

Article

Dynamic of Land Use and Associated Ecosystem Service Value in the Chengdu–Chongqing Urban Agglomeration, China

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Abstract: Understanding the long-term land use changes in the Chengdu–Chongqing urban agglomeration, a vital element of the Yangtze River Economic Belt and a key economic growth center in western China, can offer scientific basis and policy direction for improving regional ecosystem service values (ESVs), environmental conservation, and sustainable development. This study investigated the features connected to land use change, changes in landscape patterns, and variations in ESV across this region by means of time series of remote sensing and socio-economic data from 1990 to 2020. Additionally, the correlations between landscape pattern indices and ESV were examined. The findings indicated that: (1) cultivated land and grassland in the Chengdu–Chongqing urban agglomeration exhibited a declining trend, while forest, water, and construction land demonstrated increasing trends; (2) human activities significantly affected the Chengdu–Chongqing urban agglomeration, resulting in severe landscape fragmentation, heterogeneity, complexity of types, and patch separation, although the predominant patch types maintained strong connectivity; (3) the ESV of the Chengdu–Chongqing urban agglomeration initially decreased, reaching a minimum of CNY 5.017 billion in 2000, and subsequently rose again. Forest land accounted for approximately 69% of the overall ESV in the region over the preceding decades. The policy of reverting farmland to forest, the establishment of wetland parks, and the increased awareness of environmental protection have led to notable alterations in land use types and landscape patterns within the Chengdu–Chongqing urban agglomeration, which can significantly improve the regional ecosystem service value; however, the extent of influence and trends among various landscape indices are disparate.

Keywords: land use; ecosystem service value; landscape pattern; Chengdu–Chongqing urban agglomeration



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1. Introduction

Due to rapid economic development in the Chengdu–Chongqing urban agglomeration (CCUA) that derived from accelerating China’s urbanization process over recent years [1], there have been substantial changes in land use and landscape patterns. The impacts of these changes are not only felt in the regional economy but also ripple through to local ecosystem services [2]. Urban expansion, infrastructure construction, and the high-intensity development of land resources have significantly reduced forests, wetlands, and other natural landscapes, directly affecting the ecosystem’s stability and function [3,4]. Several

studies have demonstrated the significant effects of landscape patterns on ecosystem service value (ESV) [5–7]. But, in the case of the Chengdu–Chongqing urban agglomeration, systematic studies are lacking. The Chengdu–Chongqing region is located in the southwest of China, which holds a pivotal position and plays an important role within the national development strategy [8]; thus, it becomes necessary to investigate landscape pattern change variations that influence ESVs in order to elucidate regional land use–land cover (LULC) changes' eco-effects in the Chengdu–Chongqing district and empowerment for systematic local policy formulation is urgently needed. The results from this study will serve as an important theoretical basis for the green development of the Chengdu–Chongqing urban agglomeration, and it is expected that they can provide a reference framework or methodological guidance to clarify evolutionary trends in landscape pattern types and quantitatively assess ecosystem services.

As one of China's most rapidly urbanizing areas and a main driver of the western development strategy, the Chengdu–Chongqing urban agglomeration offers a convincing case study for analyzing the dynamics of land use and related ecosystem service values. This region embodies a complex interplay between urban expansion, agricultural preservation, and ecological conservation, reflecting its dual identity as both an economic powerhouse and an ecological barrier zone. The varied topography, including plains and mountains, along with considerable socio-economic diversity, provides a robust basis for examining spatial and temporal changes in land use patterns and their effects on ecosystem services. Moreover, the CCUA's strategic significance within China's national spatial planning initiatives, particularly the Chengdu–Chongqing economic circle, underscores its importance as a benchmark for crafting sustainable urban–rural development policies and achieving a balance between economic growth and environmental stewardship [9]. Nevertheless, rapid urban expansion and land use transformations have intensified challenges to the region's ecological environment and ecosystem services, particularly in the contexts of climate change [10], ecological security [11], and biodiversity conservation [12]. Addressing these pressing issues requires systematic and interdisciplinary analyses to reconcile development with environmental protection.

Currently, plenty of methods, such as the CA-Markov model [13], the InVEST model based on a geographic information system (GIS) [14], and ecosystem service evaluation model [15], have been applied. Based on time series remote sensing data, Zhong et al. [16] examined the alterations in landscape patterns of urban agglomerations in central China, integrated these findings with a landscape pattern index evaluation model, and assessed the influence of various land use types on ecosystem services during urbanization. Xie et al. [17] employed GIS-based spatial statistics and analysis techniques to assess the spatiotemporal alterations in land use, landscape patterns, and ecosystem service value in northeast Jiangxi. They introduced the elasticity index and spatiotemporal geographically weighted regression (GTWR) models to investigate the effects of land use and landscape pattern changes on ESV. Fan et al. [18] utilized the InVEST model to examine the correlation between wetland ecosystem services and landscape patterns by assessing habitat quality, carbon sequestration, and water purification services of wetland ecosystems along the Yangtze River Economic Belt and their variations. Zhang et al. [19] employed a self-organizing feature mapping neural network model and a random forest (RF) with a visual expression method to investigate the non-linear correlation mechanism between landscape pattern attributes and total ecosystem service benefits within a collaborative framework. Meng et al. [20] examined the spatial–temporal evolution characteristics of wetland landscape patterns in the southern Yellow River Basin, employed the CA-Markov model to forecast the wetland landscape pattern until 2060, and assessed the impact on wetland ecosystem services.

The research perspectives mainly include urbanization, policy impact, and ecosystem services' multi-scale and multi-dimensional impact. Wang et al. [21], from the standpoint of the influence of conservation policies, analyzed the geographical differentiation characteristics of landscape design and three typical water ecosystem services, including rain–flood control, soil and water conservation, and water quality purification. From the viewpoint of fast urbanization, Li et al. [22] investigated the landscape pattern and ecosystem services of the Fuxian Lake Basin, statistically evaluating their development and evolution dynamics. From the vantage point of medium- and high-speed urbanization in new rural construction, Xia et al. [23] investigated the spatiotemporal changes in landscape patterns and ecosystem service functions in the Lishui District of Nanjing and found the relationship between the landscape pattern index and ecosystem service function. Using multi-scale analysis techniques, Gao et al. [24] aggregated remote sensing, GIS, and other multi-source data to expose the spatial distribution and variability of landscape activities. With the importance of the Chengdu–Chongqing urban agglomeration in China, this study sought to methodically investigate the features connected to land use change, changes in landscape patterns, and variations in ESV across this area using several approaches, so offering a useful reference for the sustainable development of the regional ecological environment.

2. Materials and Methods

2.1. Description of the Study Area

Located in the upper reaches of the Yangtze River, the Chengdu–Chongqing urban agglomeration is an area with the highest degree of development and a great future for expansion in western China [25] and is among the important urban clusters included in the national 14th Five-Year Plan. The Ecological Environment Protection Plan of Chengdu–Chongqing Economic Circle emphasizes the need for fostering a high-quality, living environment and supporting the ongoing enhancement of the ecological surroundings. Warm winters and hot summers, plenty of precipitation, high relative humidity, average annual temperature of 16–18 °C, and annual rainfall of 900–1200 mm define this subtropical humid monsoon climate. The landscape fragmentation of the Chengdu–Chongqing urban agglomeration is severe, with scattered distribution of various landscape types and agglomeration of ecological patches surrounded by artificial patches. It boasts a superior geographical location, abundant natural resources, and favorable conditions that are conducive to rapid economic and social development. However, it also deals with issues including fast urban and rural building land expansion and ongoing loss of agricultural land and other ecological areas [26].

