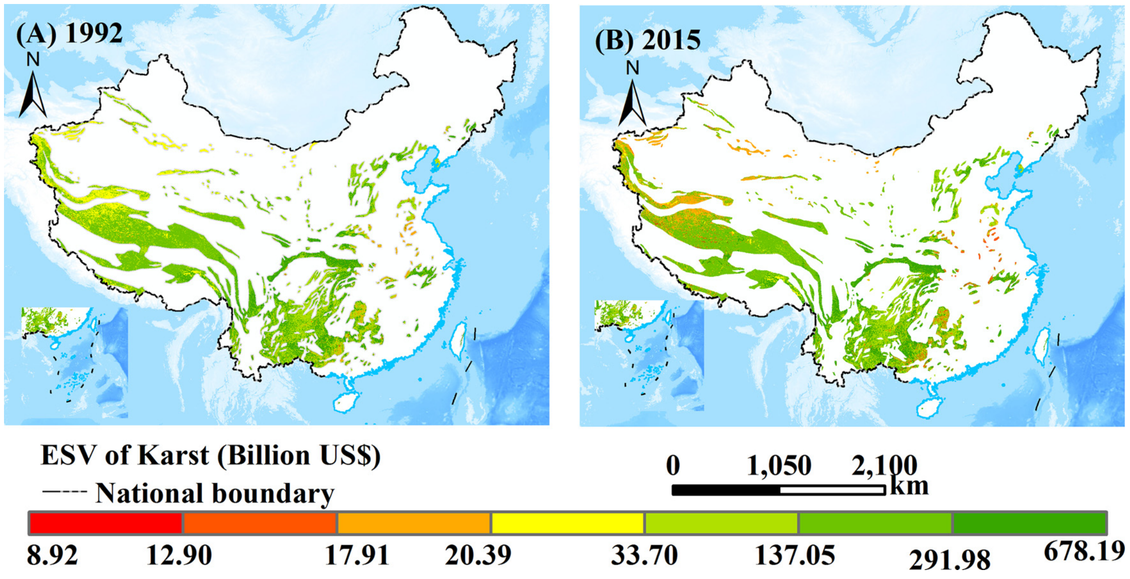

Fig. 6. The spatial distribution pattern of ESVs in Karst areas of China.

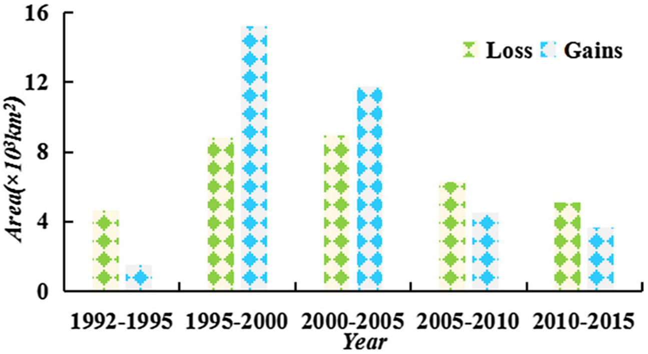

Fig. 7. Area change in ESVs during the study period (1992–2015).

services were increased slightly by US$ 0.63 billion, suggesting an increase rate of 0.35%. From 1995 to 2000, the ESVs of all of the service functions increased, and the regulation services contributed the most part, which was increased by US$ 2.51 billion, indicating an increase rate of 0.08%, followed by the cultural entertainment services, which was increased by 1.29 billion, suggesting a increase rate of 0.43%. Therefore, the ESVs of the cultural entertainment services increased more than those of the regulation services. From 2000 to 2005, the pattern of changes in ESVs was consistent with that in the previous period, but the rate of increase in the values of different ES functions in this period was higher than that in the previous period. From 2005 to 2010, the pattern of changes in the ESVs was consistent with that in the previous two periods, but the rate of changes in the ESVs of the regulation services, supply service, and support service decreased. In contrast, the values of the support services decreased during 2010-2015 compared to the previous periods, whereas those of other service functions increased. In summary, during the research period, the values of different ES increased after 1995. In particular, the value of cultural entertainment services increased faster than that of any other services, which was increased to US$ 20.70 billion at a rate of 1.45%, followed by regulation services (US$ 13.55 billion), supply services (US$ 0.19 billion), and provision services (US$ 0.87 billion) (Table 4).

3.4. Sensitivity of ESVs to LULC changes

Combining the data on LULC and ESVs changes in the karst areas of China, we estimated the CCS of land uset ype transformations of five time periods (1992–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2015) using equation 8 (Fig. 9). The CCS of ESVs of different LULC types fluctuates over time. Among them, the CCS fluctuated greatly during 1995–2000 and 2010–2015, and the conversion of other land types into water bodies was the most significant. The CCS of the rest of the period fluctuated slightly, especially during 2000-2005.

