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Original Article

Spatiotemporal evolution of ecosystem service value and topographic gradient effect in the Da-Xiao Liangshan Mountains in Sichuan Province, China

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Abstract: The Da-Xiao Liangshan mountains are critical ecological function areas and essential ecological barriers in the upper reaches of the Yangtze River in China. This study selected a total of six periods of land use land cover (LULC) data from 1995 to 2020, to estimate the ecosystem service value (ESV) and analyzed its spatiotemporal evolution and topographic gradient divergence. The results showed that: (1) The ESV increased by 1.1 billion yuan, with an increase rate of 1.47% from 1995 to 2020. Two time periods, 2005–2010 and 2015–2020, showed more significant increases than other periods. (2) The elevation and slope of mountainous areas determine the type of land use and further influence the spatial pattern of ESV. (3) Although woodland and grassland are the main land use types of the study area (more than 90%), the hydrological regulation function of the water area partially compensated for the impact of the encroachment of the built-up area on the ESV of grassland. (4) The spatial distribution of ESVs showed an inverted V-shaped characteristic as the topographic gradient increased, with the dominant position being the 5th topographic gradient zone. Finally, this study provided relevant recommendations for ecosystem protection and optimization. The findings of this study clarified the influence of topographical factors on the spatial differentiation of ESV and provided novel insights into ecosystem protection.

Keywords: Ecosystem service value (ESV); Dynamic evolution; Terrain gradient effect; Spatial pattern; Liangshan Yi region.

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1 Introduction

The national key ecological function area is proposed to optimize the spatial pattern of land resources and promote the construction of an ecological civilization, which is of great significance for maintaining national and regional ecological security in China (Chen et al. 2021; Xu et al. 2019). In 2000, the State Council issued the *National Ecological Environment Protection Initiative*, which proposed to prevent the destruction of the environment and the degradation of ecological functions through the establishment of ecological function protection areas. In 2011, the State Council issued 25 national key ecological function areas and clarified the spatial pattern of key ecological functions as well as their significance. Ecosystem service value (ESV) evaluation and spatiotemporal changes become an important theoretical basis for performance evaluation and the incentive constraints of transfer payments in key ecological functions areas (Qin et al. 2023).

The spatiotemporal differentiation characteristics of ESV reflect the spatial differences of land use patterns and the structural relationship between them, providing an important basis for optimizing regional ecosystem patterns (Gong et al. 2021; Li et al. 2010; Sauter et al. 2019; Xu et al. 2017). With the intensification of global warming, the vulnerability of the habitat environment is increasingly highlighted, and the urban heat island effect, lack of urban vitality and insufficient ecosystem services caused by ecological degradation are receiving increasing attention from scholars (Ao et al. 2021; Amanibeni et al. 2022; Luo et al. 2023; Wei et al. 2022a, 2022b; Zhao et al. 2018). At present, there are extensive research results on the value of ecosystem services (He et al. 2022b; Jia et al. 2022; Manley et al. 2022; Zhou et al. 2022; Su et al. 2012), providing guidance for the improvement of the ESV in China. However, most research in this field has focused on river basins, provinces, and cities (Yang et al. 2008; Wang et al. 2022; Xu et al. 2019), while there are few studies on key ecological function areas. In addition, numerous scholars have explored the impacts of topographic factors on the distribution of land use types (Li et al. 2022; Song et al. 2017). Few studies have paid attention to the differences in ESV caused by the spatial heterogeneity of ecosystem types, especially for complex mountainous areas, which often have the characteristics of a fragile environment and little human disturbance (Xiao et al. 2023). Some previous studies have shown that the significant impact of topographic factors on ESV in the mountains are more significant than plains. In recent years, the research on ESV has gradually shifted from value evaluation to differentiation characteristics (Wu et al. 2022), evolution patterns (Li et al. 2022; Pan et al. 2021), impact mechanisms (Zhang et al. 2020), and scenario simulation (Zhang et al. 2021). Therefore, research on the spatiotemporal differentiation of ESV based on topographic gradients has gradually attracted attention (Ma et al. 2021; Xu et al. 2019). Wang et al. (2020) suggested that ESV had spatial heterogeneity across a topographic gradient distribution. Chen et al. (2019) comprehensively examined the topographic gradient effect of ESV from four dimensions (elevation, slope, slope aspect, and topographic position) and pointed out that woodlands and grasslands were positively correlated with ESV in terms of slope and topographical position gradient. Wu et al. (2022) took the hills and mountains in southern China as an example to explore the impact of the elevation gradient on ESV. The study suggested that an elevation of less than 500 m was the topographic position for the rapid increase of ESV in the study area. The above studies demonstrated that topographic factors are important factors affecting ESV. Hence, clarifying the influence of topographical factors on the spatial differentiation of ESV is conducive to regional management and classification policies for ecosystem protection and service value improvement.

The Da-Xiao Liangshan mountains in Sichuan is a key ecological function area designated by the State Council of China. This area belongs to an important ecological security barrier in the upper reaches of the Yangtze River. Due to its special geographical location and geological structure characteristics, the topography of this area is complex and diverse, and all landform types can be found. It is a typical fragile ecological area. In recent years, with the implementation of ecological construction and protection, the quality of the environment in this area has improved significantly. Nonetheless, due to the influence of the complex topography, the most effective improvement path for the ESV in this area still needs to be clarified. In view of this, based on the long-term land use data obtained through remote sensing monitoring from 1995 to 2020, this study used the ESV evaluation model and topographic position index to explore the spatial pattern and dynamic evolution characteristics of the ESV on different topographic gradients. This study aims to (1) identify the spatial distribution and dynamic evolution characteristics of the ESV in the Da-Xiao Liangshan mountains of Sichuan and clarify the influencing factors of ESV change; and (2) analyze the topographic gradient effect of the spatial distribution of ESV and point out the key construction areas and weak areas of ESV on the topographic gradient. The study outcomes are expected to provide a theoretical reference for improving the ESV and optimizing the land use pattern in the Da-Xiao Liangshan mountains of Sichuan.