2.2. Data Sources

This study mainly used the social economy data and land use data derived from satellite remote sensing during the past three decades. The statistical yearbooks of Sichuan Province and Chongqing from 1990 to 2020 as well as the statistical yearbook and statistical commune of cities in the research region mostly provided the pertinent social and economic development data. The Chinese Academy of Sciences (<http://www.resdc.cn>; accessed on 20 June 2024) and the Data Center for Resources and Environmental Sciences helped to produce the land usage statistics of the Chengdu–Chongqing urban agglomeration. The analysis was based on four periods of data in 1990, 2000, 2010, and 2020 with a spatial resolution of 30 m × 30 m. A total of six land use types were classified, including cultivated land, forest land, grassland, water, construction land, and unused land (Figure 1).

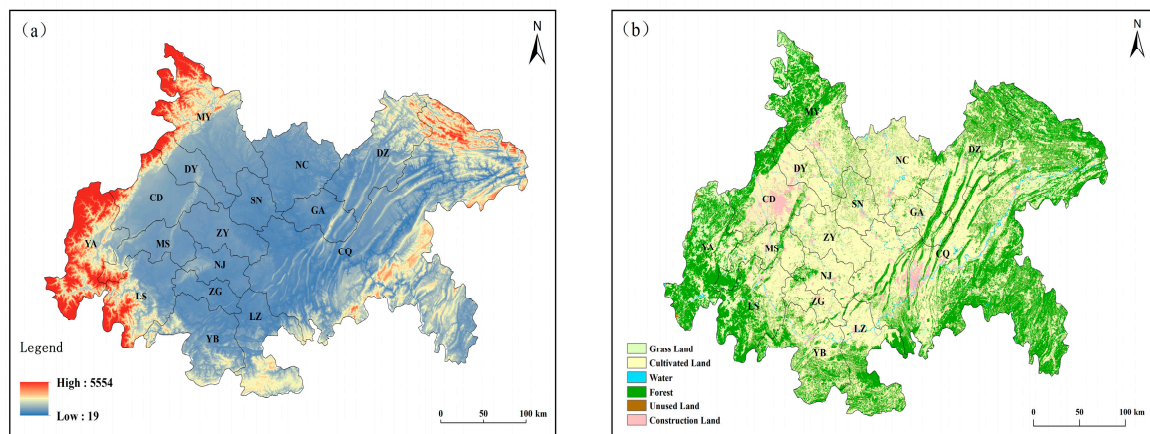


Figure 1. Sketch map of the study region. (a) Elevation map; (b) land use status map. Abbreviations: YB: Yibin; LS: Leshan; ZG: Zigong; NJ: Neijiang; SN: Suining; LZ: Luzhou; ZY: Ziyang; YA: Yaan; NC: Nanchong; MY: Mianyang; DY: Deyang; CD: Chengdu; CQ: Chongqing; GA: Guangan; MS: Meishan; DZ: Dazhou.

2.3. Research Methods

2.3.1. Dynamics of Land Use

Land use dynamic attitude can represent the degree of landscape change of several landscape types in a region and the intensity of landscape change in a certain period. It comprises a thorough land use dynamic attitude as well as a single one. Single land use dynamic attitude explains the rate of change in a given landscape during a given period [27], calculated as:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\% \quad (1)$$

K represents the dynamic attitude of a singular land use; U_a and U_b denote the areas of a certain land class in the initial and final years, respectively. T represents the duration. The dynamic nature of integrated land use indicates the overall rate of change within the entire region [28].

$$L_c = \left[\frac{\sum_{i=1}^n \Delta LU_{i-j}}{2 \sum_{i=1}^n LU_i} \right] \times \frac{1}{T} \times 100\% \quad (2)$$

where L_c represents the dynamic attitude of comprehensive land use; LU_i denotes the area of landscape type i in the initial year. ΔLU_{i-j} is the absolute value of the region where landscape type i transitioned to landscape type j during the specified period; T denotes the duration.

2.3.2. Calculation of the Land Use Transfer Matrix

The transfer matrix effectively delineates the structural attributes and directional shifts of landscape type alterations within a region and is extensively utilized in land use change studies. Three periods of transition matrix from 1990 to 2000, from 2000 to 2010, and from 2010 to 2020 were calculated. According to the data structure, a Sankey map was drawn to express the landscape type transfer more intuitively.

$$S = \begin{pmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & S_{ij} & \vdots \\ S_{n1} & \cdots & S_{nn} \end{pmatrix} \quad (3)$$

2.3.3. Landscape Pattern Index

The modifications in the quantitative composition of landscape types and the geographical variability of landscapes jointly represent shifts in the landscape pattern. These changes subsequently influence the heterogeneity, stability, diversity, and other characteristics of ecosystem services, ultimately leading to variations in the ESV within the region. The landscape pattern index reflects landscape structure composition, spatial configuration characteristics, and heterogeneity. By means of quantitative research on the dynamic changes in landscape patterns, the landscape pattern index enables one to depict these patterns both objectively and intuitively. This method helps to investigate the relationship between landscape patterns and values of ecosystem services. In this work, depending on the body of current knowledge and experience [29,30], a total of seven indices, including the patch number (NP), maximum patch index (LPI), patch density (PD), patch shape (LSI), contagion index (CONTAG), cohesion index (COHESION), and Shannon's diversity index (SHDI), were used to analyze their development rules (Table 1).

Table 1. Landscape pattern indices and definitions.

Index	Definition
NP	Reflects the overall heterogeneity and fragmentation of landscape
LPI	Reflects the dominant patch type
PD	Reflects the density of patches in the landscape
LSI	Reflects the spatial distribution characteristics and shape complexity of landscape shape
CONTAG	Reflects the development trend of different plaque types
COHESION	Reflects the degree of landscape aggregation
SHDI	Reflects the complexity of landscape

2.3.4. Evaluation of Ecosystem Service Value

This work also employed the real grain production capacity to change and eventually ascertain the extent of ESV in the Chengdu–Chongqing urban agglomeration by referencing the magnitude of China's terrestrial ESV suggested by Xie et al. [31]. The average grain price from 1990 to 2020 was chosen based on the wide research horizon and inflation's effect. The scale of ESV was built based on the real state of the research area (Table 2). The sowing area, unit yield, and average price data of important crops of rice, wheat, and corn in the Chengdu–Chongqing urban agglomeration were selected; the ESV per unit area of grain production was 1984.09 yuan/hm² using Equation (5). Given that the building land mostly disturbs the ecosystem, the ESV is not included; rather, the ESV per unit area was computed using the ESV equivalent of various functions of the ecosystem in China, then the total ESV of the study area was computed. The computation follows this formula:

$$ESV = \sum_{i=1}^n A_k \times C_{v,k} \quad (4)$$

$$ESV_f = \sum_{i=1}^n A_k \times C_{v,kf} \quad (5)$$

ESV denotes ecological service value; A_k represents the area of land use type k ; $C_{v,k}$ denotes the ecological service coefficient for land use type K ; ESV_f represents the value of the f single service function inside the ecosystem. $C_{v,kf}$ represents the ecosystem service coefficient for item f within land use type k .

