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ORIGINAL PAPER

Ecosystem services trade-offs and synergies in China, 2000–2015

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Abstract

Terrestrial ecosystem services have experienced evident decline in the past decades. Trade-offs and synergies in ecosystem services have been widely studied to understand the disturbance of human activities on ecosystems. However, the method for ecosystem services assessment remains incomplete, and a few studies of the trade-off analysis of ecosystem services have been conducted at the national scale. In this study, we conducted trade-off analysis of China's ecosystem services—including supplying, regulating, supporting, and cultural services—using a newly revised benefit transfer method and the bivariate Moran's *I* method during 2000–2015. We found an overall increasing tendency in ecosystem services value when comparing to the findings from previous studies. Synergy was the dominant relationship among the ecosystem services in China, but it varied spatially. The findings in this study have important implications for ecosystem services management in China and for ecosystem services value assessment in other regions.

Keywords Ecosystem services value · Benefit transfer method · Hotspots analysis · Bivariate spatial autocorrelation model · Trade-off · Synergy · China

Introduction

As an important linkage between natural environment and human well-being, ecosystem services (ESs) have been studied globally (Costanza et al. 1997; Costanza et al. 2014; MEA 2005; Wu, 2013). The evaluation of ESs provides important information about the goods and services that humans gain from ecosystems, either directly or indirectly (Cetin et al. 2021; de Groot et al. 2012; Troy and Wilson, 2006). An analysis of the trade-offs and synergies of ESs provides the basis for national territorial planning, biodiversity conservation, and ecological compensation (Asadolahi et al. 2018; Hatton MacDonald et al. 2014; Turkelboom et al. 2018; Obiang Ndong et al. 2020). However, the existing assessment method of ESs is still incomplete, and a few studies have examined the trade-off and synergistic relationships between *different* ESs—including supplying, regulating, supporting, and cultural services—at the national scale. That said, the diversity of ESs and imbalance of spatial distribution have led to a change in the relationships between ESs, revealing the trade-offs or synergies phenomenon (Himes et al. 2020; Hou et al. 2018; Lin et al. 2018; Shen et al. 2020). In this context, identifying the trade-offs and synergistic relationships between different ESs based on an accurate assessment is necessary for the optimal management of these vital services.

In this study, we examined ecosystem values (ESVs) in China using the revised benefit transfer method. We used the hotspot analysis method to identify the hotspots of ESV changes in China. We then employed correlation analysis and bivariate spatial autocorrelation analysis to analyze the trade-off and synergistic relationships among supplying, regulating, supporting, and cultural services in China. To this end, our study aims to address the following three questions:

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What were the spatial patterns of ESVs in China from 2000 to 2015?
What were the hotspot patterns of the changes of ESVs in China?
What were the spatial trade-off and synergistic relationships among different ESs in China?

Background

China is a fast-growing country, with a vast area of land, massive economic output, large population, and complex physical and socioeconomic circumstances. China has 1.4 billion people as of 2021 and about 7% of world farmland, and it contributes about 16% of the world's gross domestic product (NBSC 2021). The pressure of feeding such a large population demands more attention be paid to food production, which in part leads to a decrease in other ecosystem functions (e.g., soil quality degradation and a decrease in soil conservation functions) (Yu et al. 2012). A significant increase in urban built-up land area and urban population has been occurring over recent past decades, especially since the beginning of the twenty-first century (Bai et al. 2014; Chi and Ho 2018). This situation greatly increased land-use change and profoundly interfered with ecosystem synergies and trade-offs. That said, a number of ESs-related programs, including the Key Shelterbelt Construction Program (initiated in 1978), the Natural Forest Conservation Program (started in 1998), and the Grain to Green Program (GTGP, started in 1999), have greatly improved the ecosystem in China (Bryan et al. 2018; Ouyang et al. 2016). Additionally, national development strategies and land-use policies have intensified ecosystem evolution. Identifying the effects of policy-driven and urbanization-driven land-use change on ecosystem trade-offs and synergies remains critical to achieve the goal of land-use sustainability in China.

Prior research

The monetary, material, and energy evaluation methods have commonly been used to measure ESs (Cao et al. 2020; Cetin et al. 2021; Daily, 1997; Ma et al. 2015). The global ESV assessment conducted by Costanza et al. (1997) greatly promoted the valuation of ESs, and a substantial number of studies of ESV assessment have been conducted based on that method (Chen et al. 2019a, b; Costanza et al. 2014; Yi et al. 2017; Hasan et al. 2020). The benefit transfer method—incorporating the monetary value yielded in a specific area to another—has been criticized for bias because of the lack of consideration to the spatial heterogeneity of ecosystems (Plummer 2009). The diversity of ecosystems and physical conditions determine the spatial diversity of the category and intensity of ESs (Cetin et al. 2019; Fei et al. 2018). Thus, an increasing number of studies have revised the benefit transfer method on the basis of local ecosystem conditions (Fei et al. 2018; Li et al. 2017; Xie et al. 2017; Xing et al. 2018; Xu and Ding 2018; Zhang et al. 2021). Most of these studies revised the benefit transfer method by focusing on regional biomass and assuming that ESs are closely related to the biomass of an ecosystem (Wang et al. 2018; Xie et al. 2008). However, the value of ESs is not proportionally related to biomass. For example, water areas and wetlands contain little biomass, but water areas and wetlands play an important role in climate regulation, hydrological regulation, and biodiversity regulation (Chen et al. 2020). This means that revisions to ESVs based on total regional biomass may lead to the deviation of the assessment result. Chen et al. (2020) argued that it is more reasonable to spatially correct for ESs based on the biomass provided by farmland. Using the biomass of farmland to revise ESs is simple, with relatively easy data collection and high accuracy of results, especially in the large-scale study area.

These ESs assessments provide information to understand overall changes in ESVs, but they fail to reveal the internal changes, such as trade-offs and synergies between ESs. Analyzing the trade-offs and synergies of ESs can lead to an understanding of the multiple nonlinear relationships, driving mechanisms, and scale effects among different ESs (Rodriguez et al. 2006; Sil et al. 2016; Shoemaker et al. 2019; Stosch et al. 2019). Existing literature has shown significant increases in the supplying services of ecosystems (e.g., food production and raw material production) over the past few decades, but this has led to a decline in soil conservation and a loss of biodiversity (Bennett et al. 2009; Haase et al. 2012; Pergams and Zaradic 2008). ESs' trade-off relationships have been proven to exist between supporting and regulating services, while ecosystem synergies exist primarily between supporting and cultural services, as well as between regulating and cultural services (Accatino et al. 2019; Asadolahi et al. 2018; Gissi et al. 2018; Qiao et al. 2019). However, the trade-off and synergistic relationships between ESs are spatially heterogeneous and temporally dynamic, and they vary greatly across space and over time (Su and Fu 2013; Qiao et al. 2019). In prior research, the analysis of ESs trade-offs and synergies has been achieved primarily through spatial mapping and statistical analysis, such as correlation analysis of ESs (Sun and Li 2017; Yang et al. 2018; Felipe-Lucia et al. 2018), the root-mean-square deviation method (Bradford and D'Amato 2012), production possibility frontiers (Yang et al. 2016), multivariate regression tree (Obiang Ndong et al. 2020), and bivariate spatial autocorrelation (Liu et al. 2018a, b; Qiu and Turner 2013; Zhou et al. 2019). Bivariate spatial autocorrelation model can effectively reveal the spatial heterogeneity of ESs trade-offs and synergies due to the heterogenous spatial distribution of physical and socioeconomic factors (Cetin 2020; Qian et al. 2018; Zhou et al. 2019). An analysis of the trade-offs and synergies of ESs not only helps us understand the interrelated factors and mechanisms of different ESs, but it also helps accurately analyze the relationships among them and provides guidance to develop and utilize natural resources more rationally (Naidoo et al. 2008; Shen et al. 2020; Stosch et al. 2019). ESs trade-off and synergy analysis has widely been conducted at different units (e.g., administrative, watershed) (Yang et al. 2018; Zheng et al. 2018; Obiang Ndong et al. 2020); however, a few studies have been conducted at the national scale. This study attempts to analyze ecosystem service trade-offs and synergies at the county level in China. China is one of the largest countries in the world and has a diverse and uneven spatial distribution of its ESs. Identifying the trade-off and synergistic relationships among different ESs is necessary to achieve win–win outcomes in China.

Materials and methods

Data sources

Remotely sensed land-use data used in this study were provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). Using Landsat TM/ETM + remote sensing image data, Liu et al. (2014) constructed a multi-temporal land-use database going back to the late 1970s, with manual visual interpretation at a 1 km spatial resolution. This is currently the most accurate land -use data product in China (Liu et al. 2014; Ning et al. 2018). We classified the land-use data into seven land-use types: farmland, forestland, grassland, water area, construction land, unused land, and wetlands. The Normalized Differential Vegetation Index (NDVI) datasets in China for 2000, 2005, 2010, and 2015, used for determining the equivalent value of farmland were sourced from RESDC.