The main contributions of this study lie in three aspects. First, the findings of this study reveal the changing characteristics of the ESV in the Da-Xiao Liangshan mountains of Sichuan. From 1995 to 2020, the overall ESV of this area increased steadily. Woodland and grassland are the main bodies of ecosystem service functions, and water conservation was the main contributor to the increase of ESV. Based on these findings, it is recommended to strengthen the protection of water sources and improve the water conservation function in this area. Second, the mechanism of the influence of mountain topographic factors on the spatial pattern of ESV was revealed. Currently, few studies focus on the topographic gradient effect of ESV in key ecological function areas. The present study found that the peak ESV in the Da-Xiao Liangshan mountains were concentrated in the Level 4 gradient zone of elevation, the Level 5 gradient zone of slope, and the Level 5 gradient zone of topographic position factor. Therefore, it is suggested that the optimization of the land use pattern and the improvement of ESV should focus on this area, which has theoretical reference value for the construction of regional ecological function areas. Third, this study further demonstrates the necessity of ESV of key ecological function areas, and the positive significance of revealing the impact mechanism of mountain topographic factors on the ESV. Therefore, the findings of this study may attract the attention of scholars to this important research direction, which should enhance the understanding of the ESV of national key ecological function areas.

2 Study Area

The research scope of this paper covered a total of 12 counties (101°30′–103°60′E, 27°00′–29°20′N), namely Meigu County, Zhaojue County, Butuo County, Jinyang County, Xide County, Puge County, Yuexi County, Ganluo County, Mianning County, Leibo County, and Leshan County in Liangshan Yi Autonomous Prefecture of Sichuan, as well as Ebian Yi Autonomous County and Mabian Yi Autonomous County in Leshan City. The length of the study area from north to south is 229.24 km, and the width from east to west is 222.87 km, with an area of about 2.90 × 104 km². In 2020, the resident population was 2.611 million, and the urbanization rate was 24.60%. The Da-Xiao Liangshan mountains in Sichuan is located on the northeastern edge of the Hengduan Mountains system in southwestern Sichuan. It belongs to the transition area between the first and second levels of the three major topographic ladders in China and is bounded by the Sichuan Basin, the central plateau of Yunnan Province, and the southeastern edge of the Qinghai–Tibet Plateau (Sichuan Ethnic Institute 1982). The Da-Xiao Liangshan mountains was formerly one of the deeply impoverished areas of the "three districts and three continents" in China, and the 12 counties were all national-level poverty-stricken counties. The topography of the study area is complex, mainly mountainous, with an elevation range of 297–5264 m (Fig. 1). The main mountains include Huangmaogeng, Xiaoxiangling, Shizishan, and Ma'anshan. The topography is complex and diverse, and the landform types are comprehensive (He et al. 2022a). Huangmaogeng divides the study area into two distinct areas: a low area in the

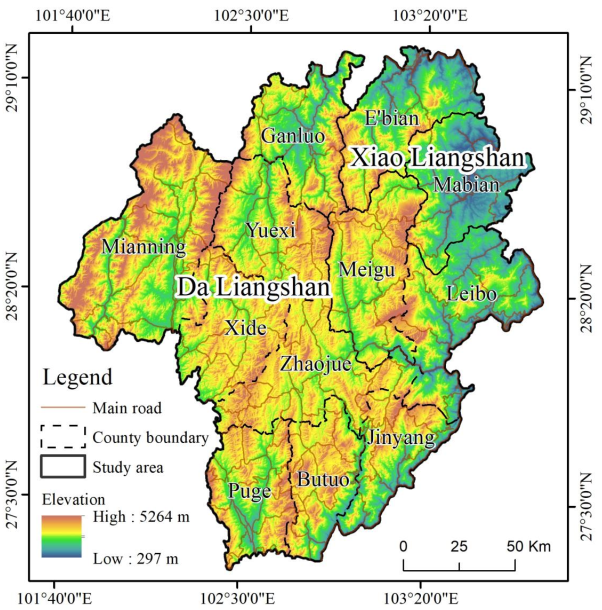

Fig. 1 Location of the study area in the Da-Xiao Liangshan mountains in Sichuan Province, China.

northeast and a high area in the southwest. The surface is undulating, the topography is rugged, there are many massive mountain peaks, the valley is deep, the walls hang thousands of feet, and the height difference is large. The study area is ecologically fragile, geological disasters occur frequently, and the conflict between human and land is prominent. Eleven counties (excluding Mianning County) have been included in the national key ecological functional areas.

3 Research Methods and Data Sources

3.1 Research methods

3.1.1 Ecosystem service value evaluation

Based on the correction rule of the ESV equivalent factor proposed by previous studies (Xie et al. 2015; He et al. 2022c), in the absence of human input, the total economic value of the natural ESV equivalent factor is equal to 1/7 of the market value of grain production (Long et al. 2022; Wei et al. 2022c). with reference to the sown area and yield per unit area of grain (rice, wheat, corn, beans) in Sichuan Province from 1990 to 2020, and based on the average unit price of grain in the same time period to obtain the standard equivalent factor of ESV. The calculation formula is as Equation (1). The calculated value of the equivalent factor per unit area of ESV in the Da-Xiao Liangshan mountains is about 1829.08 yuan hm^{-2} a^{-1}.

$$P = 1/7 \times K \times b \times c \quad (1)$$

where P is the standard equivalent factor of ESV, k represents the correction factor; b indicates the food production per unit area; and c is the average price of food during the study period.

Then, the average coefficients of the ESV per unit area in the Da-Xiao Liangshan mountains from 1995 to 2020 were further calculated based on the standard equivalent factor of ESV (Table 1). Regarding the basic scale of the research unit, relevant scholars have used grid scale divisions of 1 km, 2 km, and 3 km (Xu et al. 2017; Zhang et al. 2020). Repeated comparisons showed that the grid scale of 2 km was the most conducive to identifying the heterogeneity of the spatial distribution of the ESV in the study area. Finally, the study area was divided into 9772 grids (2 km×2 km). According to Equation (2) (Yang et al. 2018), the ESV in each grid can be calculated separately:

$$\mathrm{ESV} = P \sum_{i=1}^{m} \sum_{j=1}^{n} A_j E_{ij} \quad (2)$$

where A_j is the land use area of the j-type ecosystem in each grid, and E_{ij} is the average coefficients of the ESV per unit area of the i-type ecosystem service function of the j-type ecosystem (Table 1).