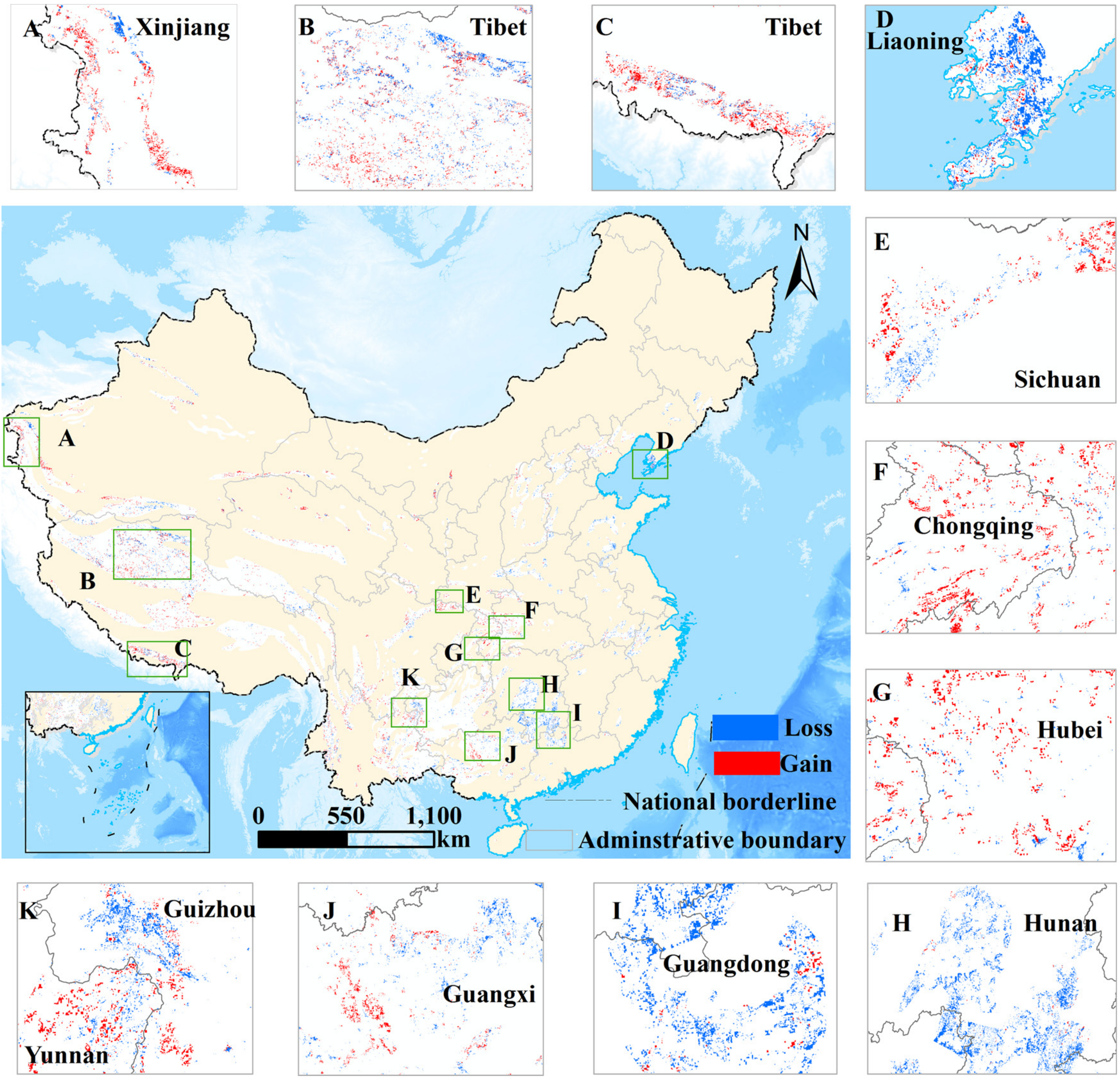

Fig. 8. Spatial distribution and partial enlargement of ESVs in karst areas of China during 1992–2015.

Table 4
Changes in different ecosystem service function values during the study period.

Type	Sub-Type	ESV(Billion US$)						ΔEV (Billion US$)						Change ratio(%·yr^{-1})					
		1992	1995	2000	2005	2010	2015	1992-1995	1995-2000	2000-2005	2005-2010	2010-2015	1992-2015	1992-1995	1995-2000	2000-2005	2005-2010	2010-2015	1992-2015
Provision	FP	53.43	53.56	53.82	53.73	53.70	53.52	0.13	0.26	−0.10	−0.03	−0.18	0.09	0.08	0.1	−0.04	−0.01	−0.07	0.01
	RM	46.97	46.93	46.95	46.96	46.92	46.85	−0.04	0.02	0.01	−0.04	−0.07	−0.12	−0.03	0.01	0	−0.02	−0.03	−0.01
	WS	28.76	28.61	28.69	29.16	29.36	29.67	−0.15	0.08	0.46	0.20	0.31	0.90	−0.17	0.06	0.32	0.14	0.21	0.13
Regulating	GR	139.97	129.11	139.74	139.93	139.76	139.59	−0.18	−0.05	0.19	−0.17	−0.17	−0.38	−0.04	−0.01	0.03	−0.02	−0.03	−0.01
	CR	334.52	333.73	333.26	335.10	335.65	336.51	−0.79	−0.05	1.84	0.54	0.86	1.99	−0.08	−0.03	0.11	0.03	0.05	0.02
	PE	98.80	98.74	98.83	99.13	99.16	99.23	−0.06	0.01	0.33	0.03	0.07	0.43	−0.02	0.01	0.07	0.01	0.01	0.02
	WR	457.42	457.08	460.06	465.79	466.87	468.92	−0.34	0.3	5.73	1.08	2.05	11.50	−0.02	0.13	0.25	0.05	0.09	0.1
Supporting	SFR	143.90	143.92	144.01	143.96	144.02	143.91	0.02	0.09	−0.05	1.50	−0.11	0.01	0.01	0.01	−0.01	0.01	−0.02	0
	MNC	15.87	15.86	15.87	15.88	15.86	15.83	−0.01	−0.01	0.26	0.07	−0.03	0.22	−0.02	0.01	0.01	−0.02	−0.04	−0.01
	BD	111.47	111.36	111.31	111.57	111.64	111.68	−0.11	−0.05	0.22	0.12	0.04	0.22	−0.03	−0.01	0.05	0.01	0.01	0.01
Culture	RCT	59.32	59.95	61.24	67.43	73.75	80.02	0.63	1.29	6.19	6.32	6.28	20.70	0.35	0.43	2.02	1.87	1.7	1.45

Abbreviations: FP: food production; WS: water supply; RM: raw material production; CR: climate regulation; GR: gas regulation; PE: purification of the environment; SFR: soil formation and retention; WR: water regulation; BD: biodiversity; MNC: maintaining nutrient circulation; RCT: recreation, culture, tourism.

