RESEARCH ARTICLE

Temporal and spatial analysis of the ecosystem service values in the Three Gorges Reservoir area of China based on land use change

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Abstract

The Three Gorges Reservoir area (TGRA) has complex geological conditions and a fragile ecological environment. The construction of the Three Gorges Project triggered ecological and environmental issues and social disputes, which have attracted considerable attention in recent years. However, how the temporal and spatial characteristics of ecosystem service value (ESV) in the TGRA changed in each stage of the Three Gorges Project with the implementation of ecological restoration plans remains ambiguous. Based on four periods of land use data from 2000 to 2018, the changes in land use were investigated, and the ESVs were estimated. Then, the spatial distribution and dynamic changes in ecosystem services were analysed. The results showed that grassland and construction land were the land use types that had the greatest reductions and increases in area over time, respectively. The conversion of cropland to forestland, grassland and construction land represented the most important land type changes. In the past 18 years, because of an increase in forestland and water area, the ESVs increased by 2.7 billion yuan, with a growth rate of 3.46%. The conversion of cropland to forestland had the largest contribution rate to the increase in ESV. The ESV was higher in the northeast and lower in the southwest, and its changes had a significant positive autocorrelation in terms of the spatial distribution. The hot spots of ESV change were mainly distributed in the main stream of the Yangtze River and the reservoir area. This research provides a reference for land resource allocation and experience for the ecological environment protection and sustainable development of the Yangtze River Basin.

Keywords Land use change · Ecosystem service value · Spatial correlation · Equivalent value factor · Human activities · Three Gorges Reservoir area

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Introduction

Ecosystem services refer to the benefits that humans obtain directly or indirectly from the ecosystem, including provisioning services, regulation services, supporting services and cultural services (Millennium Ecosystem Assessment 2005; Costanza et al. 1997). The sustainable development of the social economy depends on the sustainable supply of ecosystem services (Liu and Wu 2021; Zhou et al. 2016). However, the advancement of social technology has greatly accelerated the plundering of natural resources by humans and destroyed the ecological environment. Humans gain economic prosperity at the expense of ecosystem services (Cao et al. 2021); therefore, it is imperative to evaluate ecosystem service value (ESV) to alleviate the increasingly scarce ecosystem services and recognise the important role of ecosystem services in human survival. Global scholars have been researching ESV for approximately 30 years. In 1997, two milestone studies were published: the first milestone study,

conducted by Daily (1997), was titled "Nature's Services: Societal Dependence on Natural Ecosystems" and the second milestone study, conducted by Costanza et al. (1997), was titled "The Value of the World's Ecosystem Service and Nature Capital" and published in the journal *Nature*. The latter paper systematically calculated the total ESV worldwide and depicted its spatial distribution. The publication of these studies has triggered a global research boom on ecological capital and ecosystem services, which has become a frontier issue.

Land use change (LUC) is a significant way in which humans affect ecosystems (Yu et al. 2020); LUC can change the functions and products of ecosystem services (Hasan et al. 2020; Li et al. 2021; Liang et al. 2021; Wu et al. 2018). Millennium Ecosystem Assessment (2005) pointed out that LUC has been the most important driving force leading to changes in the value of terrestrial ecosystem services since the 1950s. As an important part of human well-being, LUC and its impact on ecosystem services have received widespread attention worldwide (Li et al. 2018; Gashaw et al. 2018; Li et al. 2021; Schirpke et al. 2020; Tan et al. 2020). Liu et al. (2020) assessed the ESV in the Bohai Rim coastal zone and found that the decrease in saltwater wetland area and the increase in construction land area contributed to the decrease in ESV. Wu et al. (2020) estimated the ESV in Jiangsu Province and proposed that rapid urbanisation in the region has placed great pressure on ecosystem services. Considering Yongshou County on the Loess Plateau as an example, Zhang et al. (2020a) found that the implementation of the ecological restoration project changed the rural land use structure, greatly improved the ecological environment and had a significant positive impact on ecosystem services. Su et al. (2020) investigated the relationship between LUC and ecosystem services in Fujian Province and provided a basis for the formulation of ecological protection policies. Gao et al. (2021) applied the CA-Markov model to simulate three land use scenarios in Shijiazhuang in 2030 and estimated the ESV for each scenario. Existing studies focus on the impact of a single type of LUC on ESV (Wang et al. 2019a); however, few related studies have deeply analysed the changes in the ESV caused by the conversion between various land types in the process of LUC. Therefore, clarifying the impact of different land use transfer types on ESV can further reveal the impact mechanism of LUC on ESV and provide guidance for the optimisation of land use.

In terms of the value estimation of ecosystem services, two main methods exist—the functional value evaluation method and the equivalent factor method. The functional value evaluation method is a common method for evaluating the characteristics of ecosystem services in small-scale regions by obtaining monitoring data from fixed point observations and combining them with related ecological models (Fu and Zhang 2014; Zhang et al. 2020c). However, this method requires a large amount of data, and the process is complicated; moreover, some parameters are not easy to obtain. The most widely used value assessment method is the equivalent factor method. This method does not require complex model calculations and uses fewer data (Wang and Dun 2015). Based on Costanza et al. (1997) and combined with the real situation in China, Chinese scholars Xie et al. (2008) conducted a questionnaire survey of 700 professionals with ecological backgrounds and proposed a value equivalent table that is suitable for the Chinese region. This table is used by many scholars to estimate changes in the ESV in China. Since the value assessment method easily summarises and compares different services, it is more suitable for the comparative study of ecosystem service changes for different LUC scenarios.

The Three Gorges Reservoir area (TGRA) is a typical ecologically fragile area in China (Huang et al. 2019; Zhang et al. 2020b), and it is an ecological barrier area of strategic significance in the Yangtze River Basin (Li et al. 2019b). As the world's largest hydroelectric project, the Three Gorges Project has affected the ecosystem of the TGRA (Yuan et al. 2013; Zheng 2016), including such features as soil erosion (Huang et al. 2020; Xiao et al. 2020), water quality (Holbach et al. 2013; Li et al. 2019a, c; Xiang et al. 2021) and biodiversity (Wu et al. 2003), as a result, it has attracted widespread attention from ecologists worldwide. With the rapid economic development in the upper reaches of the Yangtze River and the construction and impoundment of the Three Gorges Dam, the land use pattern in the reservoir has changed greatly, and the ESV closely related to it has been altered. Since 2000, the Chinese government has paid more attention to the ecological environment of the TGRA. Ecological projects, such as the Grain for Green Program and Natural Forest Protection Program, have been implemented successively, and many other land use types have been converted to forest and grassland.