3.1.2 Topographic position index

The topographic position index is a commonly used method for measuring the difference of the topographic gradient. This study used the topographic position index to synthesize the influence of elevation and slope. The calculation formula of the topographic position index is shown as follows:

$$T = \ln\left(\left(\frac{E}{\bar{E}} + 1\right)\left(\frac{S}{\bar{S}} + 1\right)\right) \quad (3)$$

Table 1 Average ecosystem service value per unit area in the Da-Xiao Liangshan mountains from 1995–2020 (Unit: yuan hm^{-2} a^{-1})

Primary services	Secondary services	Ecosystem type					
		Cultivated land	Woodland	Grassland	Water area	Unused land	Built-up area
Supply services	Food production	1834.57	461.84	426.79	798.70	0.00	0.00
	Raw material production	561.53	1060.87	627.98	445.08	0.00	0.00
	Water supply	−1417.54	548.72	347.53	7950.40	0.00	0.00
Regulatory service	Gas regulation	1466.92	3488.97	2207.09	1737.63	36.58	0.00
	Climate regulation	773.70	10439.47	5834.77	3920.33	0.00	0.00
	Purifying the environment	221.32	3059.14	1926.63	5676.24	182.91	0.00
	Hydrological regulation	1838.23	6831.61	4273.95	81455.03	54.87	0.00
Support service	Soil conservation	1324.25	4248.04	2688.75	1975.41	36.58	0.00
	Maintaining nutrient circulation	257.90	324.66	207.30	152.42	0.00	0.00
	Biodiversity	281.68	3868.50	2444.87	6359.10	36.58	0.00
Cultural service	Aesthetic landscape	126.21	1696.47	1079.16	4091.04	18.29	0.00
Total		7268.76	36028.30	22064.80	114561.38	365.82	0.00

Notes: These values are based on the average food production, prices, and correction factors from 1995 to 2020, and the ecological service value equivalent factor is calculated.

where T is the topographic position index; E and S are the elevation and slope, respectively; and $\bar{E}$ and $\bar{S}$ are the average values of the elevation and slope, respectively. Referring to previous studies (Xu et al. 2019), according to the topographic characteristics of the study area, the elevation was divided into seven categories (Fig. 2a): Level 1 (≤1000 m], Level 2 (1000–1550 m], Level 3 (1550–2100 m], Level 4 (2100–2650 m], Level 5 (2650-3200 m], Level 6 (3200–3750 m], and Level 7 (>3750 m). The slope was divided into five categories (Fig. 2b): Level 1 (≤2°], Level 2 (2°–5°], Level 3 (5°–10°], Level 4 (10–15°], Level 5 (15°–25°], Level 6 (25°–35°] and Level 7 (>35°). According to the equidistant method, the topographic position index was divided into seven categories (Fig. 2c): Level 1 (≤ 0.30], Level 2 (0.30–0.39], Level 3 (0.39–0.48], Level 4 (0.48–0.57], Level 5 (0.57–0.66], Level 6 (0.66–0.75], and Level 7 (>0.75).

3.2 Data sources

The data used in this study mainly included land-use remote-sensing monitoring data, digital elevation model data, and socioeconomic statistics. The land-use remote-sensing monitoring data were obtained from the China Science Resources and Data Science Center. A total of six periods of land use data during 1995–2020 were selected at a time interval of five years. According to the research needs, the land use types were divided into six categories: cultivated land, woodland, grassland, built-up area, water area, and unused land (Fig. 3), with a spatial resolution of 30 m. The digital elevation model (DEM) data were obtained from the geospatial data cloud, and the spatial resolution was 30 m. The socioeconomic data were obtained from the Sichuan Statistical Yearbook and the compilation of national agricultural product cost-benefit data.

4 Results

4.1 Changes in ESV

In the study period, the ESV in the Da-Xiao Liangshan mountains continued to increase. During 1995–2020 (Table 2), the ESV rose from 75.047 billion yuan to 76.146 billion yuan (i.e., an increase of 1.1 billion yuan or an increase rate of 1.47%). In comparison to previous studies by Yang et al. (2018), the changes in the ecological service value in the Da-Xiao Liangshan mountains have increased significantly. From the perspective of time series analysis, the ESV during the periods of 2005–2010 and 2015–2020 have increased by 566 million yuan and 497 million yuan, respectively. From the perspective of ecosystem types, the order of contribution is woodland > grassland > cultivated land > water area > unused land > built-up area. This finding indicates that woodland and grassland are the major contributors to the ecological service value in the study area and are important supports for the ecosystem. Comparing the evolution of the ESV of each ecosystem type during the study period showed that the ESV of woodland (+693 million yuan) and

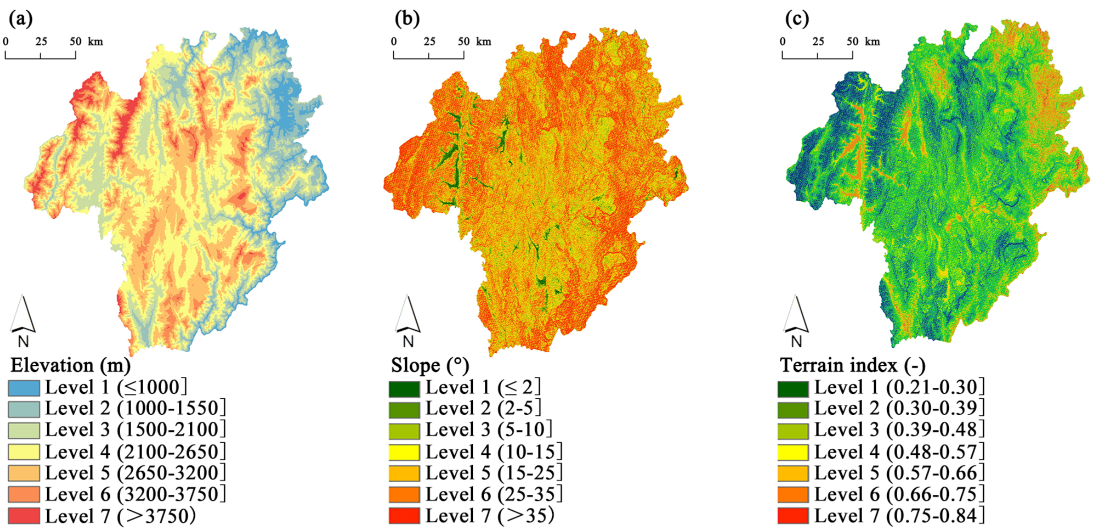

Fig. 2 Classification of altitude, slope, and terrain index in the Da-Xiao Liangshan mountains.