During 1995-2000, the CCS of dry land conversion into water bodies and wetlands was over 0.03. The conversion of dry lands into bare lands and paddy fields into woodlands were both above 0.01. During 2010-2015, the CCS of woodlands conversion into water bodies was 0.068. The CCS of dry lands converted into water bodies, and the paddy fields conversion into wetlands and water bodies range from 0.01-0.02. The CCS between the other LULC types were low. In summary, the CCS of the ESVs associated with land use conversion is mainly affected by the conversion from woodlands, dry lands and paddy fields to water bodies. In addition, the unidirectional and bidirectional modes of land use transfer between LULC types were both observed (Fig. 4). Results of the study are similar to Wang et al. (2018). In summary, the ESVs are more sensitive to the bidirectional transformation between LULC types (Fig. 9).

4. Discussion

4.1. Differences in ESVs between karst and non-karst regions

A rose diagram of the net changes in the ESVs of different ecosystems during 1992-2015 is presented in Fig. 10. As shown in Fig. 10, the ESVs of China were decreased by US$ 9.50 billion (net loss), indicating a change rate of 0.02% during 1992–2015 due to the loss of shrub lands (US$ 170.0 billion, at an annual change rate of 1.59%), followed by grassland (US$ 93.10 billion), and wetlands (US$ 66.5 billion). In contrast, the ESVs of the urban lands in low-value ecosystem were increased significantly by US$ 375.8 billion (net gain) at an increase rate of 5.34% yr^{-1} (Fig. 10A). Li et al. (2016) showed that the ESVs of China were decreased by US$ 50.75 billion (converted according to the US$ values in 2009) during 1990–2010, representing a significant annual loss rate of US$ 2.54 billion. Song and Deng (2017) used three unit values to calculate the ESVs of China, and the results showed that the ESVs decreased during 1988-2008, and the net changes in the ESVs were approximately US$ 1.56 billion, US$ 1.01 billion, and US$ 1.22 billion, respectively, suggesting a significant difference among different unit values. However, the ESVs of the karst areas of China increased during the study period. The ESVs were increased to US$ 23.42 billion at an annual rate of 0.1% (Fig. 10B). This result was consistent with those of Zhang et al. (2011), and this change was was mainly due to a series of ecological restoration projects adopted in the karst areas since 2000. Research has shown that the implementation of rocky desertification control and the GFGP in the karst areas have improved the vegetation coverage (Yang et al., 2019; Chen et al., 2019a; Tong et al., 2018), soil organic matter and biological characteristics (Bai et al., 2013), carbon sink capacity (Tong et al., 2018; Jiang et al., 2018) and reduced soil erosion (Zeng et al., 2017). These are caused probably by the significant changes in ES functions, such as carbon sequestration, soil and water conservation, nutrient accumulation, biodiversity conservation, and landscape recreation, which have eventually led to significant increases of ESVs in the karst areas (Gao et al., 2014). The results showed that ecological engineering projects, such as returning farmland to forestlands and grasslands, integrated forestation management in river basins, and orchard construction, are successful, and the quality of the ecological environment and ecosystem has been improved (Liao et al., 2018). The sharp lands increased woodland areas are consistent with the results of the ecological engineering projects (Vina et al., 2016), although some of the grasslands were converted to woodlands (Wang et al., 2018; Zhang et al., 2018). In contrast, the ESVs in the non-karst areas decreased during 1992–2015 at a net loss of US$ 32.87 billion and a loss rate of 0.17% yrˆ$^{-1}$ (Fig. 10C), due to deforestation in this region and rapid population growth, that leads to an increased demand for cultivated land. Thus, the increase rate in ESVs in the non-karst region was less than the loss rate in the karst region, which in turn leads to an overall loss of ESVs in China with a net loss of US$ 9.50 billion.