Previous studies on the LUC in the TGRA and its impact on the ecosystem have been conducted (Chu et al. 2018; Yan et al. 2014). One study showed that the LUC characteristics differed in different stages of the Three Gorges Dam construction. From 1990 to 2010, water impoundment and inundation, residential resettlement and relocation, and urbanisation led to the expansion of water areas and the reduction in cropland area (Shao et al. 2013). Guo and Zhou (2016) estimated the total ESV in the TGRA from 2000 to 2014 and explored the relationship between changes in land use and ecosystem services before and after the completion of water storage in the reservoir area. Xiao et al. (2017) examined the changes in soil conservation ecosystem services in the TGRA and explored the influencing factors. Zhang et al. (2021) analysed the changes in national land space patterns in Fengdu County in the TGRA from the perspectives of urban, agricultural

and ecological spaces and discussed the temporal and spatial changes in ESV. However, research on the specific characteristics of LUC and its ecological effects in different construction periods of the Three Gorges Project is limited. The lack of this knowledge hinders our ability to formulate the most reasonable and effective sustainable development measures for different stages.

Considering the TGRA as the research object, this paper uses the equivalent factor method to calculate the ESV in the study area and explores the impact of LUC on ecosystem services. The study aims to (1) analyse the spatiotemporal characteristics of LUC; (2) assess the temporal and spatial changes in ESV and its spatial heterogeneity and (3) analyse the impact of LUC on ESV.

Materials and methods

Study area

The TGRA, located at 105°50′–111°65′E and 28°56′–31°44′N, lies at the junction of the Sichuan Basin and the middle and lower reaches of the Yangtze River Plain (Fig. 1). Covering an area of approximately 58,000 km², the TGRA contains 26 districts or counties (4 in Hubei Province and 22 in Chongqing City). The area is located in a subtropical humid climate, with high temperatures and rain in summer and mild and humid temperatures in winter. The average annual temperature is approximately 18 °C, and the average annual precipitation is 1100 mm. With the construction of the Three Gorges Project and the socioeconomic development of the TGRA, land

use patterns have changed, which may affect ecosystem services.

Data sources

The data considered in this study mainly include land use data, digital elevation models and socioeconomic data. The land use data with a spatial resolution of 1 × 1 km from 2000, 2005, 2010 and 2018 were obtained from the Resource and Environment Data Cloud Platform of the Chinese Academy of Sciences. These data are based on Landsat-8 remote sensing images and are generated by manual visual interpretation. The land use types were divided into cropland, forestland, grassland, water, construction land and bare land. The socioeconomic statistics data were obtained from the Chongqing Statistical Yearbook, Yichang Statistical Yearbook, Enshi Statistical Yearbook, National Farm Product Cost-Benefit Survey and China Yearbook of Agricultural Price Survey.

Ecosystem services valuation

In 1997, Costanza et al. (1997) began to assess the value of global ecosystem services. Based on their research results and combined with the characteristics of China's ecosystem, Chinese scholars Xie et al. (2015) formulated the equivalent factor table of ESV in China. In this study, we modified the table of equivalent value factors based on the equivalent value factor table proposed by Xie et al. (2015) and the actual situation in the study area. Specifically, the equivalent value of cropland was multiplied by the corresponding equivalent value of the proportion of paddy fields and dry land in the study area. The equivalent value of forestland was determined based on the average values of coniferous forest,

Fig. 1 Location of the Three Gorges Reservoir area
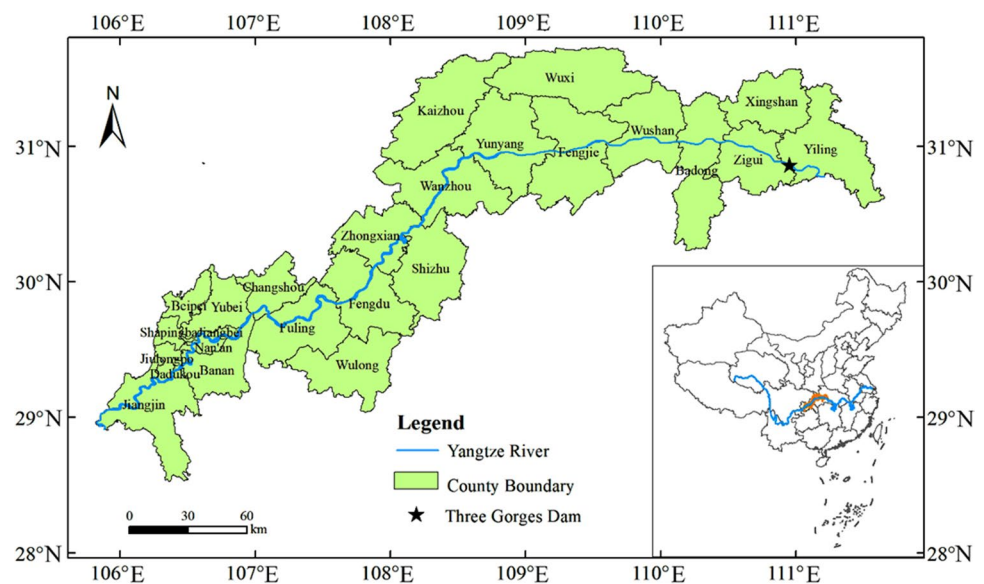
mixed coniferous and broad-leaved forest, broad-leaved forest and shrub forest. The equivalent value of grassland was determined based on the average value of shrubs and meadows. We determined that the equivalent value of the construction land was 0 according to related research (Gashaw et al. 2018; Guo and Zhou 2016; Zhang et al. 2020a, 2015). When calculating the ESV, the average grain price of the TGRA was revised according to the consumer price index (*CPI*) to construct an ESV coefficient that is suitable for the region.

The ESV model was revised as follows:

$$a_i = \frac{CPI}{100} \ (I = 0, 1, 2 \cdots, n) \tag{1}$$

$$\frac{a_1}{a_0} \times \frac{a_2}{a_1} \times \frac{a_3}{a_2} \times \cdots \times \frac{a_n}{a_{n-1}} = \frac{a_n}{a_0} \tag{2}$$

$$VC = VC_0 \times \frac{a_n}{a_o} \tag{3}$$

$$VC_0 = \frac{1}{7} \sum_{i=1}^{n} \frac{p_i q_i m_i}{M} \tag{4}$$

where a_i is the unit *CPI* of i-year, a_1/a_0 is the initial chained *CPI*, VC is the unit price of the ESV, VC_0 is the economic value of the cropland's production services, p_i is the average grain output of the study area, q_i is the average grain price of the study area, m_i is the average grain area of the study area and M is the total grain area of the study area. According to the characteristics of the study area, we selected rice, corn, soybean and potato as the main types of food crops.