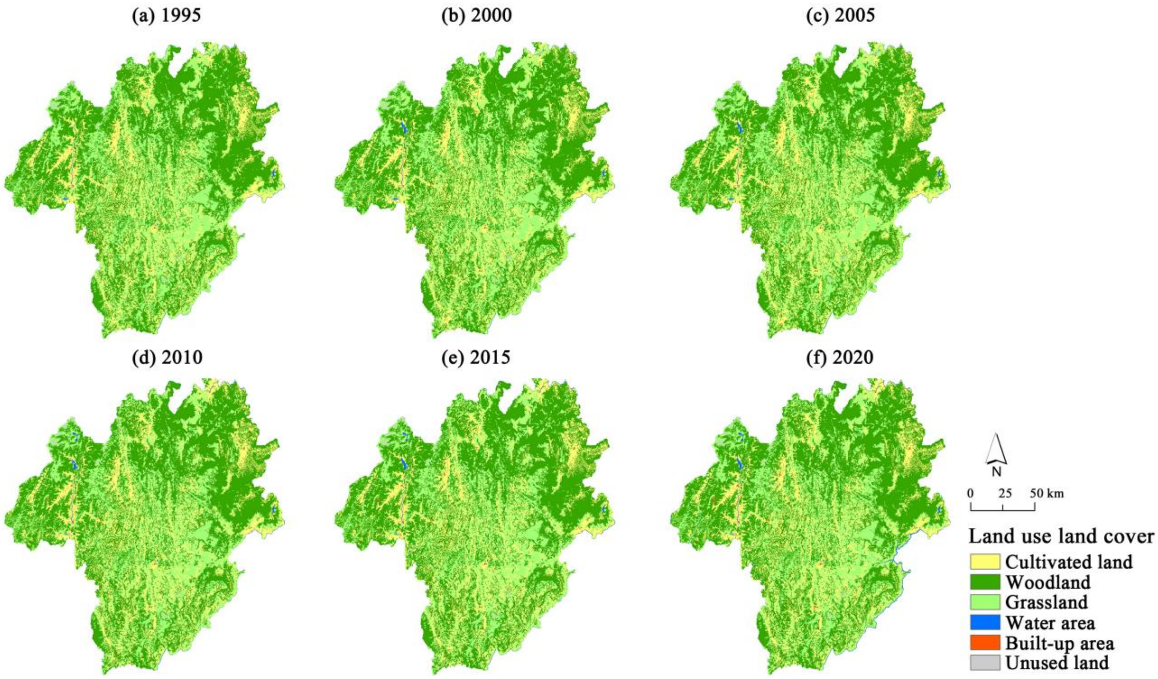

Fig. 3 Land use cover change in the Da-Xiao Liangshan Mountains from 1995 to 2020.

Table 2 Changes in the ecosystem service value of land use land cover (LULC) in the Da-Xiao Liangshan mountains from 1995–2020

Ecosystem type	Ecosystem service value (billion yuan)						1990 to 2020	
	1990	2000	2005	2010	2015	2020	Change (billion yuan)	Percentage of change (%)
Cultivated land	41.55	41.68	41.72	41.05	41.00	40.88	−0.67	−1.60
Woodland	498.12	495.11	494.98	505.39	505.34	505.05	6.93	1.39
Grassland	203.44	204.48	204.41	199.44	199.36	198.46	−4.98	−2.45
Water area	7.34	9.28	9.31	10.20	10.78	17.05	9.70	132.14
Unused land	0.02	0.02	0.02	0.02	0.02	0.02	0.00	4.02
Total	750.47	750.57	750.44	756.10	756.49	761.46	11.00	1.47

water area (+970 million yuan) increased sharply; whereas that of cultivated land (−67 million yuan) and grassland (−498 million yuan) decreased; and that of unused land remained stable. These findings indicate that although woodland and grassland are the main body of the ecosystem, the impact of water on the changes in ESV cannot be ignored. Since 1995, the woodland and water area in the Da-Xiao Liangshan mountains showed gradual increase in their support for the ecosystem. During the 13th Five-Year Plan period, by focusing on the construction and protection of the environment, a large number of woodland and grassland improvement projects were conducted in the Da-Xiao Liangshan mountains, including the "large-scale greening of Liangshan action", "returning farmland to forest and grassland", and "wetland ecological protection" initiatives. These efforts have protected a large area of woodland resources and significantly improved the water environmental management in the area.

From the total value and spatial pattern of each ecosystem service function value in Table 3 and Fig. 4, the order of contribution of primary services to the ESV is: Regulatory service > supporting service > providing service > cultural service. The spatial distribution patterns of the ESV of different service types were similar. For secondary services, climate regulation contributed the most to the ESV, followed by hydrological regulation. Taking 2020 as an example, the cumulative contribution rate of climate regulation and hydrological regulation to the ESV exceeded 47% (close to half).

Table 3 Changes in the ecosystem service value of ecosystem services function in the Da-Xiao Liangshan mountains from 1995–2020

Primary services	Secondary services	Ecosystem service value (billion yuan)						1990 to 2020	
		1990	2000	2005	2010	2015	2020	Change (billion yuan)	Percentage of change (%)
Supply service	Food production	20.86	20.89	20.89	20.77	20.76	20.75	−0.11	−0.52
	Raw material production	23.70	23.65	23.65	23.77	23.76	23.74	0.05	0.21
	Water supply	3.20	3.28	3.27	3.54	3.59	4.03	0.83	25.96
Regulatory service	Gas regulation	77.08	76.95	76.94	77.33	77.32	77.27	0.19	0.24
	Climate regulation	202.80	202.29	202.24	203.90	203.88	203.76	0.95	0.47
	Purifying the environment	61.70	61.63	61.62	62.09	62.11	62.31	0.62	1.00
	Hydrological regulation	149.59	150.63	150.62	152.10	152.47	156.67	7.08	4.73
Support service	Soil conservation	91.22	91.05	91.04	91.55	91.53	91.48	0.26	0.28
	Maintaining nutrient circulation	7.88	7.87	7.87	7.90	7.90	7.89	0.01	0.06
	Biodiversity	78.05	77.95	77.93	78.52	78.54	78.75	0.71	0.90
Cultural service	Aesthetic Landscape	34.39	34.37	34.36	34.63	34.64	34.81	0.42	1.22
Total		750.47	750.57	750.44	756.10	756.49	761.46	11.00	1.47