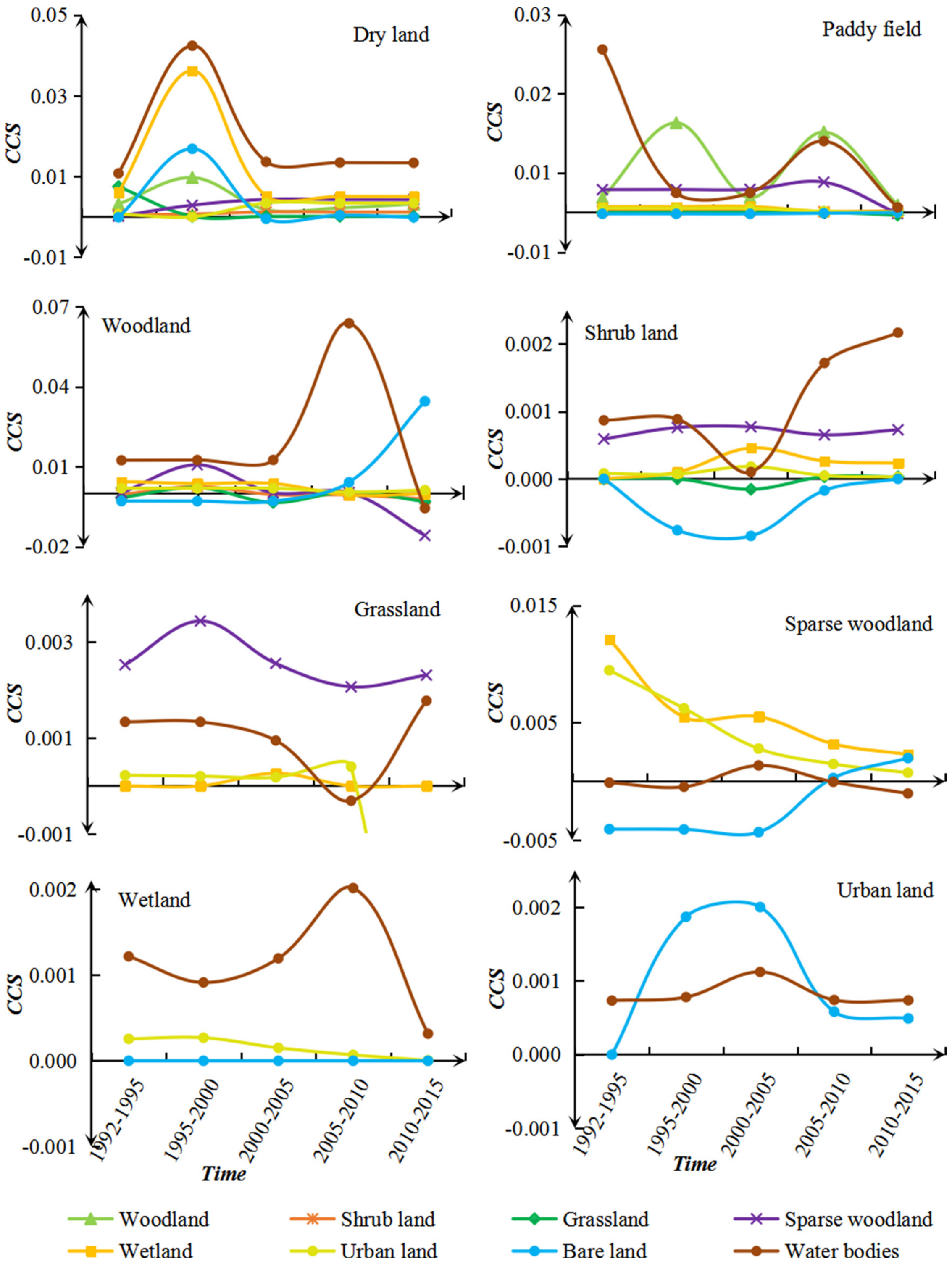

Fig. 9. The coefficient of cross-sensitivity (CCS) response matrix of the ESVs associated with land use/land cover transition in the karst areas. DL: dry land; PF: paddy field; Wo: woodland, SL: shrub land, GL: grassland, SW: sparse woodland, WL: wetland, UB: urban land, WB: water bodies, BL: bare land, GS: glacier snow.

4.2. Comparison of ESVs changes in different studies

To further explain the reliability of the results, we compared our results with those of other study areas in China (Table 5). In the study, the ESVs coefficients of the karst ESs were determined according to Costanza et al. (2014) and Xie et al. (2015), and the economic values of different ES functions were also obtained. However, our calculation probably has some limitations. Due to the difficulty of obtaining data in the karst areas, we could not develop new indicators for ES functions. In fact, the ESVs coefficient of the same ES was different among different regions. The ESVs coefficients of Costanza et al. (2014) and Xie et al. (2015) have been widely used to calculate ESVs at the regional, county, provincial, national and global levels and have been proven powerful and reliable. For example, Li et al. (2018) estimated the ESVs of Chengdu from 2000 to 2015; Song and Deng (2017) estimated the ESVs in China from 1988 to 2008; Kubiszewski et al. (2017) predicted the