According to the value equivalent factor table and unit price of the ESV, we calculated the value coefficient of ecosystem services per unit area in the study area (Table 1).

The ESV was calculated using the following equations:

$$ESV_k = \sum_f A_k \times VC_{kf} \tag{5}$$

$$ESV_f = \sum_k A_k \times VC_{kf} \tag{6}$$

$$ESV = \sum_k A_k \times VC_k \tag{7}$$

where ESV_k, ESV_f and ESV refer to the ESVs of land use type k, ecosystem service function f and the entire value, respectively; A_k is the area of land use type k; VC_{kf} is the value coefficient for land use type k with the ecosystem service function f and VC_k represents the value coefficient of land use type k.

Ecological contribution rate of land use change

The contribution of the ESV of LUC refers to the change rate of the regional ESV caused by the transformation of land use type i to land use type j. The formula is expressed as follows:

$$EL_{i-j} = \frac{(VC_j - VC_i) \times LUC_{i-j}}{\sum_{i=1}^{n} \sum_{j=1}^{n} \left[\left| VC_j - VC_i \right| \times LUC_{i-j} \right]} \times 100\% \tag{8}$$

where EL_{i-j} is the contribution of LUC to the ESV; VC_j and VC_i represent the value coefficients of land use types i and j, respectively and LUC_{i-j} is the area of land use type i changed to land use type j during the study period.

Table 1 Value coefficient of ecosystem services per unit area in the study area (yuan/hm^2)

Ecosystem services type		Cropland	Forestland	Grassland	Water	Bare land	Construction land
Provisioning services	Food production	1298.15	327.82	393.38	1049.01	0.00	0.00
	Raw material production	406.49	760.53	590.07	301.59	0.00	0.00
	Water supply	−944.11	393.38	327.82	10870.35	0.00	0.00
Regulation services	Gas regulation	1035.90	2504.51	2045.57	1009.67	26.23	0.00
	Climate regulation	550.73	7487.29	5402.39	3002.79	0.00	0.00
	Purification environment	157.35	2189.80	1783.31	7277.49	131.13	0.00
	Hydrological regulation	1258.81	4904.11	3960.01	134063.22	39.34	0.00
Supporting services	Soil conservation	970.33	3042.12	2491.39	1219.47	26.23	0.00
	Maintain nutrient cycle	183.58	236.03	196.69	91.79	0.00	0.00
	Biodiversity	196.69	2779.87	2268.48	3343.71	26.23	0.00
Cultural services	Aesthetic landscape	91.79	1219.47	996.56	2478.28	13.11	0.00
Total		5205.70	25844.93	20455.66	164707.37	262.25	0.00

Sensitivity analysis

Because of the uncertainty in the selection of the value coefficient, we conducted a sensitivity analysis to reflect the dependence of the ESV on the value coefficient over time. We calculated the sensitivity index by adjusting 50% of the value coefficient of various land use types upward and downward. The calculation process for the coefficient of sensitivity (CS) is expressed as follows:

$$CS = \left| \frac{(ESV_e - ESV_i)\ ESV_i}{(VC_{ek} - VC_{ik})\ VC_{ik}} \right| \tag{9}$$

where CS is the coefficient of sensitivity, ESV_i represents the initial ESV, ESV_e represents the ESV after adjustment, VC_{ik} represents the initial value coefficient of land use type k and VC_{ek} represents the value coefficient of land use type k after adjustment. If CS > 1, then ESV is elastic to the coefficient; that is, a 1% change in VC will lead to an ESV change greater than 1%. If CS < 1, then ESV is inelastic for the coefficient, and the calculated results are reliable.

Spatial autocorrelation analyses

Global spatial autocorrelation

In this study, Moran's I, a global spatial autocorrelation model, was used to measure whether the spatial distribution of ESV was correlated. The calculation formula is presented as follows:

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \times \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{10}$$

where I is the Moran index; x_i and x_j are the observations of space unit i and space unit j, respectively; W_{ij} is the spatial weight matrix; $\bar{x}$ is the average of observations and n is the sample size. The Moran's I index ranges from 1 to −1. When Moran's $I > 0$, it indicates a positive spatial correlation, and the larger the value is, the more obvious the spatial correlation. When Moran's $I < 0$, it indicates a negative spatial correlation, and the smaller the value is, the greater the

spatial difference. When Moran's $I = 0$, the space presents randomness.

Hot spot analysis

To further study the local performance of ESVs in space, we applied the Getis-Ord G^* to analyse the local spatial autocorrelation. The specific formula is defined as follows:

$$Gi^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}}} \tag{11}$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{12}$$

$$S = \sqrt{\frac{1}{n}\sum_{j=1}^{n} x_j^2 - \left(\bar{X}\right)^2} \tag{13}$$

where x_j is the attribute value of element j, $w_{i,j}$ is the spatial weight between elements i and j, n is the total number of elements, $\bar{X}$ is the mean value of elements, S is the standard deviation of the elements and Gi^* is the Z-score. The higher the Z-score is, the closer the clustering of high values (hot spots) becomes; the lower the Z-score is, the closer the clustering of low values (cold spots) becomes.

Results

Land use change in 2000–2018

The temporal and spatial changes in land use are shown in Table 2 and Fig. 2. From 2000 to 2018, forestland was the most important land use type, accounting for more than 46%, followed by cropland and grassland. The area of forestland increased from 46.12% in 2000 to 47.61% in 2018. The cropland area decreased from 38.58% in 2000 to 37.24% in 2018. Grassland was mainly distributed in the southwest region. From 2010 to 2018, its area decreased significantly from 12.88 to 10.35%.