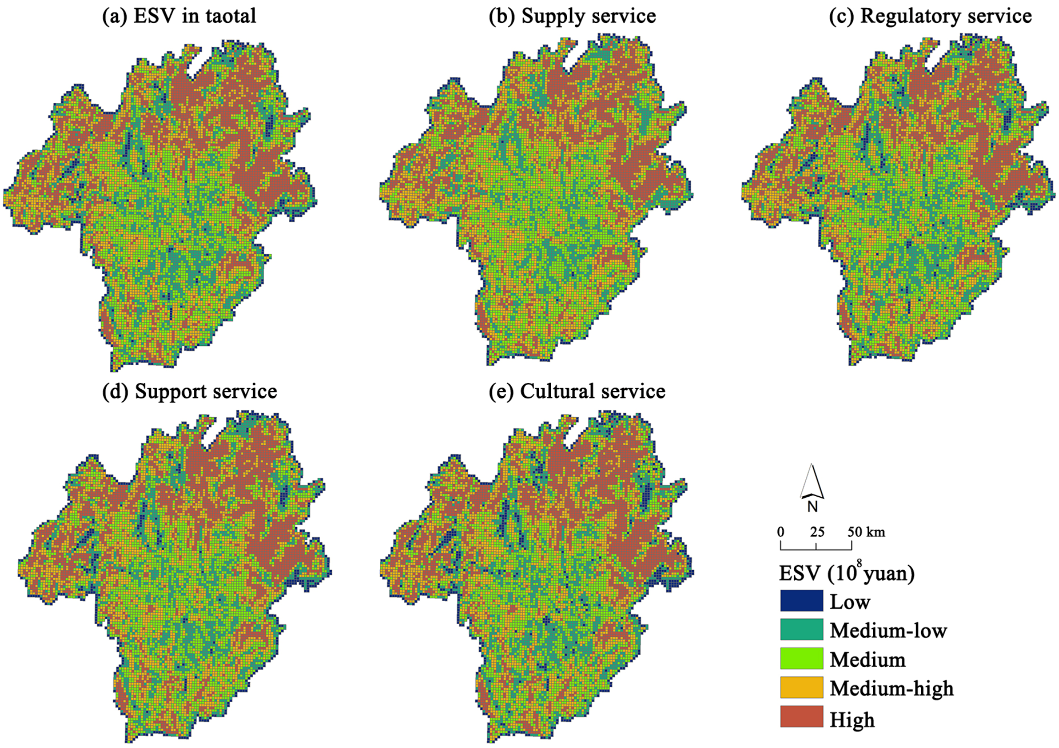

Fig. 4 Primary ecosystem service value (ESV) in the Da-Xiao Liangshan Mountains from 1995 to 2020.

The results of changes in the ESV of secondary services showed (Table 3) that except for the slight decrease in the ESV of food production, the ESV of other secondary services exhibited an upward trend. The ESV of hydrological regulation exhibited the largest increase, followed by that of climate regulation. The ESV generated by hydrological regulation continued to grow from 14.959 billion yuan in 1995 to 15.667 billion yuan in 2020, an increase of 708 million yuan, with a contribution rate of 64.36%. The ESV of climate regulation increased from 20.280 billion yuan to 20.376 billion yuan, an increase of 95 million yuan, with a contribution rate of 8.63%. In recent years, water resource management and protection have been vigorously conducted in the Da-Xiao Liangshan mountains, and a series of measures have been implemented, including water pollution prevention, water environment management, and water ecological restoration. These measures have significantly improved the regulation services of the water area (Sichuan Provincial People's Government, 2018). Notably, the ESV of food production showed a downward trend from 2.086 billion yuan to 2.075 billion yuan. This indicated that some policy factors (such as returning farmland to forest) caused the service function of food production on cultivated land to experience a downtrend.

4.2 Spatial pattern and dynamic evolution of ESV

The ESV of the grid was calculated using Eq. (1). Based on the equidistant division method, the ESV of the study area over the years can be divided into five types: low-value (0<ESV), lower-value (300<ESV≤600), middle-value (600<ESV≤900), higher-value (900<ESV≤1200), and high-value (1200<ESV) areas. Following that, the spatial patterns of the ESV during the study period could be obtained (Fig. 5).

The spatial pattern of ESV in the Da-Xiao Liangshan mountains had significant heterogeneity. From the perspective of spatial pattern distribution, the high-value areas were mainly concentrated in the northeast and northwest of the study area. The northeast was represented by Leibo County, Ebian Yi Autonomous County, Mabian Yi Autonomous County, and some Ganluo counties. These areas had low elevation, comfortable climate conditions, and rich and widely distributed forest resources, and were important contributors to the ESV. The northwest was dominated by Mianning County, which had rich natural forests, shrubs, and other forest resources despite its high elevation as well as few human activities. The low-value areas were mainly distributed in the middle region, encompassing Yuexi County, Meigu County, and Zhaojue County. Among them, Zhaojue County had the lowest ESV because it had fewer woodland resources, and the land use types were mostly grassland and cultivated land. Combined with the spatial pattern of land use types, the spatial distribution of high-value areas of ESV was consistent with the spatial distribution of woodland; that of low-value areas was consistent with the spatial distribution of cultivated land; and the water area constituted the high-value area.

From the perspective of the evolution of the spatial pattern, the ESV in the Da-Xiao Liangshan mountains trended upward during 1995–2020, and the coverage areas of the higher-value and high-value areas increased significantly (Table 4). Specifically, from 1995 to 2020, the coverage of the high-value area (1200<ESV) increased from 37.03 km^2 to 154.03 km^2, and the corresponding proportion increased from 0.12% to 0.51%. The coverage of the higher-value area (900<ESV≤1200) increased from 9716.55

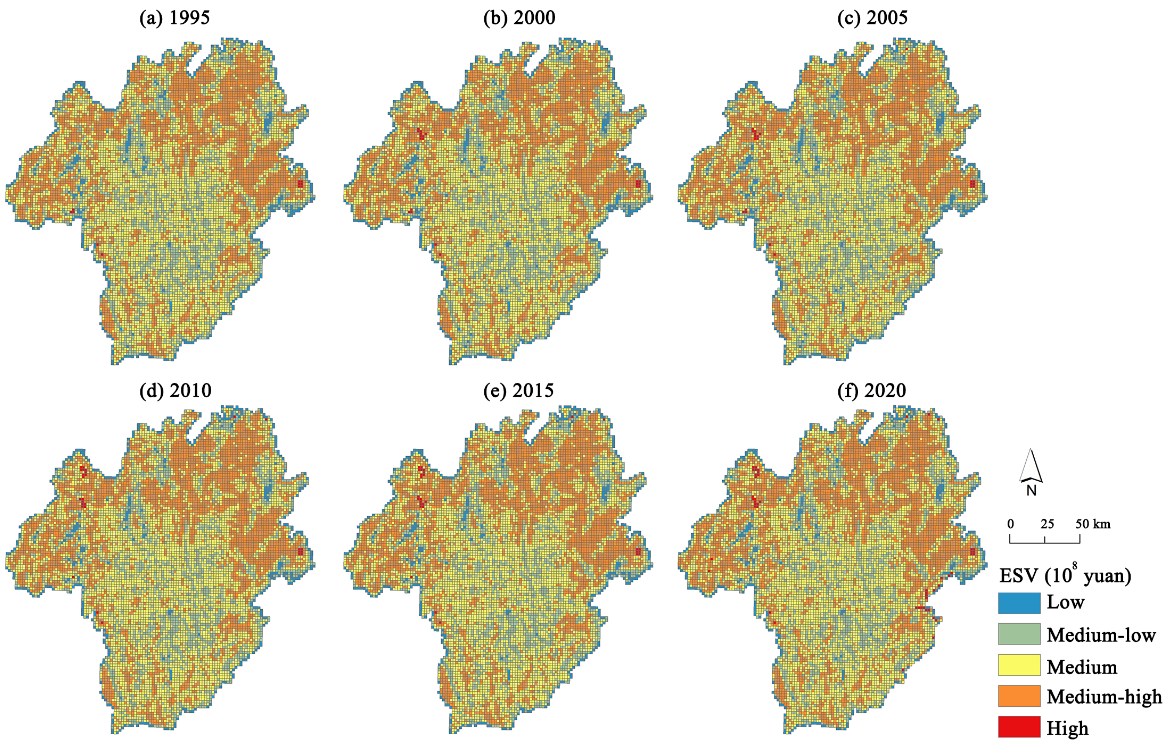

Fig. 5 Ecosystem service value (ESV) in the Da-Xiao Liangshan Mountains from 1995 to 2020.