Methods

Calculation of ESVs

Globally, the benefit transfer method has been used widely in ESV assessment (Costanza et al. 1997, 2014; Xie et al. 2017). Xie et al. (2008) reclassified ESs according to China's specific conditions and modified the ESV equivalent table based on the knowledge of more than 700 experts (Xie et al. 2008; Song and Deng 2017). ESs were reclassified into four categories and nine subcategories. The ESV equivalent value of per-unit area of food production of farmland is set to 1, and the ESV equivalent values of other ecosystems are identified by their relative importance to the food production of farmland (Song and Deng 2017). Previous studies generally showed that biomass and ESs supply capacity were positively correlated (Xie et al. 2008, 2017; Wang et al. 2018). Chen et al. (2020) argued that a correction based on the biomass of farmland was more accurate, because the equivalent value of ESs was determined according to the economic output value of farmland. In addition, the value of ESs provided by water bodies and wetlands is generally not in direct proportion to their biomass. Therefore, in our study, we revised the ESV equivalent table proposed by Xie et al. (2008) by the biomass of the farmland due to the fact that ESVs were not proportionally related to biomass in this study. Based on the biomass of farmland, we obtained a correction factor in every county in different years. The equations are as follows:

$$VCI = \left(\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \right) \times 100\% \quad (1)$$

$$ESV_{p-corrected} = \frac{VCI_j}{\overline{VCI_t}} \times \sum_{j=1}^{m} \sum_{i=1}^{n} \left(LUC_i \times VC_{ij} \right) \quad (2)$$

$$ESV_{c-corrected} = \frac{VCI_i}{\overline{VCI_f}} \times \sum_{j=1}^{m} \sum_{i=1}^{n} \left(LUC_i \times VC_{ij} \right), \quad (3)$$

where $ESV_{p\text{-}corrected}$ is the ESV from the previous studies after correction, and $ESV_{c\text{-}corrected}$ is the ESV after correction in this study. VC_{ij} is the jth ESV equivalent factor of ith land-use type, LUC_i indicates the area of ith land-use type, n indicates the number of land-use types in this study, and m indicates the number of ESs categories. $NDVI$ is the annual average $NDVI$ value for the local unit. $NDVI_{max}$ and $NDVI_{min}$ are the maximum and minimum, respectively, of the annual average $NDVI$ values across China. VCI is the vegetation condition index calculated by NDVI. VCI_j and $\overline{VCI_t}$ are the average annual VCIs of in the ith county and China, respectively. VCI_i and $\overline{VCI_f}$ are the average annual VCIs of the farmland in the ith county and China, respectively.

Hotspot analysis

Hotspot analysis is commonly used to identify spatial clusters of hotspots and coldspots, and has been widely used in socioeconomic and ecological analysis (Cetin 2019; Timilsina et al. 2013; Wang et al. 2019). Hotspots (or coldspots) represent statistically significant high-value (or low-value) spatial aggregation. This study used the hotspot analysis method to measure spatial distribution of statistically significant hotspots and coldspots using ArcGIS 10.3 (Esri, USA) software. The new output feature class provided by the Getis-Ord Gi* statistic contains a z score, p value, and confidence level bin (Gi_Bin) for each feature in the input feature class. The features with a high z score and small p

value represent the spatial clustering of hotspots, and the features with a high but negative z score and small p value represent the spatial clustering of coldspots.

Trade-off and synergy analysis

ESs trade-offs refer to two types of ESs changing in opposite directions, while ESs synergy refers to two types of ESs changing in the same direction (Bennett et al. 2009; Cord et al. 2017; Xu et al. 2018; Deng et al. 2016). Correlation analysis of two specific ESs can identify the degree of linear correlation and clarify the relative direction between the two (Felipe-Lucia et al. 2018; Sun and Li, 2017; Yang et al. 2018). The larger the absolute value of the coefficient, the stronger the correlation. A positive value indicates ESs synergy, while a negative value indicates a trade-off in ESs (Felipe-Lucia et al. 2018). Owing to the impacts of socioeconomic and natural factors, the trade-offs and synergies of ESs may change with different spatial locations (Qian et al. 2018). We employed the bivariate spatial autocorrelation model to further study the spatial distribution of trade-offs and synergies between two specific ESs (Anselin and Rey 2014; Anselin 1995; Liu et al. 2018a, b; Zhou et al. 2019). In our bivariate local Moran's I analysis results, high–high and low–low clusters indicate synergy, while high–low and low–high clusters indicate trade-offs. The equations were as follows:

$$Moran'I_{global} = \frac{n\sum_{i=1}^{n}\sum_{j\neq i}^{n} W_{ij}ES_iES_j}{(n-1)\sum_{i=1}^{n}\sum_{i\neq j}^{n} W_{ij}} \quad (4)$$

$$Moran'I_{local} = ES_i\sum_{j=1}^{n} W_{ij}ES_j, \quad (5)$$

where $Moran'\ I_{global}$ and $Moran'\ I_{local}$ are the bivariate global Moran's I index and local Moran's I index, respectively; ES_i and ES_j are the ith and jth ecosystem functions, respectively; W_{ij} is the spatial weight matrix; n is the number of units in this study.

Results and discussion

Results

ESVs in China, 2000–2015

We examined the terrestrial ESVs by multiplying the area of each land-use type by the unit value after correction. The terrestrial ESVs in China were $723.88 billion, $717.43 billion, $718.93 billion, and $727.65 billion (based on the 2007 value of the USD) in the years of 2000, 2005, 2010, and 2015, respectively (Table 1). Overall, we found that the China's ecosystem supply capacity increased slightly during the study period ($3.77 billion), with a decrease of 6.45 billion during 2000–2005 and a continual increase in the following periods. During the study period, over 54% of the ESVs were provided by forestland, while a decreasing trend was found in forestland ESV provision, from 55.36% in 2000 to 55.12% in 2015, followed by the ESVs provided by farmland (≥ 11%) and grassland (≥ 19%). Unused land provided the smallest proportion of ESV (about 1%). During the period 2000–2005, ESVs decreased 0.89% by $6.45 billion, and the supplying, regulating, supporting, and cultural services decreased by $0.71 billion, $3.13 billion, $2.15 billion, and $0.46 billion, respectively. In the following decades, ESVs in China increased. Total ESVs in China during 2005–2010 and 2010–2015 increased by $1.50 billion and $8.72 billion. Similar increases were found in other ESs, with supporting and regulating services increasing the most significantly.

The change in the spatial pattern of ESs in China during 2000–2015 was not significant, and similar spatial distribution patterns can be found in the four categories of ESs (Fig. 1). In general, ESs in southeastern China are higher than those in northwestern China. However, counties with low-value ESs can be found in southwestern China, and counties with high-value ESs still exist in northwestern China. ESVs in the mountainous areas in southeastern China are significantly higher in value than those in the plains areas. The high-valued counties in southeastern China are distributed primarily along the Greater Khingan Mountains, Lesser Khingan Mountains, Changbai Mountains, Taihang Mountains, Xuefeng Mountains, Nanling Mountains, Wuyi Mountains, Dabie Mountains, Qinling Mountains, and Hengduan Mountains. The counties having low-value ESs in southeastern China were mainly concentrated in the plains areas, including the Northeast Plain (e.g., eastern Inner Mongolia, southwestern Heilongjiang, western Jilin, and Liaoning Province), North China Plain (e.g., Beijing, Hebei, Tianjin, Shandong, Jiangsu, eastern Henan, and northern Anhui Province), Sichuan Basin, Jianghan Plain in Hubei, Poyang Lake Plain in Jiangxi, Dongting Lake Plain in Hunan Province, major urban agglomerations, and the surrounding counties of major capital cities. The counties with high-value ESs in northwestern China are distributed mainly in southeastern Qinghai, southeastern Tibet, and the northwestern border counties of Xinjiang. The spatial distribution patterns of supplying service, regulating service, supporting service, and cultural service are similar to that of average ESV in China (Fig. 2).

Table 1 Changes in ESVs during 2000–2015

	Years	Farmland	Forestland	Grassland	Water area	Unused land	Wetland	Supplying services	Regulating services	Supporting services	Cultural services	Total ESV
ESV (billion US$)	2000	85.63	400.72	145.07	30.83	9.11	52.53	73.62	387.44	211.43	51.39	723.88
	2005	86.16	394.65	143.33	32.08	9.35	51.85	72.91	384.31	209.28	50.93	717.43
	2010	86.22	394.09	144.36	31.62	9.84	52.79	72.95	385.15	209.75	51.08	718.93
	2015	87.00	401.06	144.98	32.08	10.18	52.35	73.97	389.50	212.46	51.73	727.65
Value change (billion US$)	2000–2005	0.53	− 6.07	− 1.74	1.25	0.24	− 0.67	− 0.71	− 3.13	− 2.15	− 0.46	− 6.44
	2005–2009	0.06	− 0.56	1.03	− 0.45	0.49	0.93	0.04	0.83	0.47	0.16	1.50
	2010–2015	0.78	6.97	0.61	0.46	0.34	− 0.44	1.02	4.35	2.71	0.64	8.72
	2000–2015	1.38	0.34	− 0.09	1.25	1.07	− 0.18	0.34	2.06	1.03	0.34	3.77
Change percentage	2000–2005	0.62	− 1.51	− 1.20	4.06	2.68	− 1.28	− 0.96	− 0.81	− 1.02	− 0.89	− 0.89
	2005–2010	0.07	− 0.14	0.72	− 1.42	5.23	1.80	0.05	0.22	0.22	0.31	0.21
	2010–2015	0.90	1.77	0.43	1.45	3.44	− 0.83	1.40	1.13	1.29	1.26	1.21
	2000–2015	1.61	0.09	− 0.07	4.07	11.76	− 0.34	0.47	0.53	0.49	0.66	0.52

Hotspots and coldspots of ES changes in China during 2000–2015

In this study, we used the Hot Spot Analysis tool (Getis-Ord Gi*) embedded in ArcGIS software to identify statistically significant spatial hotspots (high values of ESV changes) and coldspots (low values of ESV changes) in China during 2000–2015. Figure 3 presents the spatial distribution of hotspots and coldspots of ESs' change. The hotspots in 2000–2005 were distributed mainly in the northwest border counties of Xinjiang, the southeastern counties of Sichuan, the Loess Plateau (e.g., Gansu, Qinghai, Shaanxi, Ningxia, and Shanxi), eastern Inner Mongolia, and Guangdong Province. The coldspot counties were distributed primarily in southeastern Tibet, part of Yunnan, Guangxi, Guizhou, Hunan, Jiangxi, Fujian, Zhejiang, Taiwan, and Hainan.

However, in 2005–2010, hotspots moved to the northwestern counties of Xinjiang, central Inner Mongolia, Ningxia, Shanxi, Shaanxi, Henan, Hubei, Hunan, Chongqing, Jiangxi, Guizhou, Guangxi, Taiwan, and southern Zhejiang. The coldspot areas were distributed mainly in Sichuan, Yunnan, Guangzhou, southern Fujian, Shandong, Jiangsu, Shanghai, northeastern Inner Mongolia, and most of Heilongjiang. In 2010–2015, the hotspots were distributed mainly in the southwestern regions of China, including Yunnan, Guizhou, Chongqing, Guangxi, Sichuan, and parts of Ningxia, Gansu, and Shaanxi, and the southern counties of Tibet, northeast Inner Mongolia, and Heilongjiang. The coldspots were concentrated in the southeastern counties of Qinghai, the middle and lower reaches of the Yangtze River (e.g., Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Shanghai, and Zhejiang), the North China Plain (e.g., Henan, Shanxi, Beijing, Tianjin, and Shandong), Liaoning, and Taiwan. The spatial distribution of hotspots of different ESs provides a better understanding of the changes in various ESs (Fig. S1). We found that the hotspots of different ESs are similar to those of the total ESs.