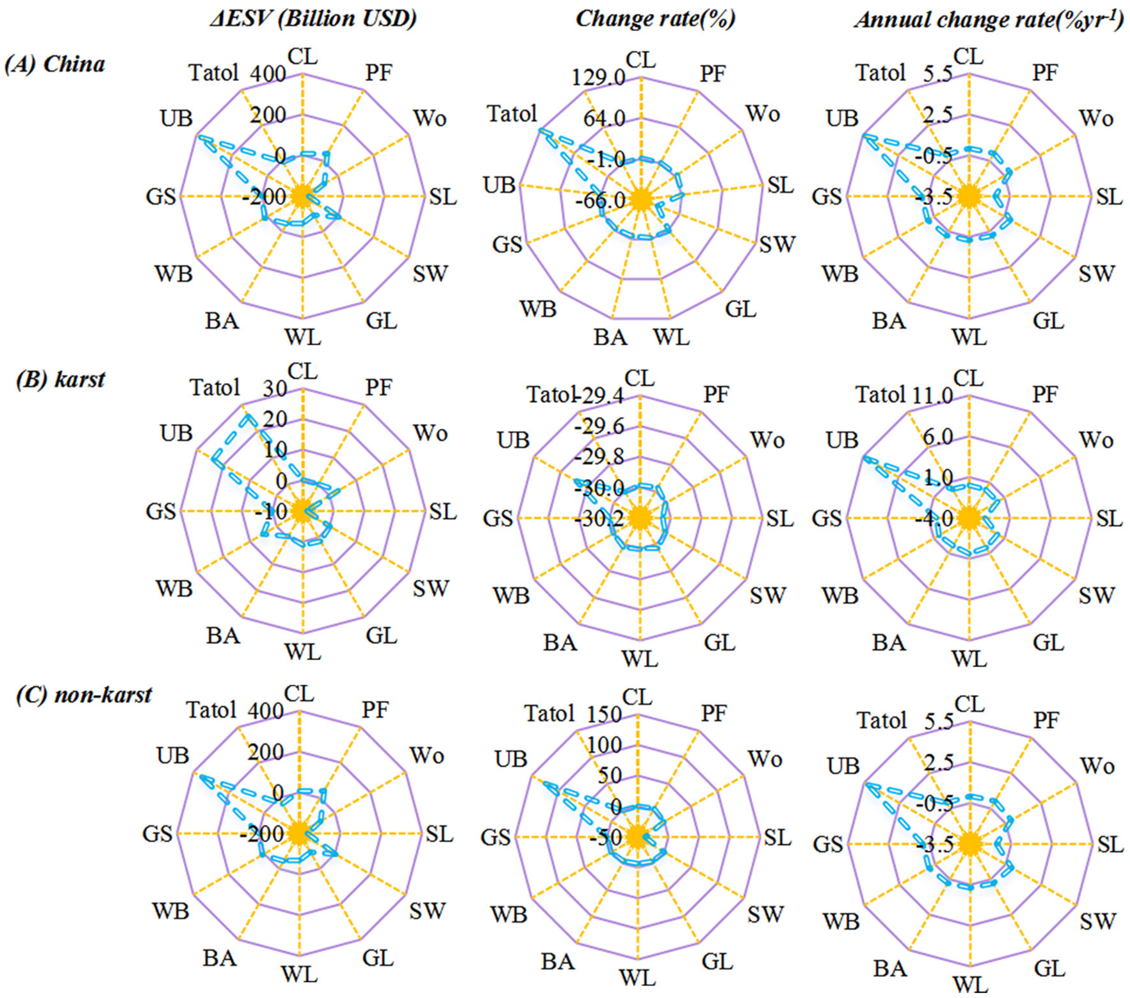

Fig. 10. Rose diagram of the changes in ESVs from 1992 to 2015. DL: dry land; PF: paddy field; Wo: woodland, SL: shrub land, GL: grassland, SW: sparse woodland, WL: wetland, UB: urban land, WB: water bodies, BL: bare land, GS: glacier snow.

global scenarios and national implications ESVs.

However, we only discussed the matching rates and ratios when comparing our results with others studies. The results showed that the absolute matching rates between our results and prior results ranged from 53.95% to 89.45% (Table 5). The absolute matching rates throughout the entire study period ranged from 34.78% to 86.95%. However, for Changsha city, the matching rate was slightly lower (Liang et al., 2017), which was mainly related to the time of the study period and data (Table 5). ESVs fluctuate (Fig. 4) with the research periods and remote sensing data, especially for LULC data. Song and Deng (2017) showed that LULC data had a significant effect on ESVs estimates. For example, we estimated an ESVs change rate of 0.54% ˆyr^{-1} for Changsha city based on the LULC data with a 300 m-resolution of Changsha from 1995 to 2010. This result is very close to the results Liang et al. (2017). The results of the present study are consistent with the results of comparable studies at other regional scales (Li et al. 2010, 2011, 2016, 2018; Zhang et al., 2011; Song et al., 2015; Han et al., 2016; Liang et al., 2017; Wang et al., 2018), indicating the

Table 5
Comparisons of ESV changes between our results and those of studies.

Sources	Research areas	Longitude	Latitude	Date	ESV change ratio(%yr^{-1})		Matching rates(%)of	
					literature	This paper (1992–2015)	Research period	ESV change
Li et al. (2010)	Zoige Plateau	101°30'–103°30' E	32°20'–34°08' N	1990–2005	−0.15	0.12	56.52	−77.15
Zhang et al.(2011)	Northwest Guangxi	104°29'–109°09'E	23°41'–25°37'N	1985–2005	0.31	0.24	56.52	78.57
Li et al. (2011)	Guizhou	103°36'–109°35'E	24°37'–29°13'N	1996–2008	0.25	0.19	52.17	75.41
Song et al. (2015)	North China Plain	112°48'–122°45' E	32°00'–40°24' N	2000–2008	3.95	2.39	34.78	60.49
Liu et al. (2015)	Hunan	108°47'–114°15'E	30°08'–24°38'N	1995–2010	−0.05	−0.06	65.22	83.68
Han et al. (2016)	Qinghai	89°35'–103°04'E	31°09'–39°19'N	1988–2008	0.01	−0.01	69.57	−87.85
Li et al. (2016)	China	73°33'–135°05'E	3°51'–53°33'N	1990–2010	−0.1	−0.09	78.26	86.96
Liang et al. (2017)	Changsha	111°54'–114°15'E	27°51'–28°40'N	2000–2010	−0.48	−0.89	43.47	53.95
Li et al. (2018)	Chengdu	102°54' –104°53' E	30°05'–31°26' N	2000–2015	5.03	5.62	65.22	89.45
Yin et al. (2018)	Shandong	114°47.5′–122°42.3′E	34°22.9′–38°24.1′N	1995–2015	−0.1	0.18	86.95	−54.79
Sheng et al. (2018)	Beijing–Tianjin–Hebei	113°04'–119°53'E	36°01'–42°37'N	2000–2010	−0.46	−0.33	43.47	72.41
Wang et al. (2019)	Hengduan Mountain	96°58′–104°27′E	24°39′–33°34′ N	1990–2010	0.07	0.13	78.26	55.68

Table 6
Changes in ESVs from 1992 to 2015.