Table 2. Ecosystem service value coefficient of Chengdu–Chongqing urban agglomeration (CNY/hm²).

First Category	Second Category	Cultivated Land	Forest Land	Grassland	Water	Unused Land
Provision of Services	Food Production	2202.34	496.02	456.34	793.64	0.00
	Raw Material	496.02	1150.77	674.59	238.09	0.00
	Water Supply	−2599.16	595.23	376.98	10,376.80	0.00
Regulation Service	Gas Regulation	1765.84	3789.62	2400.75	952.36	39.68
	Climate Regulation	932.52	11,329.17	6329.26	2817.41	0.00
	Decontaminate the Environment	277.77	3313.43	2083.30	5674.50	198.41
	Hydrological Regulation	2976.14	7420.51	4642.78	108,510.02	59.52
Support Service	Soil Conservation	1031.73	4603.09	2916.62	932.52	39.68
	Maintaining Nutrient Cycling	317.45	357.14	218.25	79.36	0.00
	Biological Diversity	337.30	4206.28	2658.68	2539.64	39.68
Cultural Service	Aesthetic Landscape	158.73	1845.21	1170.61	1964.25	19.84

Note: The table reflects the ecosystem service value per unit area, modified according to the land use classification of the Chengdu–Chongqing urban agglomeration. The corresponding factor represents the mean value of its secondary classification. Unutilized land refers to barren land in arid regions.

2.3.5. Correlation Analysis

Land use changes' effect on ecosystem service can be fairly reflected in the coupling interactions between landscape indices and ESV. The Pearson correlation coefficient is used to conduct a bivariate correlation analysis of different classes' landscape index and ESV from 1990 to 2020. Analyzing the sensitivity of ESV to every landscape index and investigating the degree of its influence will help one to determine whether there is a strong association between the changing trend of regional landscape patterns and ESV. The specific research framework is shown in Figure 2.

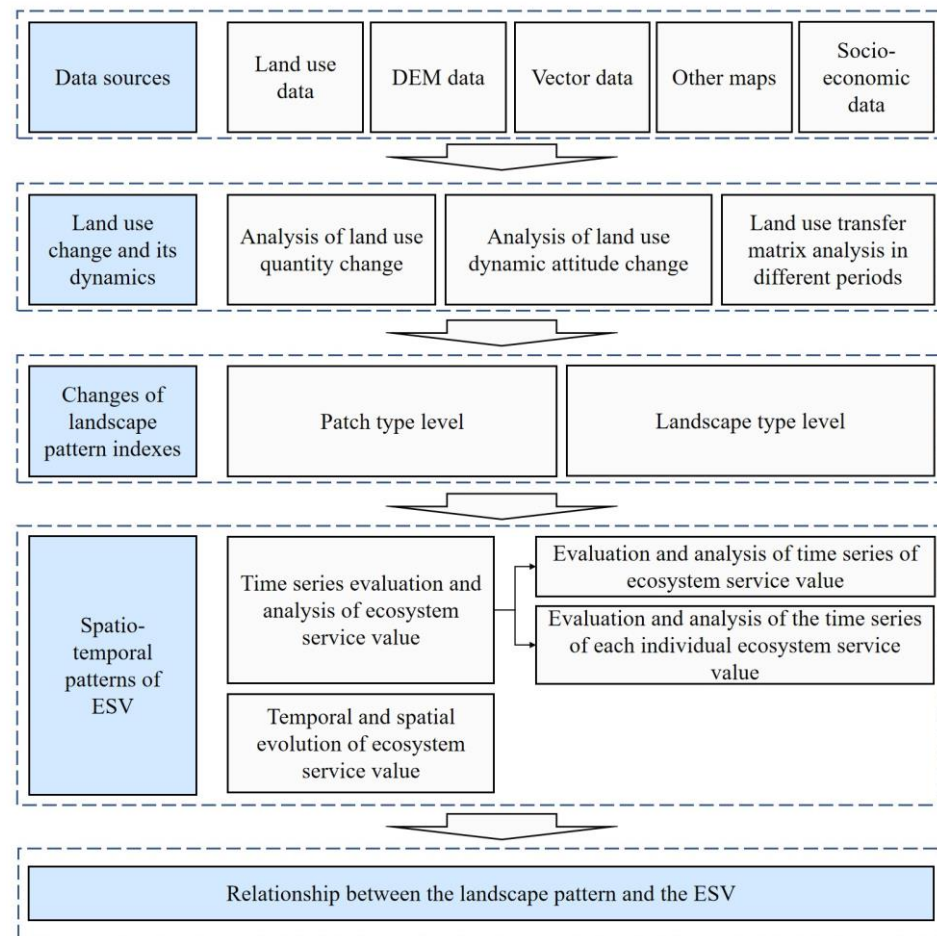


Figure 2. Research framework of this study.

3. Results

3.1. Land Use Change and Its Dynamics

While cultivated land and construction land are mostly concentrated in the center region, forests and grasslands are mostly spread in the eastern, southern, and western regions of the research area (Figure 3). Together accounting for more than 95% of the total land area in the Chengdu–Chongqing urban agglomeration, forest, cultivated land, and grassland form the main land use types (Table 3), so defining the landscape baseline of the area. With decline rates of 1.88% and 1.90%, both cultivated land and grasslands displayed a dropping tendency over the research period, declining by 4493 km² and 4539 km², respectively, representing the two most drastically diminishing land use categories. The area of forest land showed a general trend of early decline then increase. The extent of woodland dropped slightly by 135 km² between 1990 and 2000. But with the trial conversion of cultivated land to forest in the Chengdu–Chongqing urban agglomeration, the amount of forest grew positively, rising by 3136 km², with an overall growth rate of about 1.26%. With a negligible change rate of roughly 0.28%, the area of water showed a gradual increase over the past 30 years, rising by roughly 671 km². As the Chengdu–Chongqing urban agglomeration began a phase of fast development during the past three decades, the demand for land to support economic growth resulted in a notable and ongoing increase in construction land, with a major expansion concentrated mostly in Chengdu and Chongqing. Expanding by about 5241 km², the total area under development showed a 2.20% increase overall. The area of unused land remained relatively stable, with its proportion remaining largely unchanged.

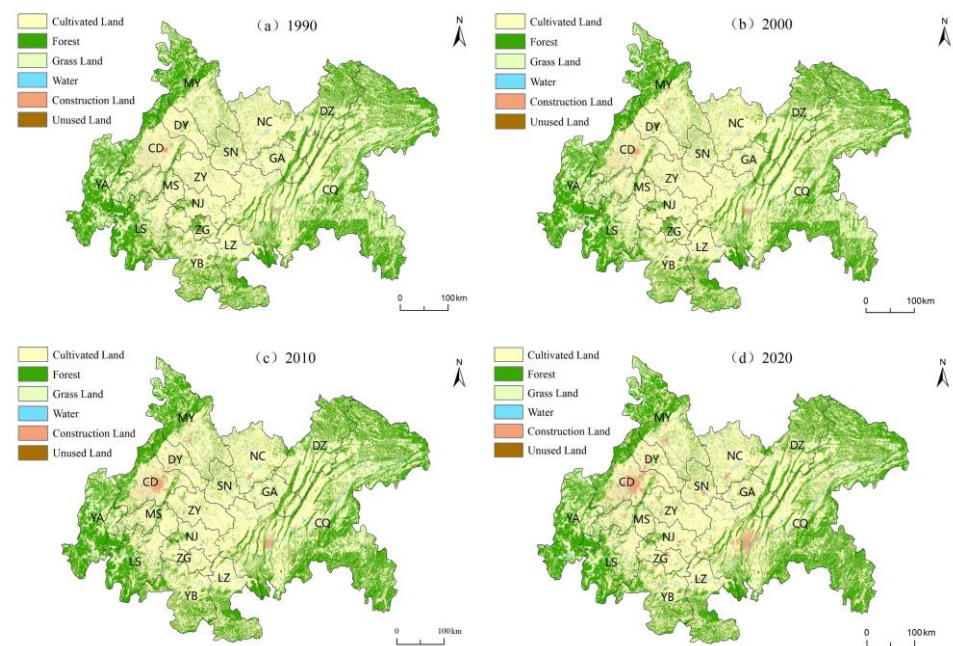


Figure 3. Land use change in Chengdu–Chongqing urban agglomeration from 1990 to 2020.