Table 2 Areas of various land use types in the Three Gorges Reservoir area from 2000 to 2018

Land use type	2000		2005		2010		2018	
	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%
Cropland	22171.98	38.58	21913.74	38.13	21584.95	37.56	21399.64	37.24
Forestland	26507.15	46.12	26739.09	46.53	26779.74	46.60	27361.98	47.61
Grassland	7560.83	13.16	7409	12.89	7404.21	12.88	5948	10.35
Water	772.34	1.34	858.42	1.49	943.31	1.64	1090.37	1.90
Bare land	9.56	0.02	7.17	0.01	7.17	0.01	3.5	0.01
Construction land	449.54	0.78	543.99	0.95	752.02	1.31	1665.44	2.90

Fig. 2 Spatial distribution of land use/cover types in the Three Gorges Reservoir area. (**a**) 2000. (**b**) 2005. (**c**) 2010. (**d**) 2018
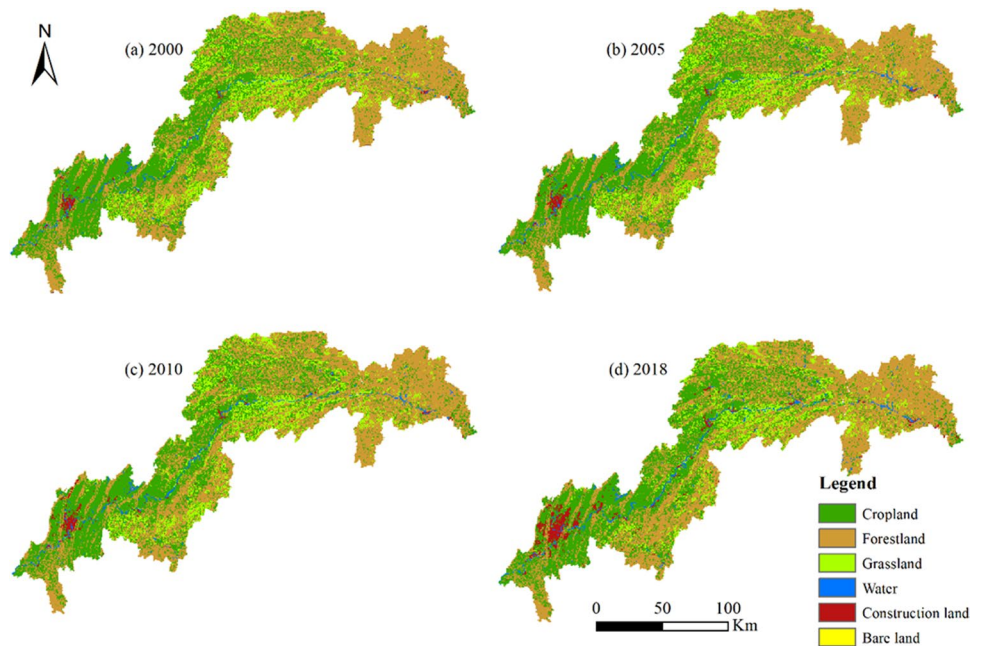
The distribution of construction land was relatively concentrated, and most of this land was located in the urban area of Chongqing. This area experienced an obvious change, with an increase of 1215.9 km^2 from 2000 to 2018. Water was mainly distributed in the main stream of the Yangtze River and the reservoir area, which continued to expand. The proportion of water increased from 1.34% in 2000 to 1.9% in 2018. Bare land covered less area and changed slightly.

From 2000 to 2018, the total area transferred to the TGRA was 22,010.6 km^2 (Table 3). Cropland, forestland and grassland were the main land use types that were transferred. Among these land use types, cropland had the largest transferred area. The area transferred from other land types to cropland was 8458.71 km^2, of which forestland contributed the most, accounting for 67.38%. The area of cropland transferred to other land use types was 9227.47 km^2, so the cropland area was reduced by 768.76 km^2 in total. The area

transferred from other land types to forestland was 8308.07 km^2, and the area of forestland transferred to other land use types was 7453.24 km^2; thus, the forestland increased by 854.83 km^2.

Grassland was mainly transformed into forestland and cropland, accounting for 45.53% and 51.98% of the change, respectively. A total of 3151.55 km^2 of other land types was transferred to grassland, of which cropland contributed the most. In the transferred area of construction land, cropland contributed the most, with an area of 1091.56 km^2; this accounted for 79.39%. Following cropland were forestland and water, where the transferred areas were 182.92 km^2 and 63.37 km^2, respectively, accounting for 13.30% and 4.61%. The water area of 373.02 km^2 did not change. The area transferred from other land types to water was 713.76 km^2. The area of water transferred to other land types was 399.33 km^2, and the water area increased by 314.43 km^2.

Table 3 Transition matrix of land use/cover change (km^2) in the Three Gorges Reservoir area from 2000 to 2018

2000	2018						
	Cropland	Forestland	Grassland	Water	Construction land	Bare land	The area of transferred out
Cropland	12931.37	6010.17	1793.37	329.98	1091.56	2.39	9227.47
Forestland	5699.32	19012.07	1315.14	254.66	182.92	1.2	7453.24
Grassland	2474.85	2167.58	2789.28	82.49	35.87	0.00	4760.79
Water	206.83	93.26	35.87	373.02	63.37	0.00	399.33
Construction land	75.32	34.67	7.17	43.04	289.33	0.00	160.2
Bare land	2.39	2.39	0	3.59	1.2	0.00	9.57
The area of transferred in	8458.71	8308.07	3151.55	713.76	1374.92	3.59	22010.6

Change in ecosystem service value from 2000 to 2018

Temporal change in ecosystem service value

The ESVs were estimated based on the land use data (Table 4). From 2000 to 2018, the total ESVs showed an upward trend, increasing from 78.5 to 81.2 billion yuan, with a total increase of 2.7 billion yuan. The ESV of forestland was the greatest contributor, at more than 62%. Although the ESV of forestland increased, its contribution initially declined and then increased. The ESV of water increased the most, with an increase of 3.8 billion yuan, which was attributed to its high value coefficient. The ESVs of cropland and grassland decreased by 3.48% and 21.33%, respectively. The ESV of bare land decreased slightly, and the construction land remained unchanged.

As shown in Table 5, in terms of the ecosystem service functions, the ESV of regulation services was the largest, accounting for 68% of the total ESV, followed by supporting services and provisioning services, whereas cultural services accounted for approximately 4%, providing the lowest ESV. The supporting services value and culture services value initially increased and then decreased, whereas the provisioning

services value continuously increased. Among the ESVs of regulation services, hydrological regulation contributed the most, reaching more than 40%, followed by climate regulation and gas regulation, which accounted for approximately 34% and 14%, respectively. From 2000 to 2005, the ESV of food production and maintenance of the nutrient cycle declined, whereas the other ESV functions increased. From 2005 to 2010, the following ecosystem services increased in value: water supply, climate regulation, purification environment, hydrological regulation, biodiversity and aesthetic landscape. From 2010 to 2018, the ESV of the water supply and hydrological regulation increased, whereas the values of other ecosystem service functions decreased.