Trade-off and synergy analysis of ESs in China during 2000–2015

Correlation analysis showed that positive correlation coefficients exist among the four ESs, indicating strong synergistic relationships during the study periods in China (Fig. 4). The global bivariate Moran's *I* indices for these ESs are presented in Table 2. We found that the global bivariate Moran's *I* indices for every pair of ESs were positive and significant at 0.0001, indicating significant synergistic relationships among these ESs. The spatial expression of trade-offs and synergies among ESs was further identified with the local bivariate LISA method. On the basis of our local bivariate spatial autocorrelation analysis, high–high

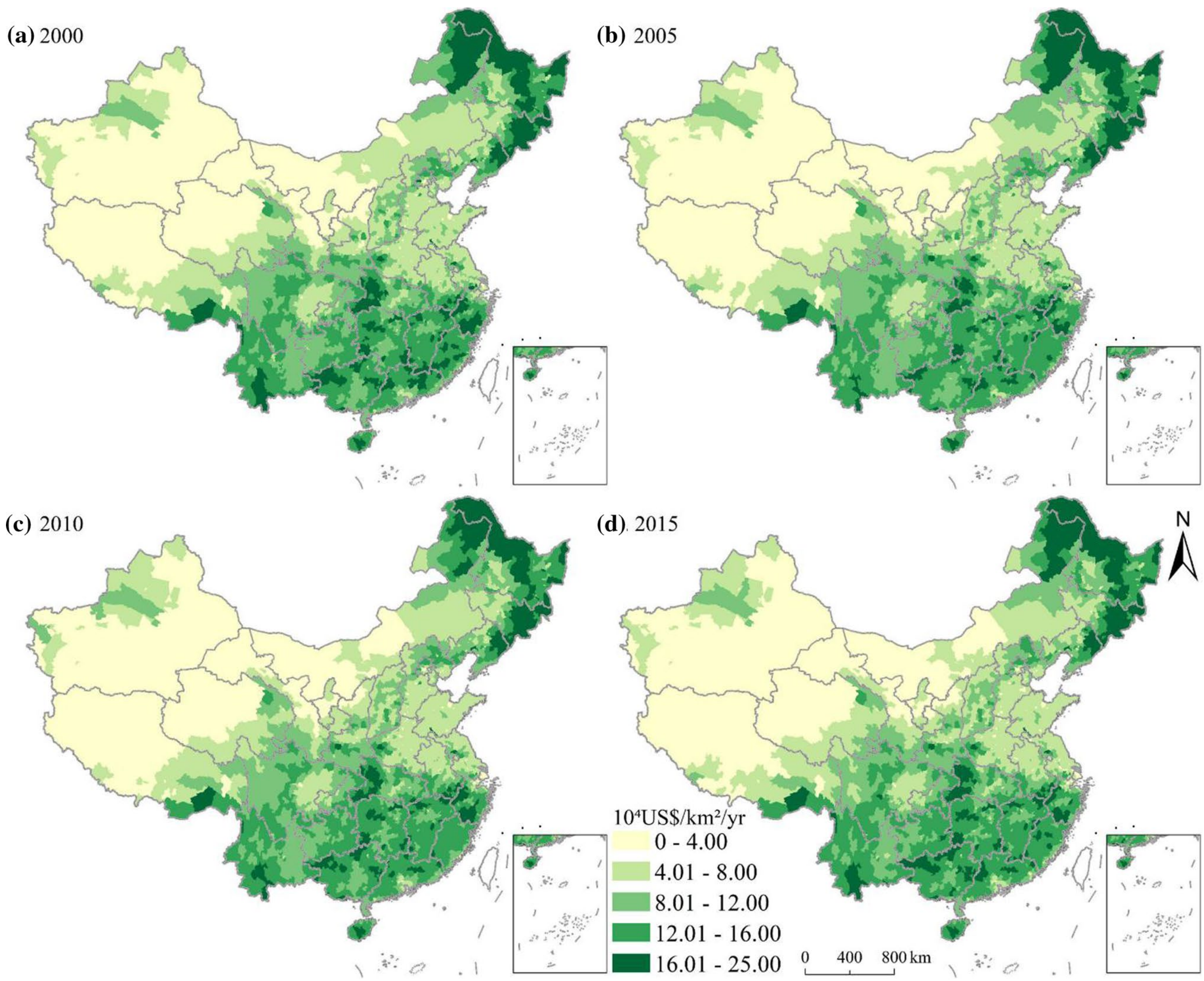

Fig. 1 Spatial distribution of total ESVs in China, 2000–2015

clusters and low–low clusters represent a synergistic relationship, and high-low types and low–high types represent a trade-off relationship. The LISA cluster maps between two typical ESs are presented in Figs. 5, 6, and 7. A significantly similar clustering pattern was found among these ESs during 2000–2005 (Fig. 5). Specifically, statistically significant high–high clusters were distributed primarily in northeast Qinghai, southeast Gansu, northern Shaanxi, and the border areas of Liaoning, Inner Mongolia, and Hebei. There were also some high–high areas randomly distributed in western Xinjiang, eastern Hubei, central Anhui, southeastern Sichuan, and the Pearl River Delta. The statistically significant low–low clusters were distributed mainly in the central part of Inner Mongolia, the Yangtze River Delta, Zhejiang Province, Fujian Province, Jiangxi Province, western Guangxi, southern Yunnan, and most of Hainan Province. During 2005–2010, statistically significant high–high clusters were located chiefly in northwestern Xinjiang, the Loess Plateau (Shaanxi, Shanxi, and Ningxia), central Qinghai, western Guangxi, and western Guizhou (Fig. 6). The statistically significant low–low clusters were distributed mainly in central Sichuan, northeast Inner Mongolia, central and eastern Heilongjiang, central Shandong, the Yangtze River Delta, and the Pearl River Delta.

We found significant synergistic relationships among the ESs in the Loess Plateau during 2000–2005 and 2005–2010. The spatial clustering pattern of trade-offs and synergies among ESs changed significantly over those two periods. The statistically significant high–high clusters were distributed primarily in western Tibet, central and northeast Inner Mongolia, northern Heilongjiang, northern Zhejiang, southern Gansu, central Sichuan, western Hubei, western Hunan, the border of Guizhou and Guangxi, and most of Yunnan. The low–low clusters were concentrated in southeastern