Table 3. Area of various landscape types in Chengdu–Chongqing urban agglomeration from 1990 to 2020.

Landscape Type	1990		2000		2010		2020	
	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)	Area (km ²)	Proportion (%)
Cultivated land	131,664	55.20	131,013	54.92	129,308	54.21	127,171	53.32
Forest	76,747	32.17	76,612	32.12	79,102	33.16	79,748	33.44
Grassland	24,561	10.30	24,627	10.32	21,329	8.94	20,022	8.40
Water	2935	1.23	2945	1.23	3285	1.38	3606	1.51
Construction land	2407	1.01	3120	1.31	5208	2.18	7648	3.21
Unused land	221	0.09	217	0.09	306	0.13	304	0.13

From the standpoint of general land use dynamics (Table 4), the land use change rate in the Chengdu–Chongqing urban agglomeration was highest between 2010 and 2020, at 0.40%; followed by 2000–2010, at 0.28%; and 1990–2000, at 0.04%. Over the 1990–2020 period, the overall land use dynamic index showed an upward trend, reflecting more pronounced land use changes, influenced by socio-economic development and policy adjustments. This trend also indicates continued significant expansion of construction land in towns and cities, with an increasing intensity of land use. The construction land demonstrated the highest dynamic index throughout the three periods, recorded at 2.96%, 6.69%, and 4.69%, respectively, signifying it was the most volatile land use category during the study duration. In contrast, the dynamic index for cultivated land remained below 0 throughout 1990–2020, indicating a high utilization rate and continuous area reduction. The dynamic index for water was positive during each period—0.03% from 1990–2000, 1.15% from 2000–2010, and 0.98% from 2010–2020—peaking between 2000 and 2010. The forest dynamic index was negative from 1990–2000, but increased to 0.33% from 2000–2010, reflecting some growth in area. The dynamic index for unused land peaked between 2000 and 2010 at 4.10%, but the dynamic index for grasslands was -1.34% , indicating it was the most significant land use type experiencing decline during the study period. The land use dynamics in the Chengdu–Chongqing urban agglomeration exhibited a persistent

increasing tendency, but with relatively small total changes. The peak land use dynamic index was seen from 2010 to 2020, signifying the most vigorous land use change phase in the research.

Table 4. Dynamic attitude of land use in the study area from 1990 to 2020.

Year	Single Land Use Dynamic Attitude						Comprehensive Land Use Dynamic Attitude
	Cultivated Land	Forest	Grassland	Water	Construction Land	Unused Land	
1990–2000	−0.05	−0.02	0.03	0.03	2.96	−0.18	0.04
2000–2010	−0.13	0.33	−1.34	1.15	6.69	4.10	0.28
2010–2020	−0.17	0.08	0.61	0.98	4.69	−0.07	0.40

3.2. Land Use Transfer Matrix

The Sankey map (Figure 4) illustrates the shifts in land use types within the Chengdu–Chongqing metropolitan agglomeration from 1990 to 2020. From 1990 to 2000, agricultural land was predominantly transformed into urban land, including 693.92 km², which represents 37.81% of the overall land area conversion in the studied area. A limited area of cultivated land was transformed into forest (194.80 km²), with negligible shifts to grasslands and water bodies. The forest underwent the most significant transition to grasslands, including an area of 314.29 km², part of which was reverted to cultivated land, while the other land types (water, built-up areas, and uncultivated land) exhibited relative stability. Between 2000 and 2010, land use transitions peaked in total area, with 13,184.11 km² experiencing alterations. During this period, cultivated land was primarily converted to forest land (2413.01 km²) and construction land (2045.43 km²), representing 18.30% and 15.51% of the total land transition area, respectively, with some areas shifting to grasslands and water. Forest also saw mutual conversions with cultivated land and minor transitions to grasslands, water, construction land, and unused land. Grasslands were primarily converted to cultivated land and forest, totaling 3209.37 km², which accounted for 23.34% of the total land transitions, while the other land types experienced relatively minor changes. Between 2010 and 2020, cultivated land continued to shift toward forest, covering an area of 4683.37 km². With greater interactions between forest and grasslands, the conversion of land to construction land, grasslands, and water changed greatly during this period. Apart from that, areas of water changed to forest and building land changed to cultivated land. The area of unmet demand stayed rather constant. With regular exchanges between several land types, except for unused land, the “Return Cultivated Land to Forest” program raised the complexity and diversity of land transitions overall.

The proliferation of construction land was the most significant among the various land use categories in the Chengdu–Chongqing urban agglomeration. The research area is encircled by mountainous and plateau regions, comprising the Qinling Mountains and Daba Mountains to the north, the Yunnan–Guizhou Plateau to the south, the Hengduan Mountains and Qinghai–Tibet Plateau to the west, and the Wushan Mountains to the east. Due to the region’s unique geographical features, forest and grasslands are concentrated in high-altitude areas and form an enclosed distribution pattern. Both natural and human factors contribute to this distribution. From a natural perspective, the eastern part of Chongqing, Mianyang, Deyang, Chengdu, the western part of Ya’an, Leshan, Yibin, and the southern part of Luzhou are predominantly mountainous plateaus, resulting in higher altitudes and a complex natural environment that is unsuitable for human habitation. Consequently, these areas are mainly covered by forest. In contrast, the central region, which forms the Sichuan Basin, is characterized by flat terrain, fertile land, and a favorable climate, making it suitable for large-scale mechanized farming and positioning it as an important

agricultural production zone in southwest China. Human elements, such the fast development of cities like Chengdu, Chongqing, and Mianyang, have spurred the conversion of vast swaths of farmed land into building land, as past studies have found. Moreover, the “Return Cultivated Land to Forest” policy has resulted in the active conversion of farmland to forest and lake in the Chongqing area, so increasing the forest area and also yielding notable changes in other areas. In contrast, regions such as Suining, Nanchong, Guang’an, and Dazhou, with slower economic development and population outflow, have seen non-construction land recover and contribute to environmental improvements.