Spatial change in the ecosystem service value

Figure 3 shows the historical spatial distribution of ESV. The spatial distribution of ESV is affected by the spatial pattern of land use in the study area. From 2000 to 2018, the distribution of areas of ESV with extremely high values was consistent with the spatial distribution of water, distributed in the main stream of the Yangtze River and the reservoir area. The areas with extremely low ESVs were mainly distributed in the urban area of Chongqing, where the main

Table 4 Ecosystem service value of different land use types (cropland, forestland, grassland, water, construction land and bare land) in the Three Gorges Reservoir area from 2000 to 2018 (10^4 yuan)

Land use types	2000 ESV	2000 %	2005 ESV	2005 %	2010 ESV	2010 %	2018 ESV	2018 %
Cropland	837069.25	10.66	827319.79	10.39	814906.83	10.11	807910.73	9.95
Forestland	4968394.41	63.29	5011868.31	62.93	5019487.59	62.28	5128620.33	63.15
Grassland	1121658.05	14.29	1099133.89	13.80	1098423.28	13.63	882392.81	10.87
Water	922569.62	11.75	1025393.23	12.88	1126795.38	13.98	1302460.36	16.04
Bare land	18.18	0.01	13.64	0.0001	13.64	0.0001	6.83	0.0001
Construction land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	7849709.50	100	7963728.87	100	8059626.72	100	8121391.06	100

Table 5 Ecosystem service value of different ecosystem service functions in the Three Gorges Reservoir area from 2000 to 2018 (10^8 yuan)

Ecosystem services functions		Value 2000	2005	2010	2018
Provisioning services	Food production	29.92	29.75	29.52	29.18
	Raw material production	24.56	24.57	24.51.	24.18
	Water supply	0.27	1.15	2.06	3.16
Regulation services	Gas regulation	76.59	76.65	76.53	75.40
	Climate regulation	184.10	184.84	185.10	182.80
	Purification environment	58.48	59.08	59.55	59.34
	Hydrological regulation	211.32	219.85	227.93	239.95
Supporting services	Soil conservation	88.43	88.56	88.49	87.14
	Maintain nutrient cycle	8.62	8.61	8.58	8.45
	Biodiversity	70.91	71.30	71.54	70.65
Cultural services	Aesthetic landscape	31.77	32.00	32.17	31.88
	Total	784.97	796.37	805.96	812.14

Fig. 3 Spatial distribution of ecosystem service value in the Three Gorges Reservoir area. (**a**) 2000. (**b**) 2005. (**c**) 2010. (**d**) 2018
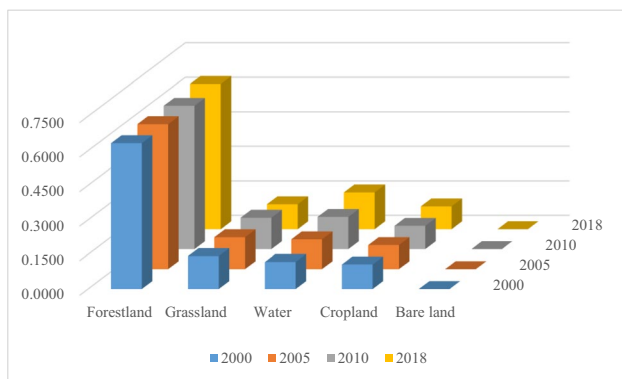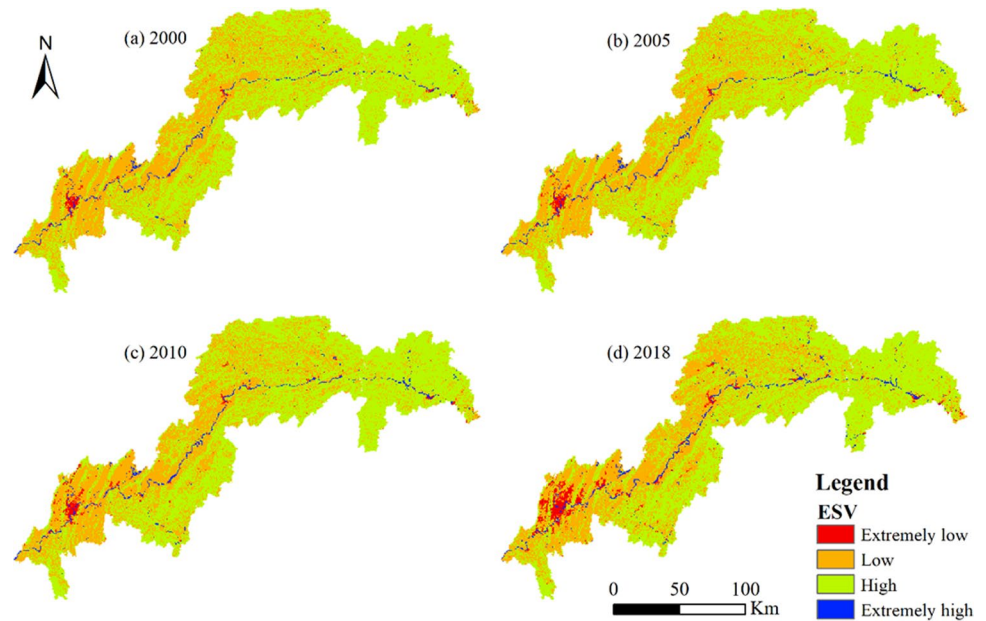
Fig. 4 Coefficient of sensitivity of ecosystem services value

type of land use was construction land. The low- and high-ESV areas were scattered, and the spatial distribution of low-ESV areas was consistent with the distribution of cropland. From the perspective of the spatial evolution of ESV from 2000 to 2018, the areas with extremely low and extremely high ESVs continued to expand because of the increase in construction land and water.

Sensitivity analysis of ecosystem service value

As shown in Fig. 4, the CS results for 2000, 2005, 2010 and 2018 were all less than 1, indicating that the calculation results of CS were inelastic to the value coefficient. The estimation of ESV was consistent with reality. Among the various land use types, the CS of forestland was the largest, at 0.6228–0.6329. The smallest CS was obtained for bare land, which showed that the change in the value coefficient had the weakest impact on the ESV of bare land.