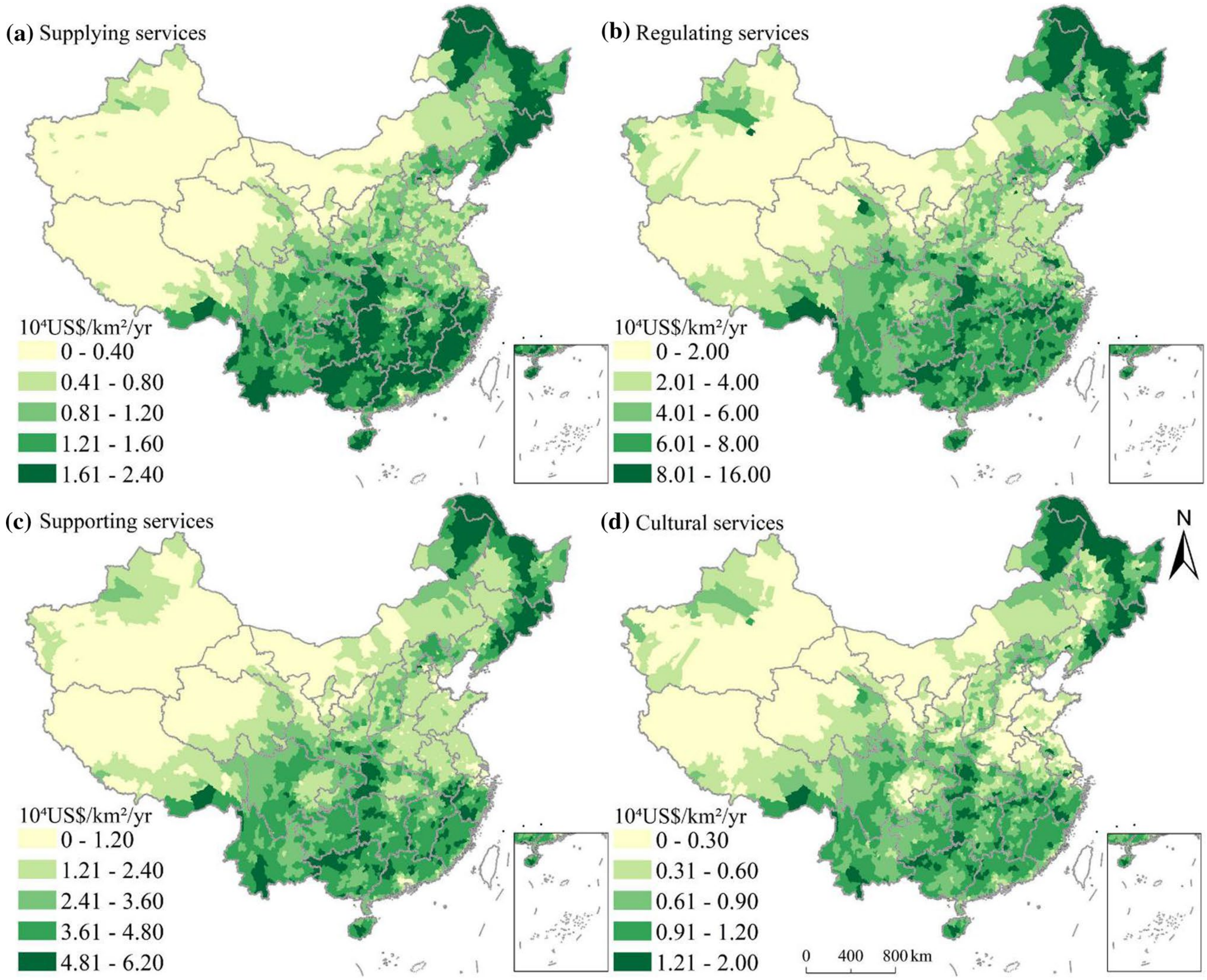

Fig. 2 Spatial distribution of different ecosystem functions in China in 2015

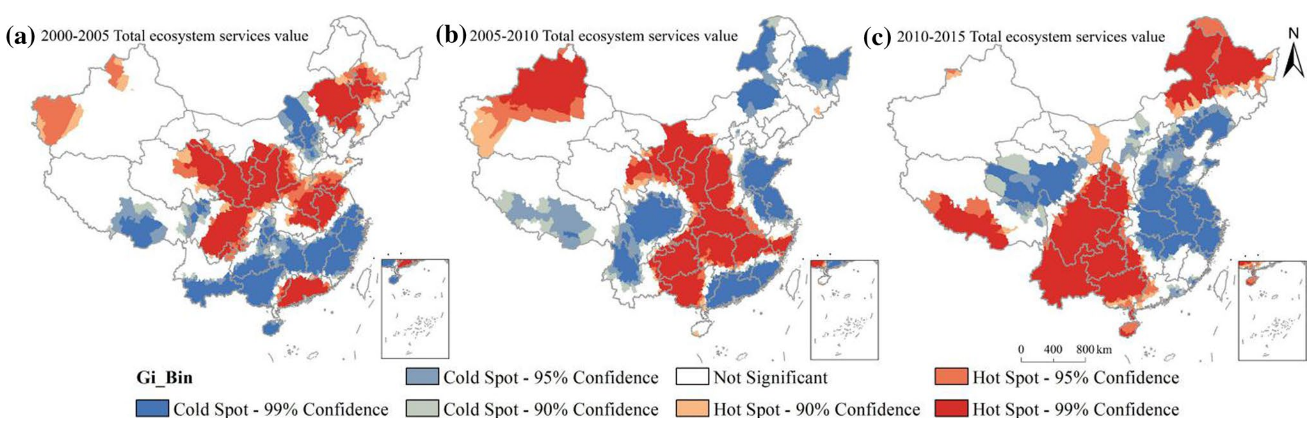

Fig. 3 Hotspots of ESVs' changes with different confidence levels during 2000–2015

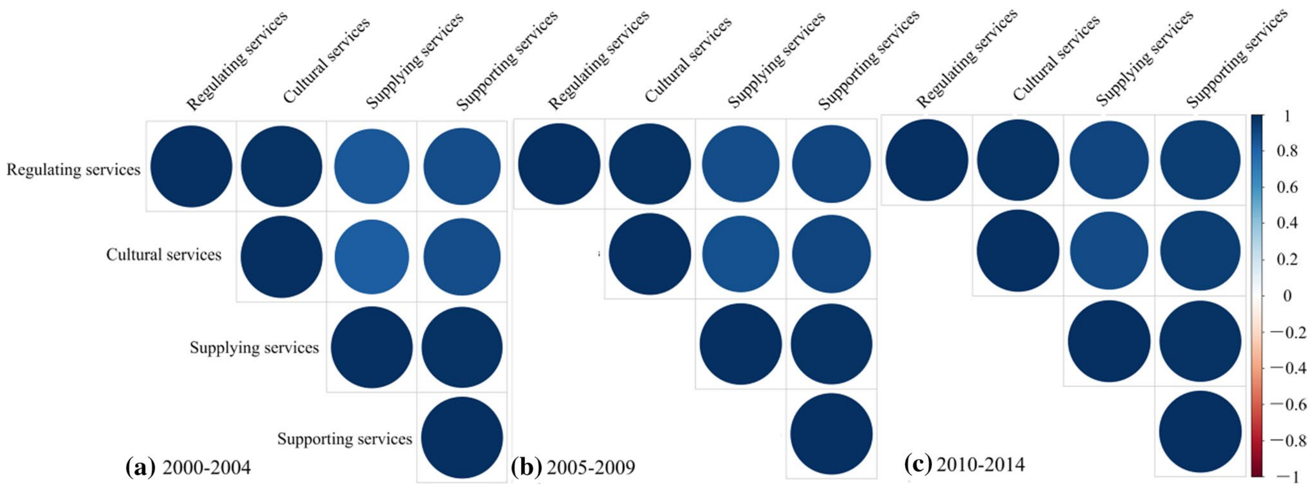

Fig. 4 Correlation matrixes of ESs during 2000–2005, 2005–2010, and 2010–2015

Table 2 Bivariate Moran's I between different ESs

ESs	Moran's *I*		
	2000–2005	2005–2010	2010–2015
Supplying services–regulating services	0.536***	0.559***	0.521***
Supplying services–cultural services	0.528***	0.547***	0.506***
Supplying services–supporting services	0.628***	0.619***	0.559***
Regulating services–cultural services	0.526***	0.563***	0.494***
Regulating services–supporting services	0.551***	0.571***	0.524***
Cultural services–supporting services	0.550***	0.563***	0.515***

The study uses the queen's contiguity weight matrix. ***$p \leq 0.0001$

Qinghai, the Bohai Rim Economic Zone, the Yangtze River Delta urban agglomeration, and northern Taiwan during 2010–2015 (Fig. 7). A few statistically significant high-low clusters and low–high clusters were distributed randomly across China during those periods.

Discussion

Interpretation of findings

Based on the newly revised benefit transfer method, we performed an empirical study of ESV re-evaluation in China during 2000–2015. Generally, we found that supply capacity of ESs in China increased during 2000–2015, with a decrease during 2000–2005 and a continual increase in the following periods. Since the 21th century, China has adopted a series of ecological protection policies with effective outcomes (Li et al. 2016a, b). For example, China's forest coverage rate increased from 16.55% in 2000 to 21.66% in 2015 due to national ecological programs. Hotspot analysis results showed that obvious cold spots of ESs can be found in southeast coastal regions of China, which is consistent with the findings of Li et al. (2016a, b). The expansion of construction land in the southeast coastal regions may be the dominant reason for the degradation of ESs in rapid urbanization. And we also found significant hot spots on the Loess Plateau; we believe that this is primarily due to the widely implemented Grain for Green Program in those areas (Li et al. 2016a, b). Finally, the trade-offs and synergies between ESs were analyzed using bivariate spatial autocorrelation model, we found that synergic relationships were the dominant relationship between ESs, with only a small proportion of units exhibiting trade-offs relationship. We can find significant spatial heterogeneity of ESs trade-offs and synergies. This is mainly due to the unbalanced natural background factors and socioeconomic factors in China, which leads to the significant spatial differences of ESs in different places (Li et al. 2018a, b).

Comparison with ESV changes found in other studies

County-level ESV assessment was conducted in only a small number of previous studies, and most of them were conducted with the benefit transfer method (Table 3). To