Type	1992–1995			1995–2000			2000–2005			2005–2010			2010–2015			1992–2015		
	ΔESV	%	% yr^{-1}	ΔESV	%	% yr^{-1}	ΔESV	%	% yr^{-1}	ΔESV	%	% yr^{-1}	ΔESV	%	% yr^{-1}	ΔESV	%	% yr^{-1}
DL	0.55	0.40	0.13	0.94	0.69	0.14	−0.91	−0.65	−0.13	0.10	0.07	0.01	−0.57	−0.41	−0.08	0.12	0.09	0.00
PF	0.16	0.89	0.30	0.21	1.18	0.24	0.01	0.08	0.02	−0.14	−0.77	−0.15	−0.19	−1.06	−0.21	0.05	0.00	0.00
Wo	−1.76	−0.26	−0.09	1.03	0.15	0.03	4.49	0.67	0.13	−1.01	−0.15	−0.03	0.45	0.07	0.01	3.20	0.00	0.00
SL	−0.27	−1.57	−0.52	−3.64	−20.97	−4.19	−3.87	−28.16	−5.63	−0.73	−7.44	−1.49	−0.21	−2.30	−0.46	−8.73	−0.49	−0.02
SW	−0.80	−0.27	−0.09	−0.67	−0.23	−0.05	0.28	0.10	0.02	0.48	0.17	0.03	0.80	0.27	0.05	0.10	0.00	0.00
GL	0.27	0.84	0.28	0.82	2.52	0.50	1.43	4.28	0.86	0.17	0.49	0.10	−1.30	−3.71	−0.74	1.39	0.04	0.00
WL	−.0.20	−1.45	−0.48	−0.51	−3.68	−0.74	−0.28	−2.09	−0.42	−0.15	−1.12	−0.22	−0.02	−0.13	−0.03	−1.15	−0.08	0.00
BA	0.12	0.57	0.19	−0.05	0.22	0.04	−0.18	−0.86	−0.17	−0.19	−0.96	−0.19	−0.13	−0.67	−0.13	−0.43	−0.02	0.00
WB	0.02	0.02	0.01	1.36	1.59	0.32	2.20	2.54	0.51	0.56	0.63	0.13	0.96	1.07	0.21	5.10	0.06	0.00
PSI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UB	0.78	8.41	2.80	1.49	14.78	2.96	7.00	60.30	12.06	7.26	39.06	7.81	7.24	27.98	5.60	23.77	2.55	0.11
Total	−1.14	−0.09	−0.03	1.00	0.07	0.01	10.18	0.77	0.15	6.36	0.47	0.09	7.03	0.52	0.10	23.42	0.02	0.01

Abbreviations: DL: dry land; PF: paddy field; Wo: woodland, SL: shrub land, GL: grassland, SW: sparse woodland, WL: wetland, UB: urban land, WB: water bodies, BL: bare land, GS: glacier snow.

reliability of our results.

4.3. Spatiotemporal heterogeneity of ESVs

To reveal the temporal heterogeneity of ESVs, the net change and annual change rate in the ESVs of different LULC types in the karst areas were calculated (Table 6). The results showed that the total ESVs in the karst area increased by 23.42 billion US$ (Fig. 5 and Table 6) during 1992-2015. Our results are consistent with the findings of Zhang et al. (2011) and Gao et al. (2014). However, the ESVs in the karst areas during 1992–1995 decreased considerably by 1.14 billion US$, ca. 0.03% yr^{-1}, which was mainly caused by the reduction in woodlands, shrub lands, sparse woodlands and wetlands The ESVs changes during this period are generally consistent with that of Li et al. (2016). In contrast, the ESVs in the karst area during 1995–2000 increased slightly by 1.00 billion US$, which was mainly caused by an increase in woodlands. Similar results were observed in the ecological engineering projects (Zhang et al., 2018). There was a considerable net ESVs gain in the karst area during 2000-2005 (10.18 billion US$), which was closely related to increases in the ESVs of woodlands, water bodies and urban lands and decreases in shrub lands and dry lands. In the other two study periods, the ESVs also increased though insignificantly. Therefore, the ESVs in the study area during the study period are characterized by significant temporal heterogeneity.

To elucidate the spatial heterogeneity of ESVs, we established a gradient of elevation and slope to reveal the associated ESVs variation (Fig. 11). The results indicated that the value of regulation services is higher than the value of other three services regardless of slope or elevation. For the slope gradient, the ESVs curve decreases with increasing slope. The ESVs are highest at 0°–2°, ca. US$ 361.18 million. However, the ESVs are higher 8°–15° than at 5°–8° (Fig. 11A) because the gradient is driven by changes in the areas of woodland and grassland (Fig. 3A). In terms of elevation gradients, the value shows a bimodal (i.e., "M") change trend with increasing elevation. Below 4000 m elevation, the total ESVs and the values of supply, regulation, and support services increase gradually with increasing areas of dry lands and woodlands. The first peak value appears at 400 m. The ESVs of supply services, regulation services, and support service are US$ 42.27 million, US$ 26.32 million, and US$ 8.81 million, respectively. However, the value curve of the cultural service remains almost unchanged. The peak value of ESVs is US$ 9.34 million and it appears at 100 m. Between 4,000 m and 6,000 m, the peak value appears at 5,000 m, and the total ESVs and the values of the supply service, regulation service, support service, and cultural service are US$ 43.39 million, US$ 28.18 million, US$ 7.89 million, US$ 2.99 million, and US$ 2.01 million, respectively. At 6,000 m, the ESVs don't change significantly but still decreases with elevation. In conclusion, the vertical spatial heterogeneity of ESVs in the karst areas is closely related to the spatial distribution of landform. Therefore, different measures should be taken as the slope and elevation increase.

4.4. Impact of LULC change on ESVs

The contributions of different LULC types to the total ESVs differs significantly, and of which the woodlands had the highest contribution to the ESVs of the karst areas in China, followed by the grasslands and dry lands (Fig. 5). Similarly, Leh et al. (2016) and Chen et al. (2019b) also showed that woodlands are the major contributor to the ESVs. Although the contribution of woodlands to the ESVs was increased by 1.76% during 1992-2015 (Fig. 4), it was dropped from 50.72% to 50.08% (Fig. 5). In contrast, although urban land accounts for less than 2% of the study area, its contribution to ESVs was increased by 1.74% (from 0.70% to 2.44%).