Impact of land use change on ecosystem service value

The ecological environmental change caused by LUC in the TGRA showed both trends of improvement and deterioration. According to the calculation of the contribution rate (Table 6), the LUCs improved the ESVs in the TGRA during the study period. From 2000 to 2018, the conversion of cropland to forestland was the main factor in the improvement of the ESV, with a contribution rate of 24.45%. The continuous expansion of water had a positive influence on the ESV, with an increasing contribution rate from 60.92% for 2000–2005 to 73.66% for 2005–2010. The main types of land use transformation that led to a decrease in the ESVs included cropland reclamation and construction land occupation; their contribution rates were 37.12% and 3.18%, respectively. From 2000 to 2005, the conversion of grassland to cropland contributed 3.68% to the reduction in ESV. From 2005 to 2010, the occupation of cropland, forestland, water and grassland by construction land contributed 11.33% to the reduction in ESV. From 2010 to 2018, the conversion of forestland, water and grassland to cropland was the main reason for the reduction in ESV, with contributions of 23.65%, 7.63% and 7.37%, respectively. The overall change in the ESV in the TGRA from 2000 to 2018 was not significant because the two trends of increase and decrease in ESVs occurred simultaneously, and they offset each other in a certain area.

Table 6 Contribution of land use/cover change to ecosystem service value in the Three Gorges Reservoir area from 2000 to 2018

Pattern	2000–2005		2005–2010		2010–2018		2000–2018	
	Land use conversion type	Contribution rate/%	Land use conversion type	Contribution rate/%	Land use conversion type	Contribution rate/%	Land use conversion type	Contribution rate/%
Ecosystem function improved	2—4	35.96	1—4	39.18	1—2	23.81	1—2	24.45
	1—2	19.43	2—4	17.52	1—4	9.38	1—4	10.37
	1—4	15.02	3—4	11.49	2—4	5.78	2—4	6.97
	3—4	5.09	1—3	5.57	1—3	5.28	1—3	5.39
	5—4	4.85	1—2	5.48	3—2	2.24	3—4	2.35
	3—2	3.71	5—4	5.47	3—4	2.07	3—2	2.30
	1—3	2.69	3—2	2.00	5—4	1.61	5—4	1.40
	Other	1.93			Other	0.63	Other	0.41
	Total	88.69	Total	86.72	Total	50.80	Total	53.64
Ecosystem function deteriorates	3—1	3.68	1—5	5.25	2—1	23.65	2—1	23.18
	2—1	2.43	2—5	2.40	4—1	7.63	3—1	7.44
	1—5	2.18	4—5	2.19	3—1	7.37	4—1	6.50
	2—5	1.06	3—5	1.49	4—2	3.45	4—2	2.55
	4—5	0.97	2—3	0.82	4—5	2.21	4—5	2.06
	3—5	0.60	2—1	0.82	2—3	1.46	2—3	1.40
	2—3	0.38	3—1	0.30	4—3	1.45	1—5	1.12
					Other	1.99	Other	2.10
	Total	11.31	Total	13.28	Total	49.2	Total	46.36

Table 7 Moran's I of the ecosystem service value in the Three Gorges Reservoir area

Year	Moran's I	p	Z
2000	0.5294	<0.001	179.63
2005	0.5365	<0.001	182.05
2010	0.5396	<0.001	183.08
2018	0.5135	<0.001	174.24
2000–2005	0.4706	<0.001	160.03
2005–2010	0.4684	<0.001	159.29
2010–2018	0.2940	<0.001	99.71
2000–2018	0.3165	<0.001	107.33

1 to 6 represent 6 types of land use (1, cropland; 2, forestland; 3, grassland; 4, water; 5, construction land; 6, bare land). 1—2 represent the conversion of cropland to forestland, etc.

Spatial autocorrelation analysis

### Global spatial autocorrelation of ecosystem service value

As shown in Table 7, the global Moran's I results of the ESVs for 2000, 2005, 2010 and 2018 were 0.5294, 0.5365, 0.5396 and 0.5135, respectively. The results indicate that the spatial distribution of the ESV in the study area had a strong positive correlation and significant clustering. Moran's I of the ESV initially increased and then decreased in the four periods, which shows that the cluster phenomenon of the spatial distribution of the ESV in the study area initially strengthened and then weakened. Analysing the spatial autocorrelation of the dynamic changes in ESV, the results show that the global Moran's I decreased, which also indicated obvious spatial aggregation.

Hot spot analysis of ecosystem service value

The statistically significant hot spots and cold spots are shown in Fig. 5. From 2000 to 2018, the hot spots of ESV change were mainly distributed in the main stream of the Yangtze River and the reservoir area. This finding is mainly attributed to the impoundment of the Three Gorges Project and ecological policies, which resulted in the conversion of land use types from cropland and forestland to water and cropland to forestland, leading to an increase in ESVs. The cold spots of ESV change had a small proportion of area and were mainly distributed around water areas (Table 8) because the local residents live by the water, resulting in an increase in construction land around the water, which reduced the ESVs. From 2000 to 2005, the hot spots of ESV change were mainly distributed in Zigui, Badong, Shizhu and Kaizhou because the conversion of forestland to water or cropland to forestland led to an increase in the value of local

Fig. 5 Spatial distribution of cold spots and hot spots of ecosystem service value changes in the Three Gorges Reservoir area from 2000 to 2018. (**a**) 2000–2005. (**b**) 2005–2010. (**c**) 2010–2018. (**d**) 2000–2018
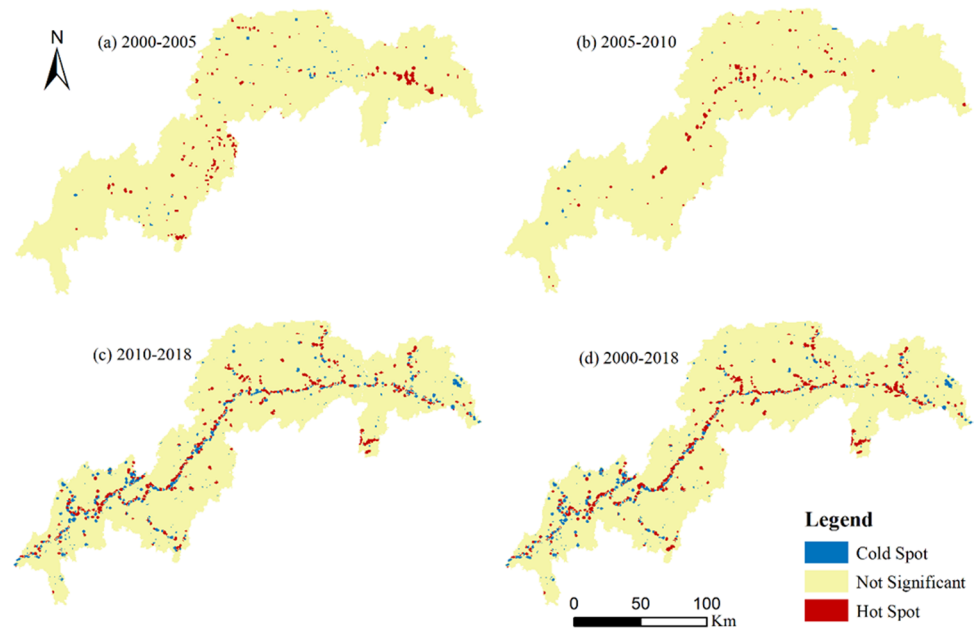
ecosystem services. The cold spots of ESV change were scattered. From 2005 to 2010, the hot spot and cold spot areas were reduced simultaneously. The hot spots were distributed in the Chongqing section of the TGRA. The increasing water storage height of the Three Gorges Project caused the expansion of the local water area, which increased the ESV. Compared with 2005 to 2010, the area of cold and hot spots expanded from 2010 to 2018. From the spatial perspective of cold and hot spots, the cold spots and hot spots were more concentrated and obvious. In each period, the area of the hot spots was significantly larger than that of the cold spots, which also verified that the ESVs of the TGRA were characterised by rising changes during the study period.