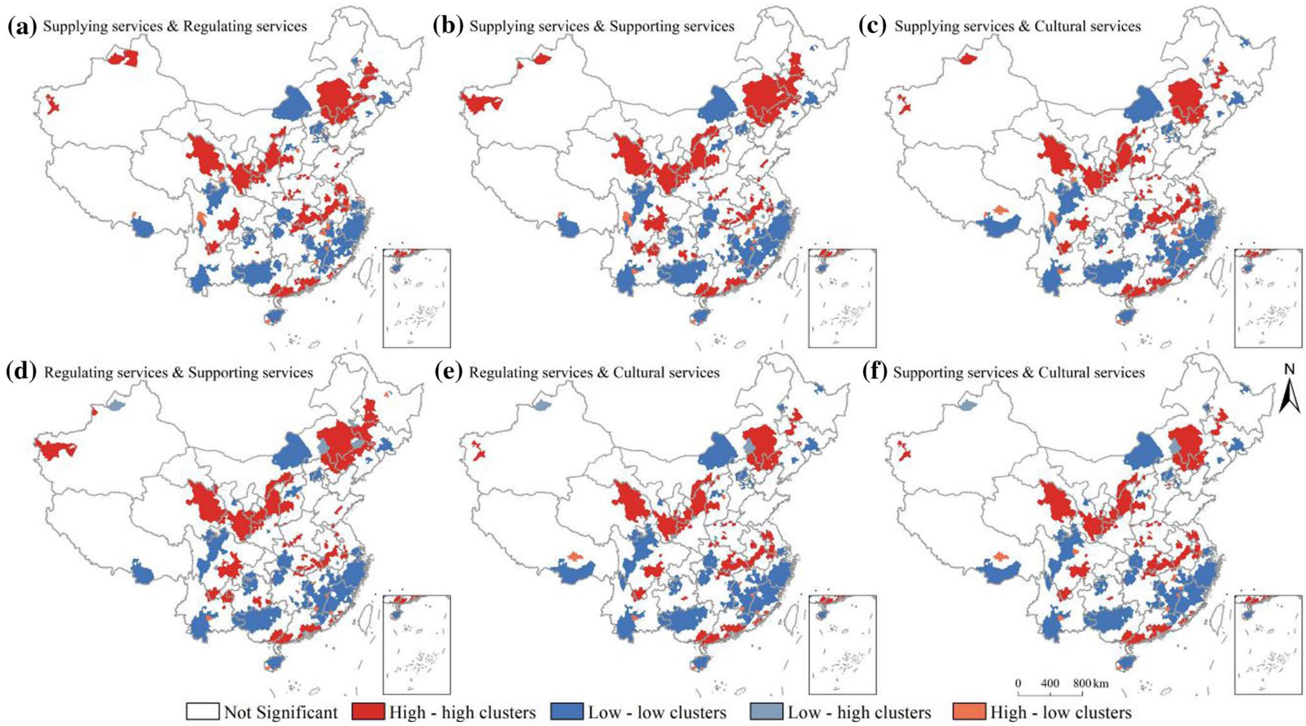

Fig. 5 LISA cluster map between two typical ESs in China during 2000–2005

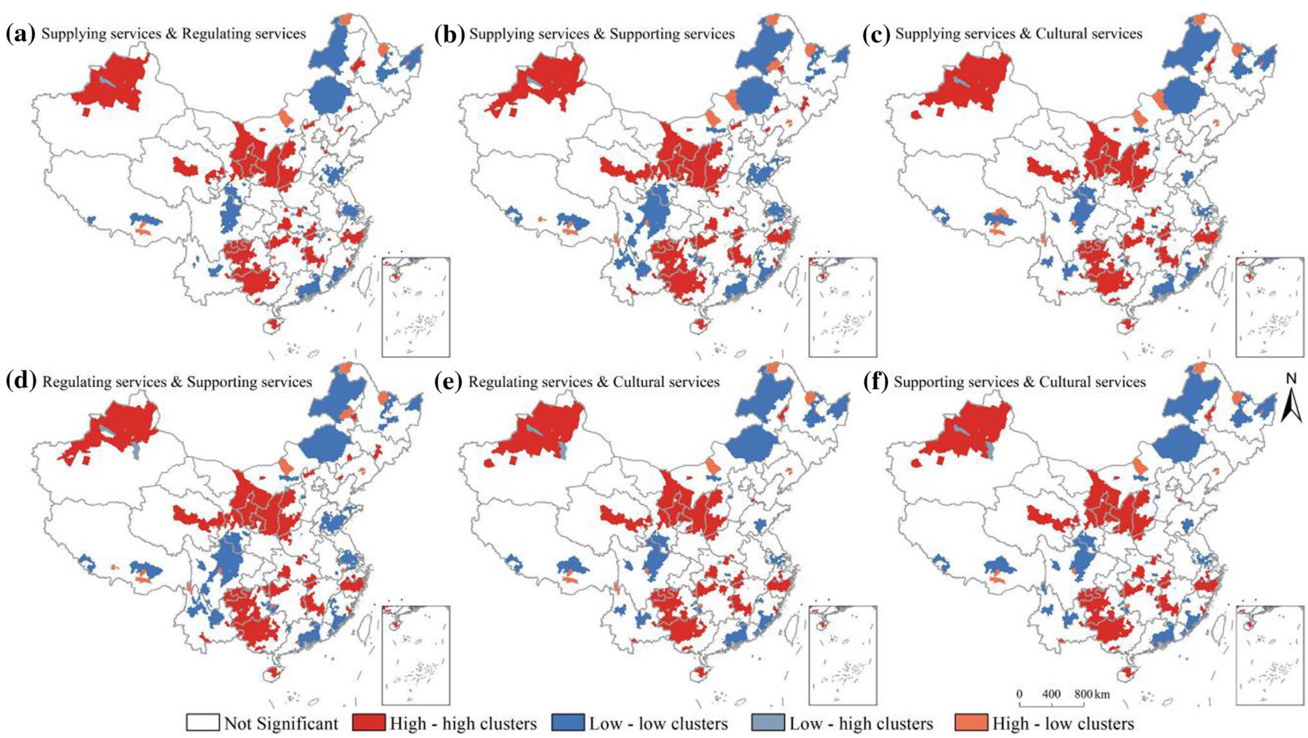

Fig. 6 LISA cluster map between two typical ESs in China during 2005–2010

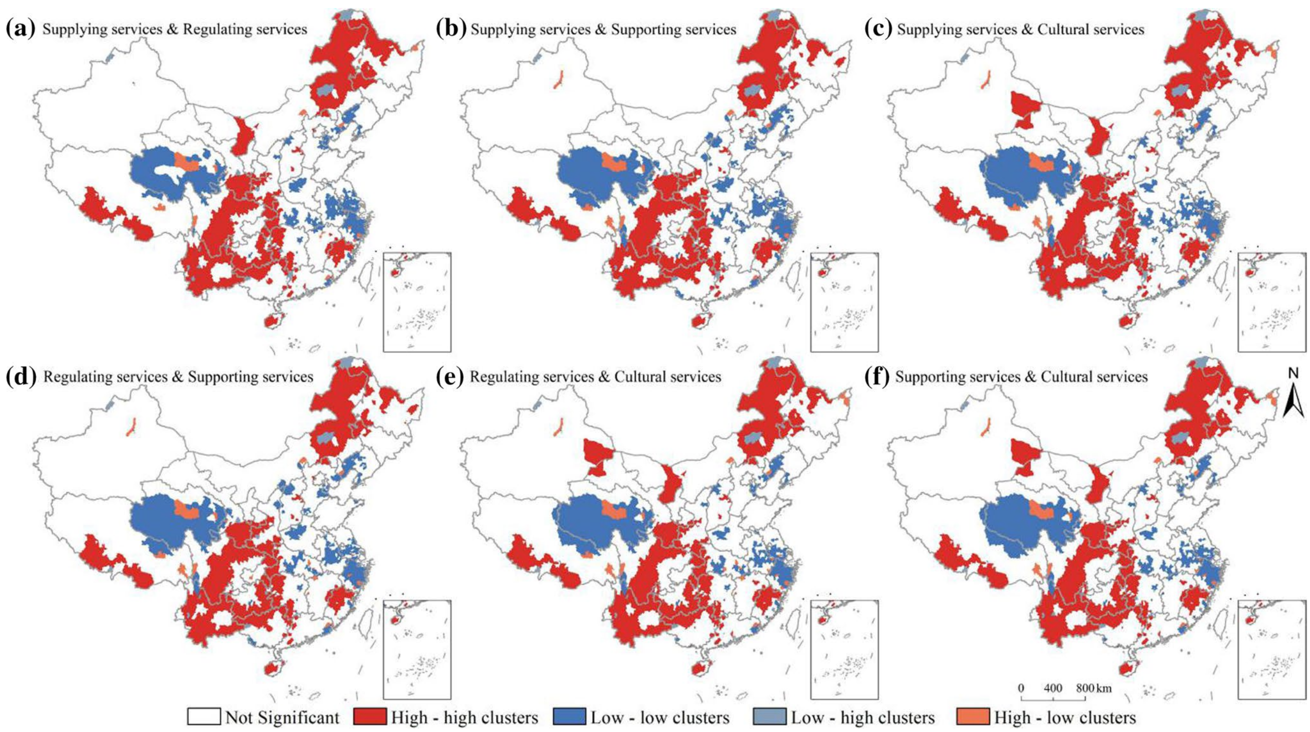

Fig. 7 LISA cluster map between two typical ESs in China during 2010–2015

compare our results with the results in other studies, we summarized the results of ESV evaluation in China. The results of Xie et al. (2017) were the highest ($5630 billion US$), followed by the results of Ouyang et al. (1999) ($4894.99 billion US$ in 2010), Xing et al. (2021) ($4675.36 billion US$ in 2015), and Li et al. (2016a, b) ($2347.56 billion US$ in 2010). The lowest result was from Bi and Ge (2004) ($529.95 billion US$ in 2000). In addition, Li et al. (2016a, b) and Song et al. (2017) found that ESVs in China continue to deteriorate. Conversely, the ESV results in our study exhibited an overall increasing trend in ESVs from 2000 to 2015. The results in our study are consistent with those of Chen et al. (2019a, b) and Xing et al. (2021). Recent MODIS satellite data clearly show that the vegetation leaf area index increased in China from 2000 to 2017 (Chen et al. 2019a, b). Moreover, Ouyang et al. (2016) found that food production, carbon sequestration, soil retention, sandstorm prevention, water retention, and the flood mitigation capacity of ecosystems in China increased, with a decrease only in the provision of habitat for biodiversity in China during 2000–2010. Xie et al. (2015) argue that the main reasons for the different results of ESVs in China include different agricultural product prices, different ESVs per-unit area, and increased awareness of the value of ESs. Over time, commodity prices increased significantly, which created an increase in ESVs. In addition, the ESV equivalent table based on expert knowledge is subjective; therefore, using both expert knowledge and physical features in ESV can provide a more accurate assessment. The value of the various services provided by ecosystems is receiving increasing attention, which also greatly improves ESVs. However, it is undeniable that rapid urbanization in China has also severely damaged the provision capacity of ESs.

In this study, we adopted the improved benefit transfer method to measure the value of ESs in China. Unlike the previous studies that used the biomass of the whole unit, we used the biomass of farmland to correct the value of ESs. The results of our study show that the overall value of ESs in China improved during the study period. To compare the differences with the previous studies, we also used the biomass of the whole unit to correct ESVs in China in this study. The results show that from 2000 to 2015, ESVs were $715.61 billion, $704.69 billion, $703.35 billion, and $714.06 billion. We also found that ESs in China decreased during the study period.

Scale effect of ES trade-offs and synergies

We found significant synergistic relationships among supplying services, regulating, supporting, and cultural services at the national scale. At the local scale, trade-off relationships still exist. Trade-off and synergistic relationships between ESs were significantly different at different scales (Hein et al. 2006). For example, Fu (2010) found that supplying

Table 3 Comparisons of ESVs estimated in other studies (billion US$)

Sources	1988	1990	1994	1995	1999	2000	2005	2008	2010	2015	Methods and data sources
Xing et al. (2021)										4675.36	Benefit transfer method with adjustment factors of NPP, precipitation, habitat quality, soil erosion level, and landscape
Xie et al. (2017)									5630		Modifying equivalent factor with net primary productivity, precipitation, and erosion prevention. ESV was calculated with Costanza's ESV assessment method
Li et al. (2016a, b)		2398.31		2380.88		2377.21	2356.95		2347.56		Equivalent factor was sourced from a number of databases. ESV was calculated with Costanza's ESV assessment method
Song et al. (2017)	760.34					756.95		756.15			Equivalent factor from Xie et al. (2008). ESV was calculated with Costanza's ESV assessment method
Song et al. (2017)	1001.02					992.19		909.92			Equivalent factor from 1997 unit values in Costanza et al. (2014). ESV was calculated with Costanza's ESV assessment method
Song et al. (2017)	625.03					619.60		617.41			Equivalent factor from 2011 unit values in Costanza et al. (2014). ESV was calculated with Costanza's ESV assessment method
Cai et al. (2014)									718.08		Equivalent factor from Bi and Ge (2004). ESV was calculated with Costanza's ESV assessment method
Chen and Zhang, (2000)			1013.47								Equivalent factor from Costanza (1997). ESV was calculated with Costanza's ESV assessment method
Bi and Ge, (2004)						529.95					Equivalent factor from Costanza (1997). ESV was calculated with Costanza's ESV assessment method
Shi et al. (2012)					888.02			855.47			Equivalent factor was sourced from a number of databases. ESV was calculated with Costanza's ESV assessment method and was revised by NDVI data
Ouyang et al. (1999)					4894.99						Indirect economic values were estimated based on ecological function analysis
He et al. (2005)						1194.01					Indirect economic values were estimated based on ecological function analysis
This study						723.88	717.43		718.93	727.65	Revised by NDVI of farmland