km² to 10075.55 km², and its proportion increased from 32.24% to 33.43%. The coverages of the low-value (0<ESV), lower-value (300<ESV≤600), and middle-value (600<ESV≤900) areas declined, and these areas were gradually converted to high-value and higher-value areas. These results indicated the significant improvement of the quality of the environment in the study area. In addition, the agglomeration advantage of the ESV in the high-value areas gradually became prominent.

4.3 Topographic gradient effect of ESV

The topographic gradient differentiation characteristics of the ESV in the Da-Xiao Liangshan mountains were significant. As shown in Fig. 6a, the spatial distribution of ESV presented an inverted V-shaped feature with the increase of elevation, and its peak was the Level 4 (2100–2650 m) elevation gradient zone. For the Level 1–4 elevation gradient zones, the ESV increased significantly with the increase of elevation and reached a maximum value of 22.838 billion yuan at the Level 4 elevation gradient. After that, the ESV decreased rapidly with the increase of elevation. From the perspective of time evolution, from 1995 to 2020, the total ESV increased in all elevation gradient zones. The largest increase occurred in the Level 1 gradient zone, with an increase of 461 million yuan; followed by the Level 3 gradient zone, with an increase of 200 million yuan.

Fig. 6b reflects the impact of slope on the spatial distribution of ESV. The ESV increased rapidly with the increase of slope, until it peaked at the Level 5 gradient zone, and then declined. The Level 4 and Level 5 gradient zones were the most significant areas of ESV change.

Fig. 6c synthesizes the influence of the two topographic factors, namely elevation and slope. For the topographic position distribution characteristics of ESV, the distribution curve was similar to the elevation factor. The peak of ESV was at the Level 5 gradient. In 2020, the Level 5 gradient ESV reached 29.116 billion, with a contribution rate of 38.24%. From the perspective of the dynamic evolution pattern, from 1995 to 2020, the ESV of each topographic position gradient increased slightly. The ESV of the Level 2 topographic position gradient experienced the largest increase of 313 million yuan,

Table 4 Changes in the area and proportion of ESV in different zones from 1995–2020.

Ecosystem service value zoning		Low-value area (0<ESV≤3)	Moderately low-value area (3<ESV≤6)	Moderate-value area (6<ESV≤9)	Moderately high-value area (9<ESV≤12)	High-value area (12<ESV)
1995	Area (km²)	1361.93	5242.04	13781.30	9716.55	37.03
	Proportion (%)	4.52	17.39	45.73	32.24	0.12
2000	Area (km²)	1383.64	5254.96	13798.77	9636.86	64.63
	Proportion (%)	4.59	17.44	45.78	31.97	0.21
2005	Area (km²)	1380.61	5291.97	13786.64	9615.01	64.63
	Proportion (%)	4.58	17.56	45.74	31.90	0.21
2010	Area (km²)	1346.14	5049.73	13718.08	9942.06	82.84
	Proportion (%)	4.47	16.75	45.52	32.99	0.27
2015	Area (km²)	1340.14	5065.29	13674.62	9969.84	88.97
	Proportion (%)	4.45	16.81	45.37	33.08	0.30
2020	Area (km²)	1271.72	4959.50	13678.05	10075.55	154.04
	Proportion (%)	4.22	16.46	45.38	33.43	0.51

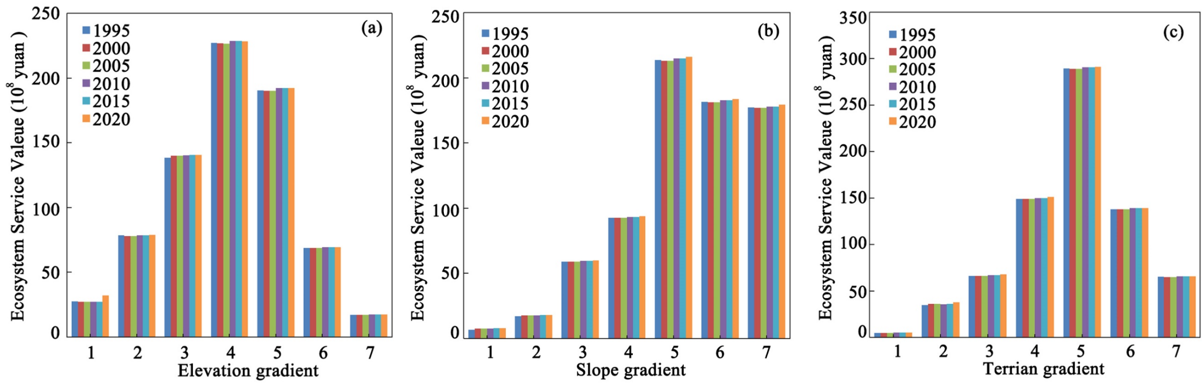

Fig. 6 Ecosystem service value statistics: (a) Elevation Gradient; (b) Slope Gradient; (c) Terrain Gradient.

followed by the Level 4 topographic position, with an increase of 203 million yuan. The ESV of the Level 1 (+31 million yuan) and Level 7 (+53 million yuan) topographic positions increased slightly.

In summary, the ESV was significantly affected by topographic factors. According to the combined influence of elevation, slope, and topographic position factors, the peak ESV in the study area were concentrated in the Level 4 gradient zone of elevation, the Level 5 gradient zone of slope, and the Level 5 gradient zone of topographic position factor. The ESV of the low topographic position was lower than that of the high topographic position.