We also found that although the change of ESVs caused by LULC was similar in different study periods, there were significant differences in the amplitude fluctuation. Among them, the ESVs fluctuated relatively significant in 1995–2000 and 2000–2010, owing to the implementation of the GFGP in the karst areas, which has resulted in significantly changes in the land use structure, especially the cultivated lands (dry lands and paddy fields), woodlands and grasslands. The LULC changes have a significant effect on ESVs, and the ESVs of the regulation services (climate regulation, gas regulation, the hydrological regulation and environmental purification) have changed the most significantly, followed by those of the support service (soil formation and retention and biodiversity) and the culture services (recreation, culture and tourism) (see Supplementary Fig. 1 and 2). In these LULC conversions (Fig. 12), the conversion of cultivated lands (dry lands and paddy fields) into woodlands and urban lands, and grasslands into woodlands have led to the significant increase in the ESVs of the regulation service, the support service and the cultural service, which ultimately leads to an increase in the total ESV. This series of changes is mainly driven by the implementation of the GFGP. Some scholars have shown that the implementation of the GFGP has promoted revegetation (Andrés et al., 2016; Zhang et al., 2016) and that the reduction of cultivated lands (Bryan et al., 2018; Chen et al., 2020) had led to the improvements in climate regulation, hydrological regulation, soil conservation and carbon sequestration (Lawler et al., 2014; Fu et al., 2017; Jiang et al., 2018). Furthermore, with the rapid development of the economy, the population growth and increasing demand of human beings for entertainment and culture have led to an increase in urban lands and a reduction of cultivated lands, which has ultimately led to an improvement of cultural services and a decline of provision services

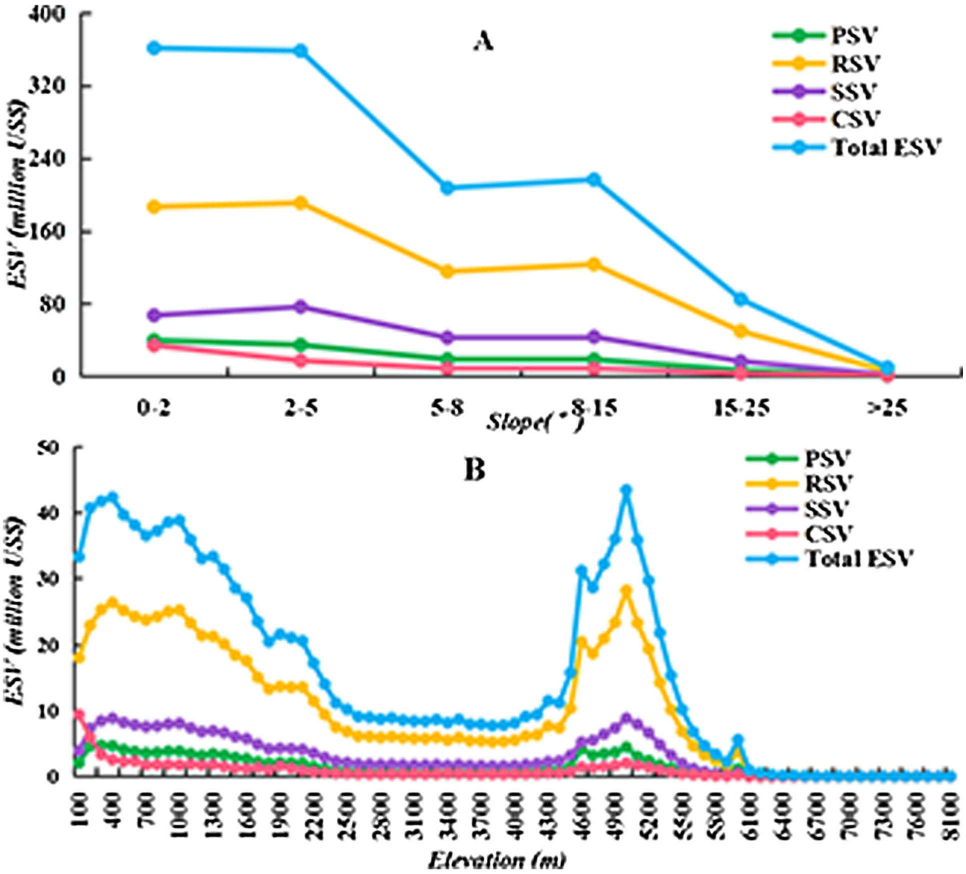

Fig. 11. The ESVs of different ecosystem service types changes with slope (A) and elevation (B).
Abbreviations: PSVprovision services value, RSVregulating services value, CSVculture services value, SSVsupporting services value.

(food production). Bren d'Amour et al. (2016) also showed that urbanization may compete with cultivated lands, thereby increasing the pressure on the food system. Since there is bidirectional conversion among different LULC types, the conversion of some woodlands into cultivated lands (dry lands and paddy fields) has resulted in a significant decline in the values of the regulation service, provision service and support service, which may ultimately reduce the values of regulation service (gas regulation and climate regulation) and support service significantly. The conversion of grasslands into water bodies has led to a significant decline in ESVs, and vice versa (Fig. 12). It is probably that the value coefficient per unit area of the water bodies is higher than that of the grasslands (Table 2). In short, the implementation of the GFGP had played a positive role in the ESs in karst areas, which is consistent with the results of a previous study (Feng et al., 2013; Hou et al., 2015; Ouyang et al., 2016; Zhang et al., 2018). The changes of LULC may affect the ecosystem dramatically but do not necessarily lead to ecosystem degradation.

4.5. Limitations and perspectives

The present study has some limitations. The ESVs calculation formula of Costanza et al. (2014) was used to calculate the equivalent ESVs per unit area in China, as proposed by Xie et al. (2015), and the equivalent value was revised on the basis of the characteristics of the karst areas in China. Indeed, there is a certain deviation in the value coefficient of the same ES in different regions. However, the use of different indicators to estimate the same ESVs in different regions was not considered in this paper. It is very difficult to obtain data in the karst areas, but this is also a direction of future research. In addition, the spatial heterogeneity of ESVs only considered the influence of elevation and slope, but ESVs are affected by many factors. Future work should quantify the effects of human activities and climate change on ESVs and explain the intrinsic driving mechanism for the progressive/retrogressive succession of the ecological environment in the karst areas.

5. Conclusions

The present study estimated the ESVs in karst areas of China, revealed its spatiotemporal evolution and spatial heterogeneity, and clarified the sensitivity of ESVs to land use change using the 1992-2015 LULC information and agricultural data. The following conclusions were made.