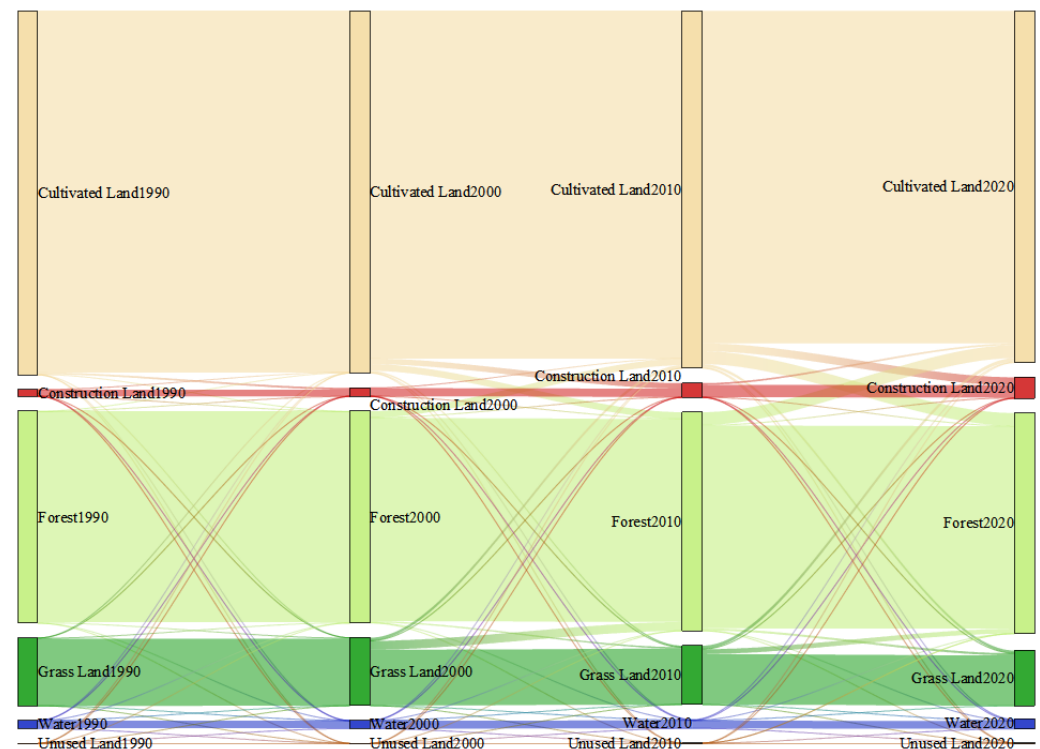


Figure 4. Transfer matrix of different land use types from 1990 to 2020.

3.3. Changes in Landscape Pattern Indices

From 1990 to 2020, the research in Table 5 shows at the landscape level that the general spatial landscape pattern indices of the Chengdu–Chongqing urban agglomeration displayed varied patterns. The NP and LPI generally showed a decline followed by an increase, while PD remained relatively stable. LSI showed an upward trend, indicating that the distribution of patch types became uneven and reflecting an increasing complexity and irregularity in the overall landscape shape. SHDI also increased, suggesting a reduction in the proportional differences among landscape types, leading to a more balanced spatial distribution and a weakened dominance of specific landscape components. CONTAG decreased, indicating a reduction in landscape continuity. Particularly from 1990 to 2010, in the early phase of urbanization, population increases and socio-economic development caused a continual decline in the number of patches, the biggest patch size, and the contagion index in the Chengdu–Chongqing urban agglomeration. This resulted in reduced landscape continuity and increased fragmentation. As urbanization progressed, urban expansion became increasingly constrained by stricter planning and management regulations, and socio-economic factors also underwent changes. From 2010 to 2020, the execution of policies like the “Return Cultivated Land to Forest” initiative, wetland restoration, urban park development, and ecological restoration led to a substantial rise in the quantity of patches, patch density, and the size of the largest patch. These changes contributed to

greater landscape diversity in the study area and fostered a shift towards a more sustainable ecological environment.

Table 5. Change in landscape indices of Chengdu–Chongqing urban agglomeration from 1990 to 2020.

Year	NP	PD	LPI	LSI	SHDI	CONTAG
1990	137,038	0.57	10.68	349.47	1.03	62.67
2000	135,881	0.57	10.64	350.45	1.05	62.30
2010	133,941	0.56	10.49	351.64	1.07	61.72
2020	136,182	0.57	19.14	358.18	1.09	60.82

At the patch type level, as shown in Figure 5, the changes in NP and PD across different years and patch types during vegetation restoration varied, indicating differing degrees of fragmentation. The number and density of cultivated land patches consistently dropped for various patch types, suggesting that degree of fragmentation dropped as the area of cultivated land declined. Originally declining, the quantity and density of patches for forest, grass, water, building land, and unused land gradually grew. In 2000, the number and density of patches for forest, grasslands, water, construction land, and unused land reached their lowest values. During this period, the “Return Cultivated Land to Forest” policy was implemented, marking the peak of area growth for these five patch types. Fragmentation began to increase after 2000, indicating that, during the restoration process, these five patch types initially expanded in large, concentrated patches. Subsequently, area growth was dominated by scattered patches, which eventually started to merge into larger, contiguous areas. From a temporal standpoint, the two most common forms of land were forest land and cultivated land; this suggests that both types of land patches were somewhat big and dispersed rather unevenly. LPI shows the relative size of the biggest patch of a landscape type to the whole area of the landscape. With a patchy distribution, LPI for cultivated land is the highest, thereby suggesting that this is the main landscape type in the studied area. LPI first dropped and then surged, implying that in the first 20 years the area under cultivation shrank and so its dominance dropped as well. But after agricultural structural changes, the area under cultivation grew significantly, which raised its prominence. While building land progressively indicated a growth in the spatial aggregation of construction land, COHESION for cultivated land, forest, grasslands, water, and unused land remained stable.

3.4. Spatiotemporal Patterns of ESV

From 1990 to 2020, the total ESV of the Chengdu–Chongqing urban agglomeration demonstrated an initial decline followed by an increase, ascending from CNY 5.02466 billion in 1990 to CNY 5.08855 billion in 2020, with an average annual growth rate of 1.27%, an increment of CNY 63.89 million, and stabilizing around CNY 5 billion (Table 6). Throughout the study period, the ESV of the Chengdu–Chongqing urban agglomeration predominantly consisted of cultivated land and forest, with the lowest ESV seen on unused land, succeeded by water and grasslands. Between 2000 and 2010, the total ESV rose by CNY 52.46 million, marking the most significant increase during the study period. Conversely, between 1990 and 2000, the ESV of the Chengdu–Chongqing metropolitan agglomeration witnessed a modest decrease of CNY 9.06 million, chiefly because of the substantial loss of cultivated land and woodland. From 2000 to 2020, the execution of ecological initiatives like the “Return Cultivated Land to Forest” program, coupled with the extensive development of building land, resulted in a decrease in cultivated and grassland areas. Nevertheless, the augmentation of forest and water resources surpassed these losses, culminating in a rise of CNY 72.95 million in ESV throughout this period, thus offsetting the ESV losses incurred

from land use changes prior to 2000. Alterations in several land use categories significantly affected ESV, with forests and agricultural land making the most substantial contributions to the overall ESV. In the context of annual ESV fluctuations within the Chengdu–Chongqing urban agglomeration, ESV decreased from 1990 to 2000, which linked favorably with the decrease in cultivated land and forested areas. Between 2000 and 2010, the annual growth in ESV was the most significant, amounting to CNY 52.46 million, predominantly propelled by the enhanced environmental service values of forests and water. From 2010 to 2020, ESV increased by CNY 20.49 million, which was positively correlated with the growth in forest and water.