From the perspective of the topographic gradient differentiation characteristics of the ESV of each land use type (Fig. 7), woodland was most significantly affected by topographic factors, followed by grassland and water. Overall, from 1995 to 2020, the spatial distribution pattern of each land use type on different terrain gradients was relatively stable. This is because that the Da-Xiao Liangshan mountains has always emphasized the protection and management of ecological resources, and its forest area has not changed significantly over the past 25 years. Despite the significant increase in built-up area, the low topographic gradient has continuously squeezed the grassland area, resulting in a decrease of 498 million yuan in the ESV of the grassland over the past 25 years. However, an increase in the water area in the study area was noted, and the contribution of its hydrological regulation function to the ESV did not decrease the total ESV but increased it by 1.1 billion yuan. In terms of the ecological dominance of land use types, the ESV of woodland, grassland, and cultivated land were mainly concentrated in the Level 5 topographic position gradient; that of the water area was mainly concentrated in the Level 2 topographic position gradient; and the ESV of unused land was mainly concentrated in the Level 1 topographic position gradient.

5 Discussion

5.1 Research significance of the ESV of national key ecological function areas

National key ecological function areas are often subjected to many restrictions on regional development and various development activities due

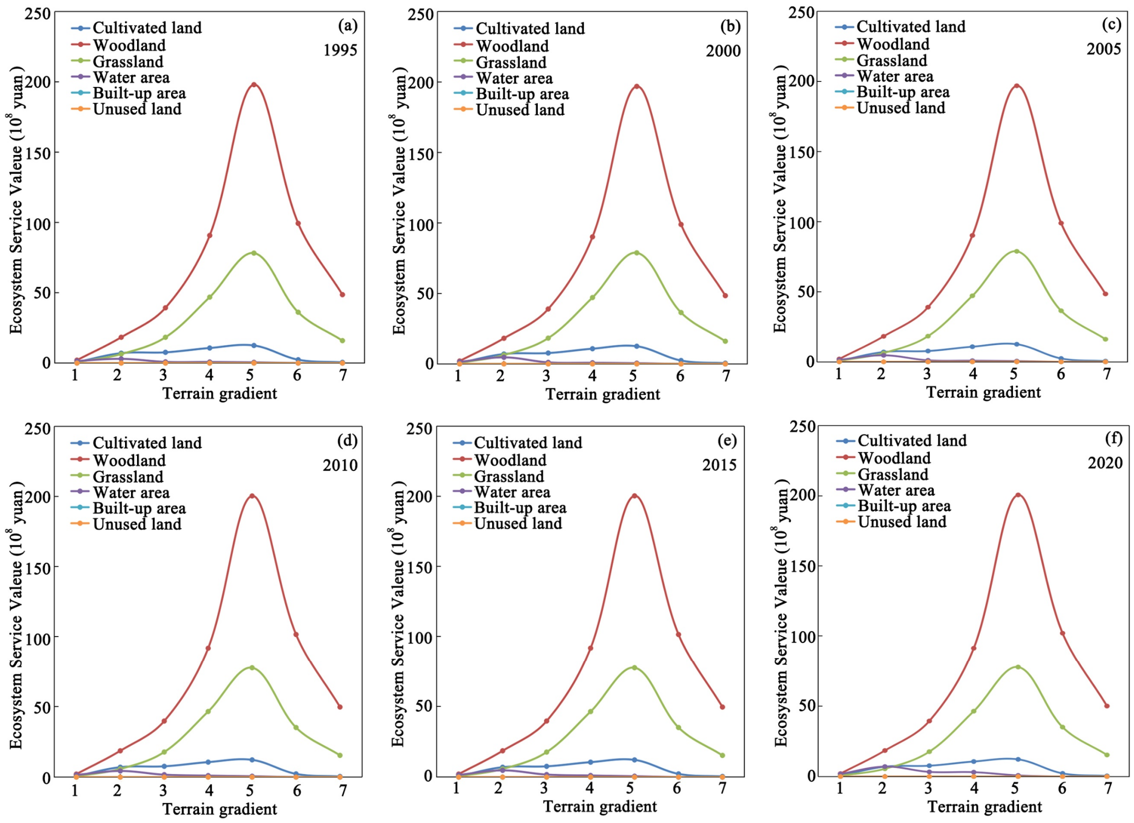

Fig. 7 Ecosystem service value statistics of different land use land cover (LULC) types.

to the importance of their water resources or ecological barriers, and the change characteristics of land use types and ESV are more complex (Xu et al. 2019). Although the study of ESV has attracted extensive attention from scholars, few related studies have focused on national key ecological function areas, especially in terms of spatiotemporal evolution and impact mechanisms. In this study, we find that the hydrological regulation function of the water area contributes a lot to the ESV. This finding is consistent with a study in Hubei Province (China) (He et al. 2022c), which provides an important perspective for enhancing the value of ecosystem services and ecological compensation in mountainous regions. Although forests and grasslands were the main components of the ecosystem in the Da-Xiao Liangshan mountains (accounting for more than 90% of the total area), the water areas dominated the changes in ESV, and their hydrological regulation function was the main reason for the continued rise in the overall ESV. As altitude increases, ecosystem diversity decreases, leading to a lower ESV. Increasing human development and construction at low elevation leads to a significant increase in water area with significant ESV for its hydrological regulation function. This further suggests that changes in climate and human-induced changes in LULC have a significant impact on ESV stability. This finding partially agrees with the research findings of Xiong et al. (2016) and Yang et al. (2023); that is, improving the water conservation function is of great significance to the ESV of national key ecological function areas. However, Wang et al. (2022) have pointed out that woodland and cultivated land are the main contributors to the change of ESV, and strengthening the protection of both is the starting point for the green development of national key ecological function areas. The above comparative analysis results showed significant differences in the spatial patterns and internal mechanisms of ESV in different types of key ecological function areas.

5.2 Impacts of mountain topographic factors on ESV

Topographic factors have important impacts on the spatial distribution of land use types, which in turn affect the function, structure, and service of ecosystem (Sauter et al. 2019; Zhang et al. 2020). In mountainous areas, the environment is more fragile than that of plain areas, and the topographic gradient effect is more significant (Tian et al. 2022; Xu et al. 2017). The Da-Xiao Liangshan area is a typical mountainous ecologically fragile area, and the topographic gradient distribution of the ESV presents an inverted V-shape, which is different from previous studies. For instance, Yang et al. (2018) found a significant logarithmic relationship between the ESV and the undulating topography in the middle reaches of the Yangtze River. Zhang et al. (2020) took the Northwest Plateau as the research object and suggested a linear negative correlation between ESV and undulating topography. This is closely related to the topographic gradient differentiation of land use types in the study area. In this study, we find that woodland and grassland were the main land types, and contributed the most to the overall ESV. This finding is in agreement with DeLoyde and Mabee (2023), which also pointed out that land use and land cover has a significant impact on the ESV. From 1995 to 2020, although the rapid increase of built-up area on the low topographic position gradient continuously encroached on grassland and caused a decline in its ESV, the increase in water area and its hydrological regulation function compensated for the above impact to a certain extent. This finding also indicates the important impact of the mutual conversion of land use types on ESV (Wang et al. 2022). Moreover, it also reveals that multiple ecological development strategies need to be adopted for different altitude.