Discussion

Characteristics of land use change in the Three Gorges Reservoir area in different periods

The main construction projects in each stage of the Three Gorges Project differed, so the relevant LUC characteristics

Table 8 Area proportion of cold spots and hot spots of ecosystem service value changes in the Three Gorges Reservoir area from 2000 to 2018

Phases	2000–2005	2005–2010	2010–2018	2000–2018
Cold spot	0.36	0.19	3.33	2.82
Hot spot	1.79	1.27	4.21	4.78
Not significant	97.85	98.54	92.46	92.4

and their driving factors were likely to differ as well (Fig. 6). Therefore, in this study, we analysed the characteristics of LUC and its change not only during the entire study period (2000–2018) but also for each 5-year construction period of the Three Gorges Project, a focus that was missing in most previous studies (Jiang et al. 2008). According to the results of the period, we obtained the specific characteristics of the LUCs during the three construction periods, which strengthened the practical application of decision makers.

From 2000 to 2005, the closure of the Yangtze River caused the expansion of water. Forestland, cropland, grassland and construction land were transferred to water, and the reservoir area was filled with water to a maximum depth of 135 m. The increase in water area was also the main feature of LUC in the TGRA from 2005 to 2010, which was attributed to the continuous storage of water in the reservoir. In October 2010, the Three Gorges Project successfully achieved the experimental water storage target of 175 m. The Three Gorges Reservoir inundated a land area of 632 km^2, including 2 medium-sized cities, Wanzhou and Fuling, and over 10 small cities. Simultaneously, the main works of the Three Gorges Project and the resettlement of a million people were also announced to have been completed. The water storage of the Three Gorges Project caused inundation at low altitudes, and local residents needed to rebuild their homes in higher altitude areas. Eighty percent of the resettlers resettled in the reservoir area, resulting in excessive cultivation of cropland. At the same time, all the submerged professional facilities, such as roads and bridges, needed to be rebuilt. The adjustment of regional centre orientation and transportation hubs had a great impact on the layout of construction land, cropland, forestland and grassland in the TGRA.

Fig. 6 Main driving factors of land use changes in the Three Gorges Reservoir area from 2000 to 2018
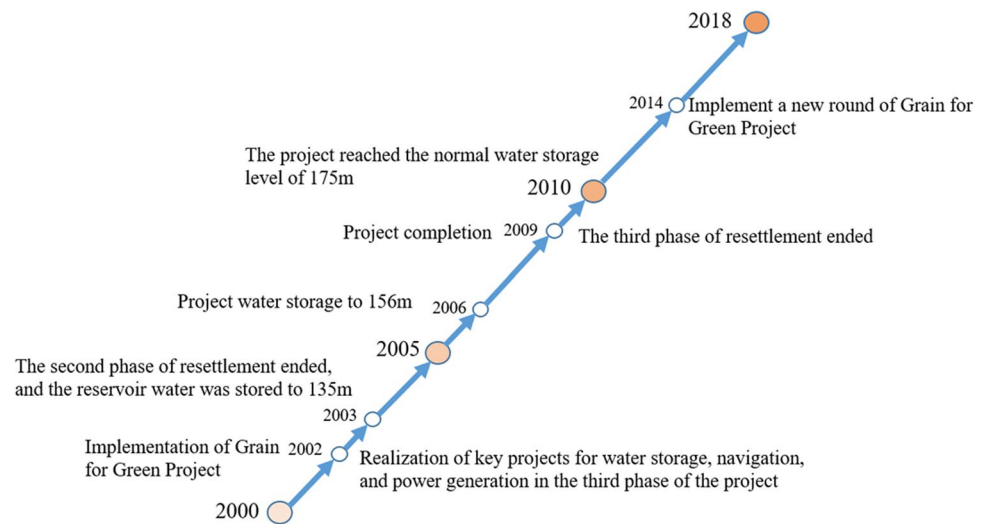
From 2010 to 2018, the policy of the Grain for Green Project showed significant effects, with part of the cropland turning into forestland. Zigui County is the head of the dam of the Three Gorges Project; it is also the national technology demonstration site for the Grain for Green Project. At the end of 2012, the forest area and forest coverage reached 0.179 km^2 and 78.98%, increasing by 15% and 11.2%, respectively, compared with before the implementation of the Grain for Green Project. Through ecological construction, the forest area and stock volume in the TGRA have increased substantially, and the forest coverage rate in the reservoir area has reached 58.49%, which is 18% higher than the average level in the Yangtze River Basin. In addition, with the development of the social economy, the average urbanisation rate in the reservoir continued to rise, increasing from 42.19% in 2010 to 59.56% in 2018, and the area of construction land continued to expand.