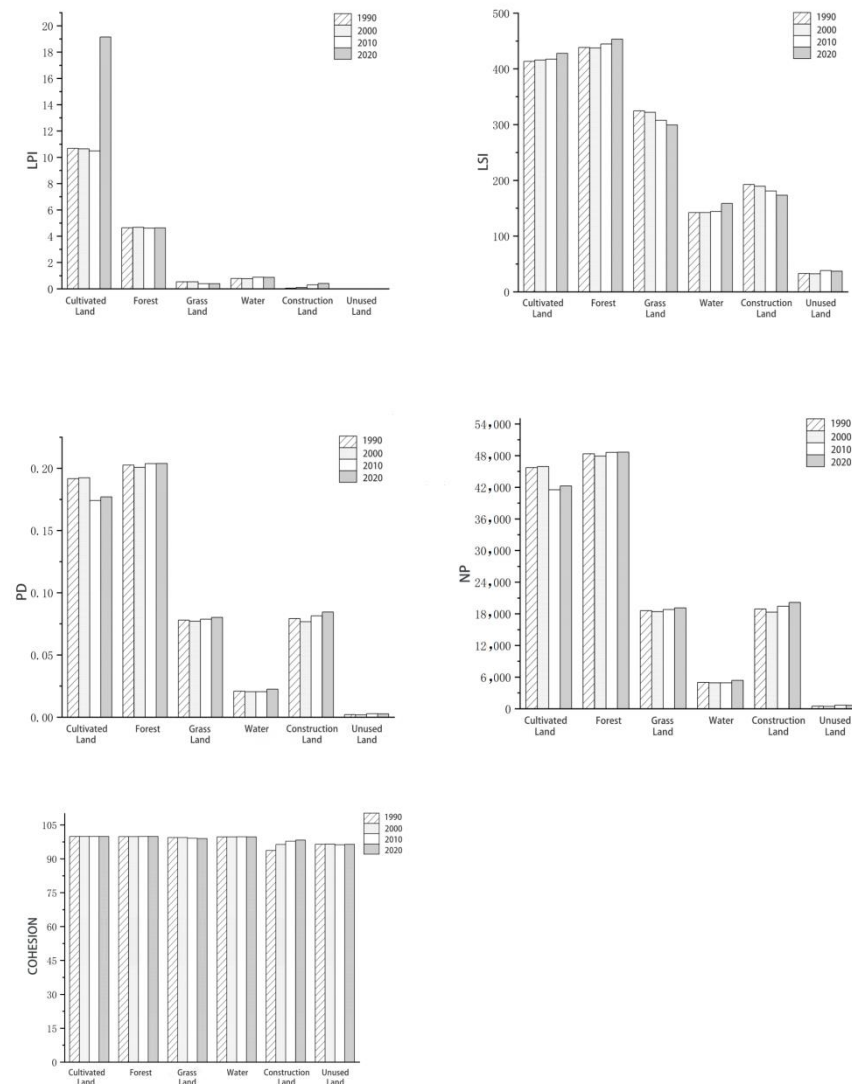


Figure 5. Horizontal change characteristics of patch types in the Chengdu–Chongqing urban agglomeration from 1990 to 2020.

Table 6. The ecosystem service value changes in different ecological types in Chengdu–Chongqing Urban agglomeration from 1990 to 2020 (ESV/10⁶ CNY).

Type	1990	2000	2010	2020	1990–2000	2000–2010	2010–2020
Cultivated Land	1039.71	1034.57	1021.10	1004.30	−5.14	−13.47	−16.80
Forest	3001.30	2996.02	3093.40	3118.67	−5.28	97.38	25.27
Grassland	587.70	587.70	510.36	479.09	0.00	−77.34	−31.27
Water	395.87	397.22	443.08	486.37	1.35	45.86	43.29
Unused Land	0.08	0.09	0.12	0.12	0.01	0.03	0.00

For the four chosen years, the ecosystem service values (Table 7) are CNY 5.02467 billion, CNY 5.01717 billion, CNY 5.06806 billion, and CNY 5.08847 billion, respectively. The ESV in the research area exhibits a declining tendency and then a rising one. The ESV dropped CNY 7.5 million between 1990 and 2000, mostly because of a decline in the extent of woodland and farmed land. By comparison, the total ESV in 2010 rose by CNY 50.89 million from 2000, the greatest rise during the study period. One can mostly ascribe this rise to notable changes in land use pattern. Later on, the use of policies such as the “Return Cultivated Land to Forest” resulted in changes in land use, which helped to sustainably raise overall ESV in the study area. ESV ranked according to ecosystem service type as follows during the study period: regulating services > supporting services > provisioning services > cultural activities. With the biggest proportion of total ESV, regulating services dominated the ecosystem type used in the Chengdu–Chongqing urban agglomeration. From the standpoint of individual service functions (Table 5), the value of controlling ecosystem services was the largest, making up more than 69% of the total ecosystem service value in the urban agglomeration of Chengdu–Chongqing. Between 1990 and 2020, supporting services came next, accounting for 21%; most of this value comes from hydrological and climate control; soil protection and biodiversity are the main drivers of supporting services. With respective rates of 5.1% and 3.9%, however, provisioning and cultural services made rather lesser contributions. The ESV trends for hydrological control, biodiversity, and aesthetic landscapes matched the general trend of total ESV. On the other hand, especially for water supply services, which stayed negative, the value of other individual tasks kept declining. The main causes of this drop were population increase and the spread of urban building, which significantly raised water use for industrial and household uses. Especially between 1990 and 2020, the ESV for hydrological control rose noticeably, which immediately helped ESV to rise generally in the Chengdu–Chongqing urban agglomeration.

Table 7. Ecosystem service value of different service functions in Chengdu–Chongqing urban agglomeration from 1990 to 2020.

Ecological Service Type		1990	2000	2010	2020
Supply Service	Food Production	341.58	340.11	336.36	331.63
	Raw Material	170.89	170.46	170.34	169.22
	Water Supply	−256.82	−255.08	−246.88	−238.10
Regulating Service	Gas Regulation	585.11	583.62	582.45	578.29
	Climate Regulation	1155.98	1154.29	1160.99	1158.95
	Clean the Environment	358.74	358.30	361.15	361.80
	Hydrologic Regulation	1393.87	1392.33	1427.31	1454.51
Support Service	Soil Conservation	563.50	562.40	562.81	560.06
	Maintain Nutrient Circulation	74.80	74.56	74.22	73.51
	Biodiversity	439.99	439.40	441.40	440.74
Cultural Service	Aesthetic Landscape	197.03	196.78	197.91	197.86
Overall		5024.67	5017.17	5068.06	5088.47

By analyzing the unit-area ESV of different land patches, this study investigates the spatial variations in ESV from 1990 to 2020, as depicted in the four-period spatial distribution of ESV (Figure 6). From a spatial standpoint, locations with high ESV often line up with the distribution of lakes, woods, and grasslands over the past 30 years. Mostly mountainous with heights ranging from 500 to 1000 m, areas including Ya’an, Chengdu,

Deyang, and western Mianyang lie in the transitional zone between the first and second steps of China's topography. These areas are less affected by human activities due to geographical constraints, with slow urbanization and extensive forest coverage, leading to rich biodiversity. Consequently, these regions exhibit the highest and most evenly distributed ESV. In contrast, the higher ESV areas in the eastern region are located in the parallel canyons of eastern Sichuan, characterized by complex terrain and lower levels of development. Low ESV areas show a grouped and distributed pattern that corresponds with that of cultivated land, unused land, and building site distribution. Low ESV thus also follows a similar clustered and scattered distribution, mostly found in the Chengdu Plain and its environs. From 1990 to 2020, both Chengdu and Chongqing consistently exhibited lower ESV compared to other regions. This is mainly attributed to the flat terrain, fertile soils, and abundant water resources, which promote extensive agricultural use. Furthermore, swift urbanization and the impact of socio-economic activities have resulted in the proliferation of construction land and population density. As a result, the ESV contribution of cultivated land is relatively low, while construction land contributes negatively to ESV, thereby explaining the low or reduced ESV in this region.