Xing et al. (2021), Li et al. (2016a, b), Shi et al. (2012), Song and Deng (2017), Xie et al. (2017), Bi and Ge (2004), Cai et al. (2014), Chen and Zhang (2000), He et al. (2005), Ouyang et al. (1999)

and regulating services are mutually inhibiting factors in a trade-off relationship. To protect the ecosystem, a number of land-use policies were implemented in China, such as the Grain for Green and Grain for Blue policies (Song et al. 2015). These policies improved the provision capacity of the ecosystem, but led to decreases in food production (Fu et al. 2015). Li et al. (2012) believe that synergistic effects can be found in all four ESs, but that mutual enhancement among regulating, supporting, and cultural services was more common (Li et al. 2012). Li et al. (2016a, b) found a trade-off between ecosystem regulating and supplying services in the Guanzhong–Tianshui Economic Zone in China (Li et al. 2016a, b); Yu et al. (2020) found that ESs trade-offs and synergies changed significantly at different scales in Qinba Mountains, and the reasons for these changes include climate, vegetation, and geomorphic features. In addition, the synergies and trade-offs relationships of ESs did not stay the same; rather, they may change in different periods of time (Rodriguez et al. 2006; Yu et al. 2020). For example, Liu et al. (2018a, b) found that the trade-off relationships between ESs such as environmental purification, hydrological regulation, and water resource supply increased after 2005 in the Danjiangkou area in China, while the units of trade-offs among other ESs decreased after 2005 (Liu et al. 2018a, b). Zhang et al. (2020) found significant differences in the trade-offs and synergies between forest ESs on different slopes and altitudinal zones in the Funiu Mountains in China (Zhang et al. 2020).

Many researchers have examined the trade-offs and synergies of ESs at the national, regional, and watershed scales (Asadolahi et al. 2018; Haines-Young et al. 2012; Hu et al. 2018; Obiang Ndong et al. 2020). Previous studies have found differences in trade-offs and synergies between the same pair of ESs at different research scales or in different regions (Accatino et al. 2019; Gong et al. 2019; Li et al. 2018a, b; Obiang Ndong et al. 2020; Wang and Dai 2020). Studies have shown that water conservation, carbon fixation, and oxygen release are mainly synergistic at large spatial scales (Jopke et al. 2015), while they are trade-offs at small and medium scales (Qiao et al. 2019; Wang and Dai 2020). This is due mainly to the significant difference in the demand for ESs and the supply capacity of ESs at different scales and the significant mismatch in the spatial characteristics of ESs (Onaindia et al. 2013; Turner et al. 2014; Peng et al. 2017). In addition, various stakeholders and interest groups place their emphases at different spatial scales and place different emphases on the products and services provided by different ecosystems. For example, regulating services are given more attention in large-scale ecosystems, while supplying services are given more attention in smaller scale ecosystems (Fu et al. 2011). Likewise, flood control and disaster reduction, supply of agricultural products, and wood production and water conservation are important at the regional scale, while urban environment, biodiversity conservation, climate regulation, carbon sequestration, and oxygen release are important primarily at the global scale (Li et al. 2012). This division inevitably leads to the varying emphases of different stakeholders on different types of ESs and trade-offs among management strategies (Deng et al. 2016; Peng et al. 2017; Zhang et al. 2020; Zheng et al. 2019).

Policy implications

The ESs' assessment that we conducted in this study shows that the supply capacity of China's ESs improved from 2000 to 2015, indicating that China's land-use policies and ecological engineering projects have played a positive role in the improvement of ESs (Chen et al. 2019a, b). Most notably on the Loess Plateau, we found a significant synergistic relationship between various ESs, indicating a substantial improvement of their ecosystem (Deng et al. 2019; Jiang et al. 2018). The spatial difference of the land-use modes may lead to differences in the provision capacity of ESs, which in turn may lead to the spatial heterogeneity of ESs trade-offs and synergies. Therefore, we believe that ESs can best be managed by zoning based on the actual ecological functions of different regions. Zoning management is an effective means to improve the supply capacity of ESs and construct a pattern of national ecological security based on the actual ecological function of different regions and to delimit and strictly observe the "red line" of ecological protection. In fact, China has set forth several policies to determine ecological function goals such as water and soil conservation, biodiversity maintenance, wind prevention, and sand fixation, as well as to protect sensitive and fragile ecological environment areas from soil erosion, land desertification, rocky desertification, and salinization. These ESs management policies also identify the spatial distribution of important ecological function areas and sensitive and fragile ecological environment areas (Hu et al. 2020; CPC and SC 2017). We recommend that the major ecological improvement programs should continue to be carried out in order to protect virgin forests, return farmland to forestlands and grasslands, prevent and control desertification and shelterbelts in the three Northern regions of China, and launch major projects to protect and restore the territorial ecosystem.

Because of regional differences in ESs relationships and the fact that different services have different trade-offs and synergies in various research regions, studying the trade-offs and synergies between ESs cannot be confined to a single scale. The actual needs of stakeholders at different spatiotemporal scales should be considered comprehensively (Onaindia et al. 2013; Turner et al. 2014). Clarifying the trade-off and synergistic relationships among various services, as well as the characteristics of scale dependence and spatial differences, is a prerequisite for the formulation of effective ESs' management policies (Qiao et al. 2019; Yu et al. 2020; Zhang et al.

2020). It is especially challenging in the process of ecosystem management to avoid ESs trade-offs as much as possible and to strengthen ESs' synergies. At different scales, ESs for stakeholders vary greatly. ESs supply capacity in different scales, different cultural background, different effects on the economic activity, and the utilization of ESs differs significantly in ways and degrees (Hein et al. 2006). Therefore, fully understanding the relationship of ESs at different scales would contribute to solving the conflicts between different interest groups (Li et al. 2012).

Limitations and future directions

This study has several limitations and future research directions that are worth noting. First, the ESV assessment in this study considered only the biomass of farmland. However, other factors (e.g., precipitation, erosion prevention, the Consumer Price Index accumulation coefficient, and the marginal value coefficient) also have important influence in localizing equivalent values (Li et al. 2017; Xie et al. 2017). We argue that additional factors should be taken into consideration in modifying the benefit transfer method in future research. Second, the synergy and trade-off relationships among the four ESs (supplying, regulating, supporting, and cultural services) were identified at the national scale for the years 2000–2005, 2005–2010, and 2010–2015 using bivariate spatial autocorrelation analysis. The correlation analysis method can directly reveal the numerical relationship of ESs trade-offs and synergies. The bivariate spatial autocorrelation model can capture the spatial relationship of trade-offs and synergies of ESs, but the model cannot fully reflect the internal mechanism of ESs evolution. Further exploration and in-depth analysis are needed by means of other methods. Third, when examining the synergy and trade-off relationships among these four ESs, it is difficult to identify the relationship between specific ESs, such as the synergy and trade-off relationships between food production services and soil conservation services. A future study may choose specific ESs for targeted specific ecological issues at the national scale. Fourth, the trade-off relationship of ESs varies greatly over time and space because of the existing scale effects of ESs. The trade-off relationship between a specific pair of ESs in different regions and at different research scales would not be consistent. Future research should comprehensively explore ESs at multiple scales to systematically understand the internal mechanism of the formation of trade-off relationships.

Conclusion

In this study, we revised the benefit transfer method based on the biomass on farmland and conducted an empirical analysis of ESV assessment in China. From the results of the evaluation, we found an overall increase in ESVs with fluctuations from 2000 to 2015, providing strong evidence that land-use activities in China improved ESVs. Our hotspot analysis revealed that ESVs in the southern and southeastern regions China have severely deteriorated and the national ecological programs have obvious effect in protecting ecosystems from degradation. Both the correlation analysis and global spatial autocorrelation showed that a synergistic relationship existed among the ESs in China during the periods of 2000–2005, 2005–2010, and 2010–2015. The spatial distribution of synergies and trade-offs among the four ESs exhibited a similar clustering pattern during each period. We found that the high–high clusters and low–low clusters representing a synergistic relationship were the dominant relationship types, while the high–low types and low–high types representing a trade-off relationship were scattered throughout the country. Our study provides important implications for understanding the trade-offs and synergies of ESs in China and for conducting ESV assessment in other regions.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Accatino F, Tonda A, Dross C, Léger F, Tichit M (2019) Trade-offs and synergies between livestock production and other ecosystem services. Agr Syst 168:58–72

Anselin L (1995) Local indicators of spatial association-LISA. Geogr Anal 2:93–115

Anselin L, Rey SJ (2014) Modern spatial econometrics in practice: a guide to GeoDa. GeoDa Press LLC, GeoDaSpace and PySAL

Asadolahi Z, Salmanmahiny A, Sakieh Y, Mirkarimi SH, Baral H, Azimi M (2018) Dynamic trade-off analysis of multiple ecosystem services under land use change scenarios: Towards putting ecosystem services into planning in Iran. Ecol Complex 36:250–260

Bai X, Shi P, Liu Y (2014) Realizing China's urban dream. Nature 509:158–160

Bi X, Ge J (2004) Evaluating ecosystem service valuation in China based on the IGBP land cover datasets. Mount Res 1:48–53

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett 12:1394–1404

Bradford JB, D'Amato AW (2012) Recognizing trade-offs in multi-objective land management. Front Ecol Environ 10:210–216

Bryan BA, Gao L, Ye Y, Sun X, Connor JD, Crossman ND, Stafford-Smith M, Wu J, He C, Yu D, Liu Z, Li A, Huang Q, Ren H,