(1) Great changes have occurred in the LULC in the karst areas of China during 1992-2015. In particular, the area of urban lands increased significantly by 71.83% at the expense of woodlands and shrub lands. This suggests intense human activity during the study period.
(2) The ESVs in the study area increased by US$23.42 billion, or by 1.75%, at a rate of 0.1% yr$^{\wedge -1}$ during 1992-2015 due to woodlands destruction and an expansion of urban lands and dry lands.
(3) The functional values of different ESs differed significantly. The greatest contributor to the ESV was the regulation services ca. 69.05%, followed by the support service, ca. 18.23%, the supply services, ca. 8.54%, and the cultural service, ca.4.15%.
(4) The ESVs had a significant vertical spatial heterogeneity. At the elevation level, the total ESVs and the values of the regulation, supply, support, and cultural services showed a biomodal curve. However, along the slope level, the total ESVs and the values of the regulation, supply, support, and cultural services decreased.
(5) In terms of land use transfer, the CCS of the conversion of water bodies into woodlands, shrub lands, dry lands, and grasslands was

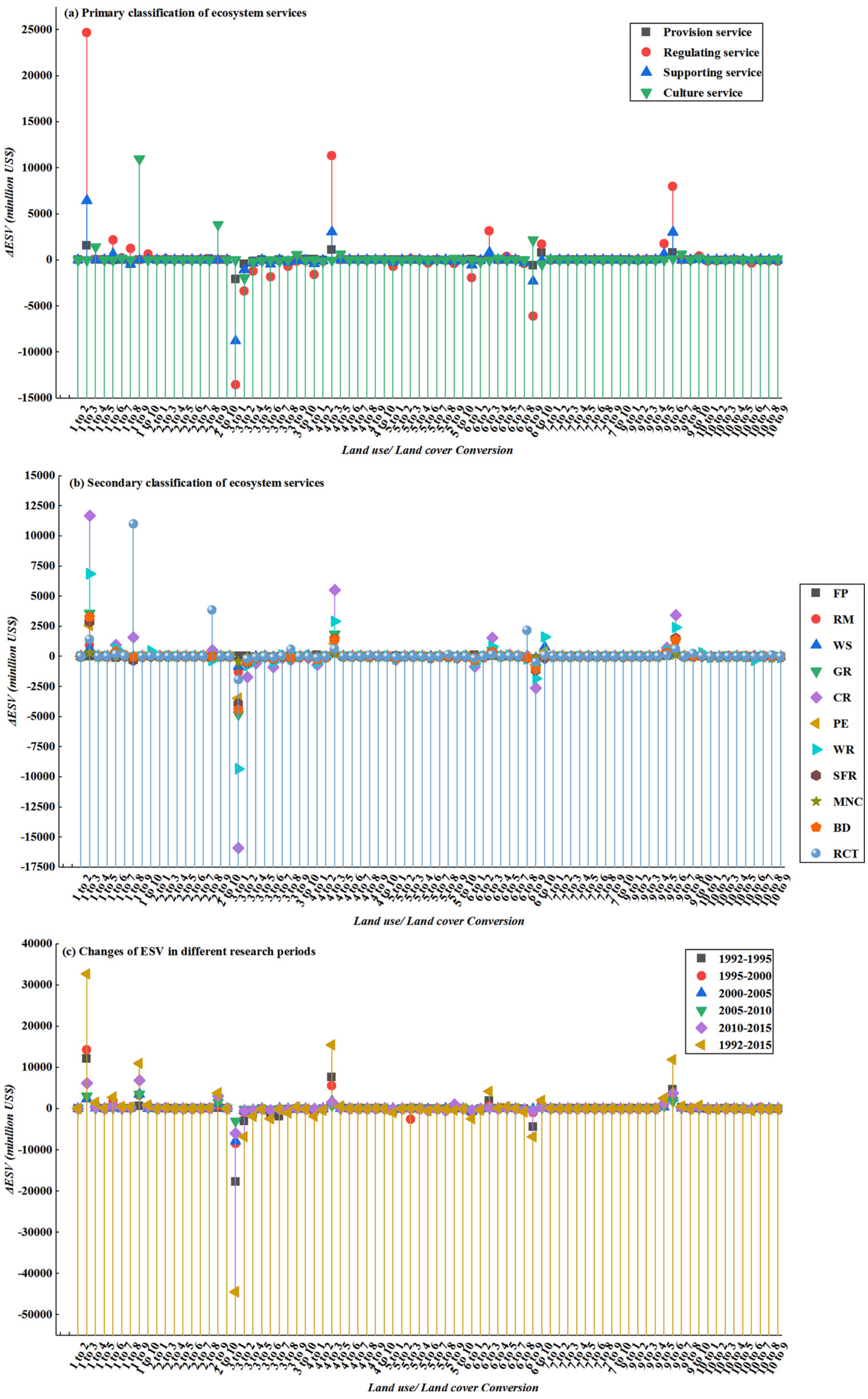

Fig. 12. Impact of LULC on ESVs. (a) Primary classification of ESVs; (b) secondary classification of ESVs. Note: Nos. 1–10 represent dry land, paddy field, woodland, shrub land, sparse woodland, grassland, wetland, urban land, water bodies, and bare land, respectively. Code 1 to 2 represent dry land converted to paddy field, and the other codes follow the same rule. Abbreviations: FP: food production; RM: raw material production; WS: water supply; GR: gas regulation; CR: climate regulation; PE: purification of the environment; WR: water regulation; SFR: soil formation and retention; MNC: maintenance of nutrient circulation; BD: biodiversity; RCT: recreation, culture, tourism.

greater than 0.03 during the study period. The ESVs were insensitive to the conversion between water bodies and bare lands, but the CCS increased over time.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.107026.

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