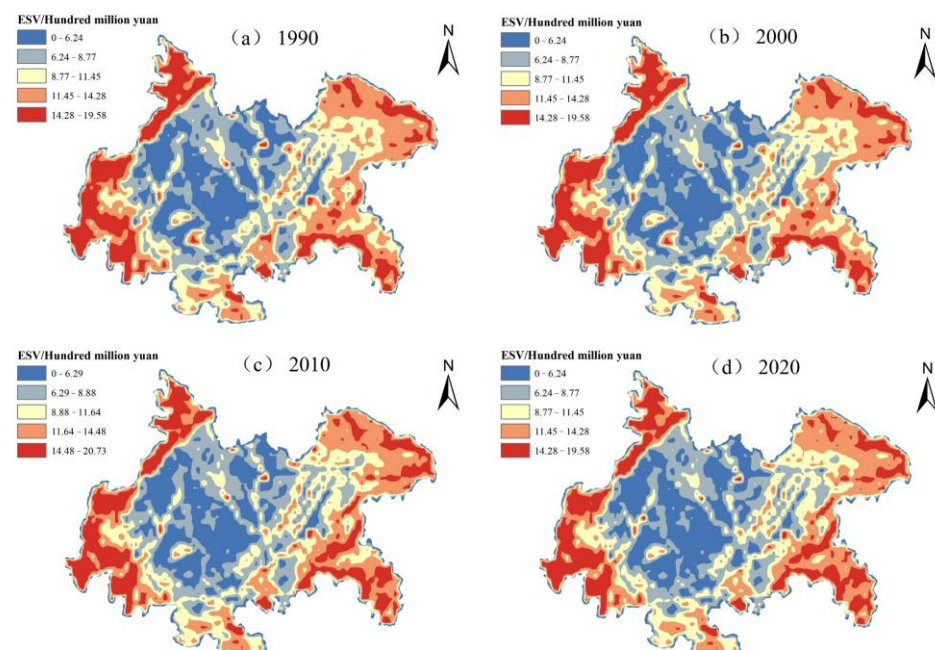


Figure 6. Spatial distribution of the ESV in the Chengdu–Chongqing Urban Agglomeration from 1990 to 2020.

3.5. Correlation Between ESV and Landscape Pattern

The association between landscape pattern indices and several ecosystem services in the research area was investigated by means of Pearson correlation analysis (Figure 7). With modest correlations noted for several indicators, the results show a noteworthy link between ESV and landscape pattern indices. Particularly, total ESV is positively connected with LSI and SHDI and considerably inversely correlated with CONTAG. These results imply that to some degree landscape complexity and variety may improve the general ecosystem service functions. Among several ecosystem services, hydrological control and climatic control help ESV most; both also show strong connections with landscape pattern indices. Hydrological regulation is negatively correlated with NP and PD and also shows a significant negative correlation with CONTAG. This implies that when landscape structure becomes more fragmented and dispersed, hydrological regulation may be weakened. Similarly, climate regulation is negatively correlated with NP, PD, and LSI, indicating that an increase in

patch number and density may reduce the climate regulation function. At the same time, climate regulation is positively correlated with CONTAG and SHDI, suggesting that the spread and diversity of the landscape may help enhance the climate regulation function in the region. Moreover, certain ecosystem service functions, including soil conservation, environmental purification, and nutrient cycling, have notable associations with specific landscape pattern indices. Soil conservation exhibits a negative correlation with LPI and LSI, while demonstrating a positive correlation with SHDI and CONTAG, suggesting that more intricate and diversified landscape structures may enhance soil conservation and nutrient cycling.

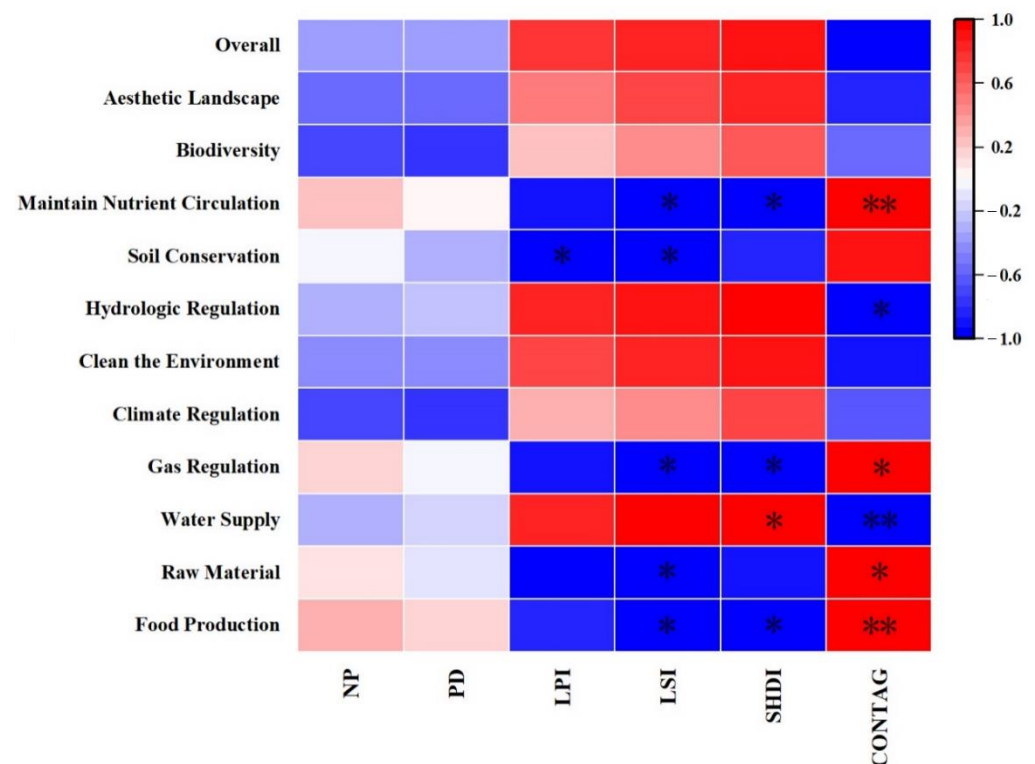


Figure 7. The correlation coefficient between landscape pattern indices and ecosystem service function in Chengdu–Chongqing urban agglomeration from 1990 to 2020. Note: * and ** indicate the significance level with $p < 0.05$ and $p < 0.01$, respectively.