Deng X, Zheng H, Niu J, Han G, Hou X (2018) China's response to a national land-system sustainability emergency. Nature 559:193–204
Cai Z, Wang Q, Liu G (2014) Value re-evaluation for ecosystem services of China. Ecol Econ 30:16–18
Cao S, Suo X, Xia C, Yu Z, Feng F (2020) Net value of forest ecosystem services in China. Ecol Eng 142:105645
Cetin M (2019) The effect of urban planning on urban formations determining bioclimatic comfort area's effect using satellitia imagines on air quality: a case study of Bursa city. Air Qual Atmos Health 12:1237–1249
Cetin M (2020) Climate comfort depending on different altitudes and land use in the urban areas in Kahramanmaras City. Air Qual Atmos Health 13:991–999
Cetin M, Adiguzel F, Gungor S, Kaya E, Sancar MC (2019) Evaluation of thermal climatic region areas in terms of building density in urban management and planning for Burdur, Turkey. Air Qual Atmos Health 12:1103–1112
Cetin M, Agacsapan B, Cabuk SNS, Kurkcuoglu MA, Isik Pekkan O, Baran Argun E, Dabanlı AK, Tuncay Yilmazel B, Cabuk A (2021) Assessment of the ecological footprint of Eskisehir Technical University-Iki Eylul Campus. J Indian Soc Remote Sens 49:2311–2327
Chen Z, Zhang X (2000) The value of ecosystem services in China. Chin Sci Bull 45:17–22
Chen C, Park T, Wang X, Piao S, Xu B, Chaturvedi RK, Fuchs R, Brovkin V, Ciais P, Fensholt R, Tømmervik H, Bala G, Zhu Z, Nemani RR, Myneni RB (2019a) China and India lead in greening of the world through land-use management. Nat Sustainability 2:122–129
Chen W, Chi G, Li J (2019b) The spatial association of ecosystem services with land use and land cover change at the county level in China, 1995–2015. Sci Total Environ 669:459–470
Chen W, Zhao H, Li J, Zhu L, Wang Z, Zeng J (2020) Land use transitions and the associated impacts on ecosystem services in the Middle Reaches of the Yangtze River Economic Belt in China based on the geo-informatic Tupu method. Sci Total Environ 701:134690
Chi GQ, Ho HC (2018) Population stress: a spatiotemporal analysis of population change and land development at the county level in the contiguous United States, 2001–2011. Land Use Policy 70:128–137
Cord AF, Bartkowski B, Beckmann M, Dittrich A, Hermans-Neumann K, Kaim A, Lienhoop N, Locher-Krause K, Priess J, Schröter-Schlaack C, Schwarz N, Seppelt R, Strauch M, Václavík T, Volk M (2017) Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. Ecosyst Serv 28:264–272
Costanza R, DArge R, DeGroot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, ONeill RV, Paruelo J, Raskin RG, Sutton P, VandenBelt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253–260
Costanza R, de Groot R, Sutton P, van der Ploeg S, Anderson SJ, Kubiszewski I, Farber S, Turner RK (2014) Changes in the global value of ecosystem services. Global Environ Chang 26:152–158
CPC and SC, (General Office of the CPC Central Committee and the State Council issued the Opinions), Several Opinions on Delimiting and Strictly Observing the Red Line for Ecological Protection, http://cpc.people.com.cn/n1/2017/0208/c64094-29064687.html
Daily GC (1997) Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC, U.S.A
De Groot R, Brander L, van der Ploeg S, Costanza R, Bernard F, Braat L, Christie M, Crossman N, Ghermandi A, Hein L, Hussain S, Kumar P, McVittie A, Portela R, Rodriguez LC, Ten Brink P, van Beukering P (2012) Global estimates of the value of ecosystems and their services in monetary units. Ecosyst Serv 1:50–61
Deng L, Kim D, Li M, Huang C, Liu Q, Cheng M, Shangguan Z, Peng C (2019) Land-use changes driven by 'Grain for Green' program reduced carbon loss induced by soil erosion on the Loess Plateau of China. Global Planet Change 177:101–115
Deng X, Li Z, John G (2016) A review on trade-off analysis of ecosystem services for sustainable land-use management. J Geogr Sci 26:953–968
Felipe-Lucia MR, Soliveres S, Penone C, Manning P, van der Plas F, Boch S, Prati D, Ammer C, Schall P, Gossner MM, Bauhus J, Buscot F, Blaser S, Blüthgen N, de Frutos A, Ehbrecht M, Frank K, Goldmann K, Hänsel F, Jung K, Kahl T, Nauss T, Oelmann Y, Pena R, Polle A, Renner S, Schloter M, Schöning I, Schrumpf M, Schulze E, Solly E, Sorkau E, Stempfhuber B, Tschapka M, Weisser WW, Wubet T, Fischer M, Allan E (2018) Multiple forest attributes underpin the supply of multiple ecosystem services. Nat Commun 9:4839
Fei L, Shuwen Z, Jiuchun Y, Liping C, Haijuan Y, Kun B (2018) Effects of land use change on ecosystem services value in West Jilin since the reform and opening of China. Ecosyst Serv 31:12–20
Fu B (2010) Trends and priority areas in ecosystem research of China. Geogr Res 3:383–396
Fu B, Su C, Wei Y, Willett IR, Lü Y, Liu G (2011) Double counting in ecosystem services valuation: causes and countermeasures. Ecol Res 26:1–14
Fu B, Zhang L, Xu Z, Zhao Y, Wei Y, Skinner D (2015) Ecosystem services in changing land use. J Soil Sediment 15:833–843
Gissi E, Gaglio M, Aschonitis VG, Fano EA, Reho M (2018) Soil-related ecosystem services trade-off analysis for sustainable biodiesel production. Biomass Bioenerg 114:83–99
Gong J, Liu D, Zhang J, Xie Y, Cao E, Li H (2019) Trade-offs/synergies of multiple ecosystem services based on land use simulation in a mountain-basin area, western China. Ecol Indic 99:283–293
Haase D, Schwarz N, Strohbach M, Kroll F, Seppelt R (2012) Synergies, Trade-offs, and Losses of Ecosystem Services in Urban Regions: an Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany. Ecol Soc 17:22
Haines-Young R, Potschin M, Kienast F (2012) Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. Ecol Indic 21:39–53
Hasan SS, Zhen L, Miah MG, Ahamed T, Samie A (2020) Impact of land use change on ecosystem services: a review. Environ Dev 34:100527
Hatton MacDonald D, Bark RH, Coggan A (2014) Is ecosystem service research used by decision-makers? A case study of the Murray-Darling Basin, Australia. Landscape Ecol 29:1447–1460
He J, Shi X, Fu Y, Yuan Y (2005) Measurement of terrestrial ecosystem service value in China. Chin J Appl Ecol 6:1122–1127
Hein L, van Koppen K, de Groot RS, van Ierland EC (2006) Spatial scales, stakeholders and the valuation of ecosystem services. Ecol Econ 57:209–228
Himes A, Puettmann K, Muraca B (2020) Trade-offs between ecosystem services along gradients of tree species diversity and values. Ecosyst Serv 44:101133
Hou Y, Li B, Müller F, Fu Q, Chen W (2018) A conservation decision-making framework based on ecosystem service hotspot and interaction analyses on multiple scales. Sci Total Environ 643:277–291
Hu Y, Peng J, Liu Y, Tian L (2018) Integrating ecosystem services trade-offs with paddy land-to-dry land decisions: a scenario approach in Erhai Lake Basin, southwest China. Sci Total Environ 625:849–860
Hu T, Peng J, Liu Y, Wu J, Li W, Zhou B (2020) Evidence of green space sparing to ecosystem service improvement in urban