5.3 Recommendations and prospects of the research

Based on the above findings, we found the significant effect of topographic factors on the ESV in mountain areas. The contribution of this study is that we found that topography has a significant influence on land use patterns and further determines the spatial pattern of ESV in the region. We have clarified the characteristics of ESV in mountainous regions along the topographic gradient, which provides a basis for classifying and guiding scientific decisions on ecosystem conservation. Furthermore，this also has led more scholars to focus on the three-dimensional space of ESV. We have to reflect on the limitations of the established paradigms and governmental decisions on ecosystem conservation strategies. For ecosystem at different altitudes, we should take measures to guide the classification.

Second, in recent years, with the implementation of rural revitalization strategy in remote mountainous areas of China and the increasing intensity of human activities, we should pay attention to the contribution of ecosystem service functions of land use types to ESV for ecosystem conservation.

Additionally, the following recommendations for Da-Xiao Liangshan mountains are put forward. (1) In view of the low ESV in Zhaojue County and Yuexi County in the middle of the study area, and Puge County and Butuo County in the south, the implementation of ecological restoration and management projects should be strengthened, the spatial pattern of land use should be optimized, and the service functions of the forest and grassland ecosystem types in the area should be improved. (2) The protection and enhancement of ecological service functions should focus on the Level 4 elevation gradient zone (2100–2650 m), Level 5 slope (15°–252°), and Level 5 topographic position index (0.57–0.66), which represented the peak ESV of the study area.

This study has several limitations that need to be addressed. Firstly, using the equivalent factor calculation method, it was found that the hydrological regulation function had a compensation effect on the reduction of the ESV caused by the expansion of built-up area. However, this study did not investigate the underlying mechanism. Secondly, the ESV of the hydrological regulation function in the paper was calculated based on the area of the land use type, while ignoring its structure and landscape pattern characteristics (Amani-Beni et al. 2021; Cheng et al. 2022). In the future, the influencing factors and mechanism of the ESV should be investigated in combination with geographic detectors and geographic regression models.

6 Conclusions

This paper selected the national key ecological function area of the Da-Xiao Liangshan area in Sichuan as the study area. By combining the long-term land-use remote-sensing monitoring data with the topographic factor index, this study quantitatively revealed the spatiotemporal differentiation characteristics of the ESV in the Da-Xiao Liangshan area and the topographic gradient effect. The main findings are as follows:

(1) The ESV of the Da-Xiao Liangshan area have significant spatial heterogeneity, showing a trend of being lower in the south, low in the middle, and high in the north, with a significant gradient feature.

(2) During the period of 1995-2020, the quality of the environment in the Da-Xiao Liangshan mountains improved significantly, and the ESV increased by 1.1 billion yuan, with a growth rate of 1.47%. During the periods of 2005–2010 and 2015–2020 the ESV increased significantly.

(3) Woodland and grassland are important supports of the ecosystem in the Da-Xiao Liangshan mountains, and their contribution to the ESV exceeded 90%. Nonetheless, the comparison found that water area was the key factor underlying the change of the overall ESV during the study period, and its hydrological regulation function was the main reason for the continuous increase of the overall ESV.

(4) The spatial distribution of ESV demonstrated an inverted V-shaped feature as the elevation increased, and its peak was at the Level 5 (0.57–0.66) topographic position gradient zone. The ESV in Da-Xiao Liangshan mountains was more significantly affected by topographic factors. Combining the results of the influence of elevation, slope and topographic position factors, the dominant ESV in Da-Xiao Liangshan mountains were concentrated in the 4th gradient band of elevation, the 5th gradient band of slope and the 5th gradient band of topographic position factor. The ESV of low topographic position is lower than that of high topographic position.

Research on the valuation of ESV can be traced back to the 1980s. Since Costanza et al. (1997) first proposed a framework for the economic valuation of ESV, research results on the valuation of ESV have been abundant. However, it is worth noting that there were fewer studies on the valuation of ESV in China published in international journals, which have only come to the fore in recent years. Most of these studies took urban agglomerations, river basin, and provinces as the study areas, and focused on analyzing the evolution and driving mechanisms of ESV. Fewer studies have focused on the differences in ESV caused by spatial heterogeneity of ecosystem types, especially for complex mountainous regions.

(1) In this study, we tried to expand the scope of ESV research in China and draw more scholars' attention to the value of ecosystem services in mountainous areas. Also, we attempted to analyze the value of ESV in high-altitude mountainous areas,

which is a key ecological protection function area in China, and its land use types and ecosystem service functions have distinctive regional characteristics and policy limitations, so focusing on the value of ecosystem services in this type of area is of great significance for scientific management of the ecosystem and protection of ecological security patterns. To the best of our knowledge, few relevant researches focused on the similar areas. This was one of the contributions of our study, which will likely draw the attention of scholars to this research direction, which was undoubtedly useful for enhancing the value of ecosystem services in national key ecological function areas.

(2) In terms of ESV valuation methods, we used the current mainstream and mature methods, and did not explore innovative methods. However, we used six periods of high-resolution land use data to reveal the evolutionary characteristics of ESV over the past up to 40 years, and used the topographic position index method to analyze the topographic gradient divergence characteristics of ESV. Most importantly, we found that forest land and grassland are the main ecosystem in the Da-Xiao Liangshan mountains (accounting for more than 90% of the total), however, it is the watershed that is the key factor in the change of ESV, and its hydrological regulatory function is the main reason for the sustained increase of ESV. In addition, the spatial distribution of ESV shows an "inverted V" pattern with the increase of topographic gradient, and the dominant position is the 5th level (0.57 - 0.66) topographic gradient band. These original findings would provide important reference for the protection and optimization of ecosystem services.

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Author Contribution

JIN Tao: data curation, formal analysis, methodology, writing-original draft, writing-review and editing. CHEN Yang: conceptualization, methodology, writing-original draft, writing-review and editing. SHU Bo: conceptualization, formal analysis, methodology. GAO Min: data curation, formal analysis, visualization. QIU Jian: conceptualization, methodology, funding acquisition, writing-review and editing.

Ethics Declaration

Data Availability: Due to the sensitive nature of the data, it is not made openly accessible. Researchers interested in accessing the data can contact the corresponding author.

Conflict of Interest: The authors declare no conflicts of interest.

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