4. Discussion

4.1. Effect of Land Use Changes

One of the most important human actions influencing ecosystems is change in land use. Urban master planning, as a macro-level guiding policy for urban growth, has greatly changed the structure, functions, and processes of urban ecosystems, so affecting ecosystem services [32] and, hence, the ecological well-being of urban inhabitants. Natural environmental variations and socio-economic development patterns of various areas affect the degree of influence on ESV [33]. The effect of land use change on ESV in the Chengdu–Chongqing urban agglomeration throughout two stages is investigated in this work. From 1990 to 2000, the first stage witnessed a drop in the ESV of the Chengdu–Chongqing metropolitan agglomeration [34]. The major cause of this drop was the fast socio-economic development [35], which led to the ongoing expansion of building sites over woods, agricultural areas, and undeveloped territory [36]. Construction land has a lower ESV than the land types it substitutes. Furthermore, the rapid expansion of buildings and roads exacerbated landscape fragmentation [37], disrupting the original balance of energy and material exchange between different landscape types. Consequently, the

decrease in vegetation cover resulted in a decrease in the value of providing, regulating, and supporting services, so contributing to the general drop in ESV over this period. From 2000 to 2020, the second stage saw a growth in ESV mostly due to the “Return Cultivated Land to Forest” program [38], important soil erosion prevention projects [39], and other ecological restoration projects [40] as well as the creation of wetland parks. During this period, water areas increased by 661 km² and forest grew by 3136 km², making them the fastest-growing land use types at this stage. This large increase in forests and water contributed significantly to the enhancement of regulating services. While urbanization was pushing the expansion of cultivated land, the rate of the rise in these regions was far slower than that of woods and water. Consequently, throughout this stage ESV in the Chengdu–Chongqing urban area showed an overall increasing trend. Future expansion of the Chengdu–Chongqing urban agglomeration must include the protection of forests and grassland as a first priority. Policies should concentrate on improving the land use structure, creating wetland parks around cities, and encouraging the return of farmed land to forests. These steps will not only boost the coverage of green areas but also assist in stopping the spreading concentration of building sites. Furthermore, it is advisable to promote balanced development among several land use categories by means of afforestation of appropriate vacant areas.

4.2. Impact of Landscape Pattern Evolution

An important economic area of China, the landscape design of the Chengdu–Chongqing urban agglomeration greatly affects the regional ESV [3]. Over the previous three decades of urbanization, our study chose four time periods when the Chengdu–Chongqing urban agglomeration underwent significant landscape transformation. Aiming to obtain more precise results, Pearson correlation analysis was applied in this setting to investigate the link between landscape patterns and ESV. The results reveal that the aggregation and dispersion of landscape types inside the Chengdu–Chongqing urban agglomeration have clearly changed with the deepening of urbanization. Particularly, the spread of urban building land has resulted in fragmentation of natural environments, drastically limiting communication between several landscape units [41]. This has then influenced the ecosystem’s support systems and control mechanisms. Our study also considered topography and ecological variables [42]. We found that natural elements like rivers and mountains somewhat restrict the landscape pattern in the Chengdu–Chongqing urban agglomeration. Thus, it is imperative to concentrate on restricting the too rapid expansion of building land in order to stop more fragmentation of the landscape pattern and thus preserve ecosystem stability and support the sustainable development of regional ecological services. Moreover, improving the design of green areas and building ecological corridors can help to increase the capacity of services in ecosystems, so maximizing the regional ESV.

4.3. Implications and Limitations

To provide scientific support to policymakers in ecological protection and natural resource management, it is essential to clarify the baseline characteristics of land use and landscape patterns, understand the spatiotemporal dynamics of these patterns, and explore the driving factors behind these changes. Additionally, the non-built-up land plays a crucial role as the primary contributor to ESV through its spatial distribution, compositional structure, and scale. Based on the findings of this study, the following recommendations are proposed for the future planning of the Chengdu–Chongqing urban agglomeration. In order to enhance ESV and promote sustainable development, it is essential to prioritize the integrated protection and restoration of forests, water, and wetlands, given their

critical roles in maintaining ecological balance and supporting key ecosystem functions such as water conservation, biodiversity, and climate regulation. Strengthening policies like afforestation, erosion control, and ecological restoration of barren mountains will further reinforce these functions, particularly in ecologically fragile mountainous areas [40]. Concurrently, balancing farmland protection with diverse ecosystem services is vital, as the reduction of cultivated land threatens food security and ecological stability. Optimizing the spatial relationship between farmland, forests, and water bodies, while maintaining strict adherence to the farmland protection red line, will ensure multi-functional benefits such as food production, biodiversity, and landscape aesthetics [43]. In parallel, urban development must focus on optimizing the layout of built-up areas to maintain ecological connectivity. Strategies such as redeveloping underutilized urban land, encouraging high-density and mixed use development, and minimizing encroachment on ecologically sensitive areas will mitigate the environmental impacts of urban expansion.

Meanwhile, plenty of uncertainties remain in this study. For example, the coefficients of ESV in the Chengdu–Chongqing urban agglomeration were based on the magnitude of China’s terrestrial ESV suggested by Xie et al. [31], but these proposed coefficients cannot be directly used for this study owing to spatial heterogeneity. Meanwhile, such coefficients are dynamic and can change over time, particularly for the long-term assessment from 1990 to 2020, which can affect the accuracy. Additionally, only Pearson correlation analysis was used in this study, whereas future studies can use regression models or factor analysis to quantitatively evaluate the contributions of each factor [44]. Since built-up land negatively impacts ESV, its exclusion from the ESV calculations could influence the final outcomes. Furthermore, the study did not analyze the spatial variation of landscape pattern indices in the region, limiting its ability to reveal the mechanisms by which landscape patterns influence the spatial differentiation of ecosystem services.

5. Conclusions

This study examined the changes in land-use-based landscape patterns, alterations of ecosystem service value alterations, as well as their correlations in the Chengdu–Chongqing urban agglomeration from 1990 to 2020 by utilizing time series of land use data, land use change analysis, landscape pattern assessment, ESV calculation, and Pearson correlation. The study draws the following conclusions:

- (1) The landscape types in the Chengdu–Chongqing urban agglomeration have experienced substantial alterations, predominantly characterized by cultivated land and forest, which collectively comprise over 86%. Throughout the study period, the extents of cultivated and grassland diminished, whilst other land uses proliferated, with construction land experiencing the most significant expansion, primarily at the expense of cultivated land and forest. The most significant reduction transpired in arable land.
- (2) Dividing the study period at 2010, the early years were significantly affected by human interference, leading to increased landscape fragmentation. This, in turn, challenged the diversity, evenness, and stability of the ecosystem. However, in the later period, the implementation of the “Return Cultivated Land to Forest” program and the curbing of unplanned urban expansion, along with enhanced ecological protection measures, significantly reduced landscape fragmentation. The strengthening of connection among dominating patches and the appropriate management of landscape fragmentation have fostered more advantageous conditions for the augmentation of ecosystem service value.
- (3) With forest showing more than 60% on average, the total ESV of the Chengdu–Chongqing urban agglomeration exhibits an overall rising tendency. In terms of

individual ecosystem functions, the regulating services make the largest contribution, with an average share exceeding 69%.

- (4) The impact on ESV of the landscape pattern indices in the Chengdu–Chongqing urban agglomeration reveals notable variations. Both LPI and PD exert a negative inhibitory effect on ESV, with LPI having a particularly pronounced influence. In contrast, LSI is strongly positively correlated with ESV, indicating that increased diversity promotes ecosystem service functions. The impact of SHDI on ESV generally shows a positive trend, with its influence strength significantly increasing over the study period.

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