Impact of land use change on ecosystem service value

The impact of LUCs on ESVs is highly complex, and an LUC will lead to changes in ecosystem service structure and function (Aziz 2020; Raviv et al. 2021; Tan et al. 2020). During the study period, the ESVs increased because of the implementation of the Grain for Green Project's policy (Wang et al. 2019b) and the impoundment of the Three Gorges Project, which led to significant changes in land use structure, especially in grassland and water. This finding is consistent with the results of other relevant studies. Ecological programs such as the Natural Forest Protection Program and the Soil and Water Conservation Program in the Upper Reaches of the Yangtze River in the TGRA and the Three North Shelterbelt Development Program in the Loess Plateau and Northeast China, effectively enhanced the

ESV in the region (Wang et al. 2021; Xu et al. 2020; Zhang et al. 2020a). In contrast, the expansion of construction land caused by urbanisation and resettlement had a certain negative impact on ecosystem services (Chu et al. 2018). Similarly, from 2000 to 2015, the decrease in cropland and increase in construction land led to a decrease in ecosystem services in Jiangsu Province (Wu et al. 2020). Moreover, as Zhou et al. (2018) pointed out, the ESVs showed a downward trend and were low in areas with high urbanisation levels during the urbanisation process of the Jingjinji urban agglomeration. From the perspective of the evaluation results for ESVs in the TGRA, our findings are similar to those of Guo and Zhou et al. (2016) and Zhang et al. (2019). The main reason for the slight differences is that the calculation methods of the value coefficient of ecosystem services per unit area differed. Therefore, the standardisation of the ESV estimation system should be accelerated. The direction of the total change in ESVs from 2000 to 2018 revealed by this study is consistent with Wang et al. (2020) research results, but there are certain differences in the results for ESVs. This is because different research methods were used: Wang et al. (2020) utilised the alternative cost, shadow engineering, carbon tax, market value and water balance methods to quantify the ESVs in the TGRA from 2000 to 2015.

From the perspective of the contribution rate, during the study period, the conversion of cropland to forestland contributed the most to the increase in ecosystem services, mainly because of the implementation of the policy related to the Grain for Green Project, Natural Forest Protection Program and Yangtze River Basin Shelter Forest Project. It should be noted that although the area of water did not increase much, the change that did occur has had a great impact on the ecosystem of the reservoir area, as similarly concluded by Zhang et al. (2015). These authors claimed that water bodies had major roles in ecosystem services

in the Chaohu Lake Basin, mainly because the equivalent factor coefficient of water is higher than that of other land use types. Compared with other land use types, water has stronger ecological functions (Acuna-Alonso et al. 2021; Aznar-Sánchez et al. 2019), such as water supply and hydrological regulation. In addition, the increase in the water area mainly occurred in the main stream of the Yangtze River and surrounding the reservoir area, so the ESV in the area was high. Although large- and medium-sized hydropower projects cause a certain amount of damage to the environment, with the expansion of the water area, they have a positive effect on the ecosystem services in the area. Therefore, the construction of large- and medium-sized hydropower projects should be evaluated from various perspectives. The conversion of forestland to cropland had the largest contribution rate to the reduction in ESV in the study area; this conversion caused the loss of regional ecosystem services. Simultaneously, the expansion of construction land adversely affected the ESVs. In general, the Three Gorges Project for water storage and Grain for Green Project have had an important positive role in the ESVs in the TGRA, and urbanisation and resettlement have had a certain negative impact on the ESVs. LUCs may significantly affect ecosystems, but they do not necessarily cause ecosystem degradation (Yi et al. 2016).

Policy implications

During the study period, the LUCs in the TGRA were active, with a large increase in construction land and a decrease in cropland. Future land planning should strengthen the protection of ecological land, such as water, forestland and cropland, and it should focus on optimising and controlling the spatial pattern of land use. It is important to balance economic development and ecological land protection because this is imperative for the sustainable development of the TGRA.

The TGRA is an important ecological barrier area. The construction of the Three Gorges Project has had a series of impacts on the ecological environment of the region. However, the ESVs showed a steadily increasing trend during the study period, indicating that the ecological policies of the Grain for Green Project have made effective progress in recent years. Therefore, water conservancy and hydropower projects in developing countries should not be opposed to ecological protection. Instead, measures should be taken to promote the coupling and coordination of regional economic and social development and ecological environment governance while projects are being constructed. It is possible to achieve a win-win situation between investment in development water projects and ecological protection by formulating targeted policies to remediate and restore the ecological environment based on resource and environmental changes.

In the future, ecological construction should still be given priority, and the core task being faced is intensifying efforts to restrict access to mountains, cultivate forests and promote ecological environmental protection policies. Moreover, because of the regional development status and local conditions, the development of green and less polluting industries should be given priority to ensure the simultaneous development of resources and ecological restoration. While developing the economy, damage to the environment should be minimised so that stability and improvement of the regional environment can be achieved.

The main urban area of Chongqing in the TGRA had the lowest ESV. Through the spatial distribution of ESVs, it is possible to identify ecological control areas, formulate reasonable territorial spatial planning, strengthen the control of the ecological protection redline (Yang et al. 2020) and restore the ecosystem. In addition, understanding the ESV of the TGRA can help establish an ecological compensation mechanism and explore ways to realise the value of diversified ecological products (Fan and Chen 2019).

Limitations

The main limitation of this study relates to whether accurate results have been obtained, including the classification and precision of land use data and the ESV valuation method (Zhang et al. 2020a). This study used the benefit transfer method to estimate ESVs; however, this method is widely criticised because of its uncertainties and lack of reliability (Fu et al. 2010; Ye et al. 2018). Nevertheless, we adopted this approach because of the low cost of collecting primary data and the ability to quickly assess the value (Troy and Wilson 2006). Although our assessment results may only have a certain amount of accuracy, these results reflect the changing trend of ESV in the TGRA and serve as a reference for further research. In addition, there is a lack of quantitative analysis on the complex driving forces of ESV change, which should be further explored in the future.

Conclusions

This study estimated the spatiotemporal changes in ESVs in the TGRA from 2000 to 2018 and analysed the impact of land use on the ESVs. The main research conclusions are as follows:

(1) Forestland and cropland were the most important land use types from 2000 to 2018, accounting for 80% of the TGRA. Simultaneously, the land use in the study area underwent tremendous changes, where grassland and construction land were the largest land use types with area reduction and increase.

(2) From 2000 to 2018, because of an expansion in water and an increase in forestland and construction land, the ESV of the study area increased by 2.7 billion yuan, with a growth rate of 3.46%. From the perspective of the contribution rate, the conversion of cropland to forestland exhibited the largest contribution rate to the increase in ESV, and the conversion of forestland to cropland showed the largest contribution rate to the reduction in ESV.

(3) The ESV in the study area exhibited prominent spatiotemporal changes, significant spatial correlation and high spatial clustering. From 2000 to 2018, the hot spots of ESV change were mainly distributed in the main stream of the Yangtze River and the reservoir area, and the cold and hot spots covered a small proportion of the area.

(4) The main reasons for the changes in ESV in the study area were the impoundment of the Three Gorges Project, resettlement associated with the Three Gorges Project, urbanisation development and ecological policies, such as the Grain for Green Program.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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