regions: a case study of China's Ecological Red Line policy. J Clean Prod 251:119678
Jiang C, Zhang H, Zhang Z (2018) Spatially explicit assessment of ecosystem services in China's Loess Plateau: patterns, interactions, drivers, and implications. Global Planet Change 161:41–52
Jopke C, Kreyling J, Maes J, Koellner T (2015) Interactions among ecosystem services across Europe: Bagplots and cumulative correlation coefficients reveal synergies, trade-offs, and regional patterns. Ecol Indic 49:46–52
Li G, Fang C, Wang S (2016a) Exploring spatiotemporal changes in ecosystem-service values and hotspots in China. Sci Total Environ 545–546:609–620
Li B, Chen N, Wang Y, Wang W (2018a) Spatio-temporal quantification of the trade-offs and synergies among ecosystem services based on grid-cells: a case study of Guanzhong Basin, NW China. Ecol Indic 94:246–253
Li G, Sun S, Fang C (2018b) The varying driving forces of urban expansion in China: Insights from a spatial-temporal analysis. Landscape Urban Plan 174:63–77
Li J, Li H, Zhang L (2016b) Ecosystem service trade-offs in the Guanzhong-Tianshui economic region of China. Acta Ecol Sin 36:3053–3062
Li P, Jiang Lu, Feng Z, Yu X (2012) Research progress on trade-offs and synergies of ecosystem services: an overview. Acta Ecol Sin 32:5219–5229
Li Y, Zhan J, Liu Y, Zhang F, Zhang M (2017) Response of ecosystem services to land use and cover change: a case study in Chengdu City. Resour Conserv Recy 132:291–300
Lin S, Wu R, Yang F, Wang J, Wu W (2018) Spatial trade-offs and synergies among ecosystem services within a global biodiversity hotspot. Ecol Indic 84:371–381
Liu C, Xu Y, Huang A, Liu Y, Wang H, Lu L, Sun P, Zheng W (2018a) Spatial identification of land use multifunctionality at grid scale in farming-pastoral area: a case study of Zhangjiakou City, China. Habitat Int 76:48–61
Liu H, Wu J, Chen X (2018b) Study on spatial-temporal change andtrade-off/synergy relationships of ecosystem services in the Danjiangkou water source area. Acta Ecol Sin 38:4609–4624
Liu J, Kuang W, Zhang Z, Xu X, Qin Y, Ning J, Zhou W, Zhang S, Li R, Yan C, Wu S, Shi X, Jiang N, Yu D, Pan X, Chi W (2014) Spatiotemporal characteristics, patterns, and causes of land-use changes in China since the late 1980s. J Geogr Sci 24:195–210
Ma FJ, Eneji AE, Liu JT (2015) Assessment of ecosystem services and dis-services of an agro-ecosystem based on extended emergy framework: a case study of Luancheng county, North China. Ecol Eng 82:241–251
Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being. Island Press, Washington, DC
Naidoo R, Balmford A, Costanza R, Fisher B, Green RE, Lehner B, Malcolm TR, Ricketts TH (2008) Global mapping of ecosystem services and conservation priorities. PNAS 105:9495–9500
National Bureau of Statistics of China (NBSC) (2021) China Statistical Yearbook 2021. China Statistical Publishing House, Beijing
Ning J, Liu J, Kuang W, Xu X, Zhang S, Yan C, Li R, Wu S, Hu Y, Du G, Chi W, Pan T, Ning J (2018) Spatio-temporal patterns and characteristics of land-use change in China during 2010–2015. J Geogr Sci 28:547–562
Obiang Ndong G, Villerd J, Cousin I, Therond O (2020) Using a multivariate regression tree to analyze trade-offs between ecosystem services: application to the main cropping area in France. Sci Total Environ 764:142815
Onaindia M, Fernández De Manuel B, Madariaga I, Rodríguez-Loinaz G (2013) Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. Forest Ecol Manag 289:1–9
Ouyang Z, Wang X, Miao H (1999) A primary study on Chinese terrestrial ecosystem services and their ecological-economic values. Acta Ecol Sin 19:19–25
Ouyang Z, Zheng H, Xiao Y, Polasky S, Liu J, Xu W, Wang Q, Zhang L, Xiao Y, Rao E, Jiang L, Lu F, Wang X, Yang G, Gong S, Wu B, Zeng Y, Yang W, Daily GC (2016) Improvements in ecosystem services from investments in natural capital. Science 352:1455–1459
Peng J, Hu X, Zhao M, Liu Y, Tian Lu (2017) Research progress on ecosystem service trade-offs: from cognition to decision-making. Acta Geogr Sin 72:960–973
Pergams OR, Zaradic PA (2008) Evidence for a fundamental and pervasive shift away from nature-based recreation. Proc Natl Acad Sci USA 105:2295–2300
Plummer ML (2009) Assessing benefit transfer for the valuation of ecosystem services. Ecosyst Serv 7:38–45
Qian C, Gong J, Zhang J, Liu D, Ma X (2018) Change and trade-offs synergies analysis on watershed ecosystem services: a case study of Bailongjiang Watershed, Gansu. 2018. Acta Geogr Sin 73:868–879
Qiao X, Gu Y, Zou C, Xu D, Wang L, Ye X, Yang Y, Huang X (2019) Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China. Sci Total Environ 651:218–229
Qiu J, Turner MG (2013) Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proc Natl Acad Sci USA 110:12149–12154
Rodríguez JP, Beard TD Jr, Bennett EM, Cumming GS, Cork SJ, Agard J, Dobson AP, Peterson GD (2006) Trade-offs across space, time, and ecosystem services. Ecol Soc 11:28
Shen J, Li S, Liang Z, Liu L, Li D, Wu S (2020) Exploring the heterogeneity and nonlinearity of trade-offs and synergies among ecosystem services bundles in the Beijing-Tianjin-Hebei urban agglomeration. Ecosyst Serv 43:101103
Shi Y, Wang R, Huang J, Yang W (2012) An analysis of the spatial and temporal changes in Chinese terrestrial ecosystem service functions. Chinese Sci Bull 57:2120–2131
Shoemaker DA, BenDor TK, Meentemeyer RK (2019) Anticipating trade-offs between urban patterns and ecosystem service production: scenario analyses of sprawl alternatives for a rapidly urbanizing region. Comput Environ Urban 74:114–125
Sil Â, Rodrigues AP, Carvalho-Santos C, Nunes JP, Honrado J, Alonso J, Marta-Pedroso C, Azevedo JC (2016) Trade-offs and synergies between provisioning and regulating ecosystem services in a mountain Area in Portugal affected by landscape change. Mt Res Dev 36:452–464
Song W, Deng X (2017) Land-use/land-cover change and ecosystem service provision in China. Sci Total Environ 576:705–719
Song W, Deng X, Liu B, Li Z, Jin G (2015) Impacts of Grain-for-Green and Grain-for-Blue policies on valued ecosystem services in Shandong Province, China. Adv Meteorol 2015:1–10
Stosch KC, Quilliam RS, Bunnefeld N, Oliver DM (2019) Quantifying stakeholder understanding of an ecosystem service trade-off. Sci Total Environ 651:2524–2534
Su C, Fu B (2013) Evolution of ecosystem services in the Chinese Loess Plateau under climatic and land use changes. Global Planet Change 101:119–128
Sun X, Li F (2017) Spatio-temporal assessment and trade-offs of multiple ecosystem services based on land use changes in Zengcheng, China. Sci Total Environ 609:1569–1581
Timilsina N, Escobedo FJ, Cropper WP, Abd-Elrahman A, Brandeis TJ, Delphin S, Lambert S (2013) A framework for identifying carbon hotspots and forest management drivers. J Environ Manage 114:293–302

Troy A, Wilson MA (2006) Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. Ecol Econ 60:435–449

Turkelboom F, Leone M, Jacobs S, Kelemen E, García-Llorente M, Baró F, Termansen M, Barton DN, Berry P, Stange E, Thoonen M, Kalóczkai Á, Vadineanu A, Castro AJ, Czúcz B, Röckmann C, Wurbs D, Odee D, Preda E, Gómez-Baggethun E, Rusch GM, Pastur GM, Palomo I, Dick J, Casaer J, van Dijk J, Priess JA, Langemeyer J, Mustajoki J, Kopperoinen L, Baptist MJ, Peri PL, Mukhopadhyay R, Aszalós R, Roy SB, Luque S, Rusch V (2018) When we cannot have it all: Ecosystem services trade-offs in the context of spatial planning. Ecosyst Serv 29:566–578

Turner KG, Odgaard MV, Bøcher PK, Dalgaard T, Svenning J (2014) Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. Landscape Urban Plan 125:89–104

Wang J, Zhou W, Pickett STA, Yu W, Li W (2019) A multiscale analysis of urbanization effects on ecosystem services supply in an urban megaregion. Sci Total Environ 662:824–833

Wang Y, Dai E (2020) Spatial-temporal changes in ecosystem services and the trade-off relationship in mountain regions: a case study of Hengduan Mountain region in Southwest China. J Clean Prod 264:121573

Wang Y, Dai E, Yin L, Ma L (2018) Land use/land cover change and the effects on ecosystem services in the Hengduan Mountain region, China. Ecosyst Serv 34:55–67

Wu J (2013) Landscape sustainability science: ecosystem services and human well-being in changing landscapes. Landscape Ecol 28:999–1023

Xie GD, Zhang CX, Zhang LM, Chen WH, Li SM (2015) Improvement of the evaluation method for ecosystem service value based on per unit area. J Nat Res 30(8):1243–1254

Xie GD, Zhang C, Zhen L, Zhang L (2017) Dynamic changes in the value of China's ecosystem services. Ecosyst Serv 26:146–154

Xie GD, Zhen L, Lu CX, Xiao Y, Chen C (2008) Expert knowledge based valuation method of ecosystem services in China. J Nat Res 23:911–919

Xing L, Xue M, Wang X (2018) Spatial correction of ecosystem service value and the evaluation of eco-efficiency: a case for China's provincial level. Ecol Indic 95:841–850

Xing L, Zhu Y, Wang J (2021) Spatial spillover effects of urbanization on ecosystem services value in Chinese cities. Ecol Indic 121:107028

Xu D, Ding X (2018) Assessing the impact of desertification dynamics on regional ecosystem service value in North China from 1981 to 2010. Ecosyst Serv 30:172–180

Xu X, Yang G, Tan Y, Liu J, Hu H (2018) Ecosystem services trade-offs and determinants in China's Yangtze River Economic Belt from 2000 to 2015. Sci Total Environ 634:1601–1614

Yang S, Zhao W, Liu Y, Wang S, Wang J, Zhai R (2018) Influence of land use change on the ecosystem service trade-offs in the ecological restoration area: dynamics and scenarios in the Yanhe watershed, China. Sci Total Environ 644:556–566

Yang X, Zhou Z, Li J, Fu X, Mu X, Li T (2016) Trade-offs between carbon sequestration, soil retention and water yield in the Guanzhong Tianshui Economic Region of China. J Geogr Sci 26:1449–1462

Yi H, Güneralp B, Filippi AM, Kreuter UP, Güneralp İ (2017) Impacts of land change on ecosystem services in the San Antonio River Basin, Texas, from 1984 to 2010. Ecol Econ 135:125–135

Yu Y, Huang Y, Zhang W (2012) Modeling soil organic carbon change in croplands of China, 1980–2009. Global Planet Change 82–83:115–128

Yu Y, Li J, Zhou Z, Ma X, Zhang C (2020) Multi-scale representation of trade-offs and synergistic relationship among ecosystem services in Qinling-Daba Mountains. Acta Ecol Sin 40:5465–5477

Zhang G, Zheng D, Xie L, Zhang X, Wu H, Li S (2021) Mapping changes in the value of ecosystem services in the Yangtze River Middle Reaches Megalopolis, China. Ecosyst Serv 48:101252

Zhang J, Zhu W, Zhu L, Li Y (2020) Multi-scale analysis of trade-off/synergy effects of forest ecosystem services in the Funiu Mountain Region. Acta Geogr Sin 75:975–988

Zheng H, Wang L, Wu T (2019) Coordinating ecosystem service trade-offs to achieve win–win outcomes: a review of the approaches. J Environ Sci-China 82:103–112

Zheng W, Ke X, Zhou T, Yang B (2018) Trade-offs between cropland quality and ecosystem services of marginal compensated cropland—a case study in Wuhan, China. Ecol Indic 105:613–620

Zhou R, Lin M, Gong J, Wu Z (2019) Spatio-temporal heterogeneity and influencing mechanism of ecosystem services in the Pearl River Delta from the perspective of LUCC. J Geogr Sci 29:831–845