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The Spatiotemporal Evolution of Ecosystem Services in the Minshan Section of the Giant Panda National Park and Its Response to Landscape Pattern Changes

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Abstract

Landscape pattern changes are one of the main reasons affecting the supply and maintenance of ecosystem services, and they also form the basis for the management of ecosystem services and the optimization of landscape spatial configuration. Clarifying the impact of landscape pattern changes on ecosystem services is of significant theoretical and practical importance for the protection of the ecological environment and the scientific management of ecosystems. This paper selects four important ecosystem services: soil conservation, water conservation, habitat quality, and net primary productivity. By using the InVEST and CASA models, it quantitatively assesses the characteristics of changes in ecosystem services in the Minshan area of the Giant Panda National Park from 2000 to 2020 and explores the response of ecosystem services to changes in the landscape pattern. The results indicate that: 1) From 2000 to 2020, the dominant landscapes were forests and grasslands, with land types mainly converting between forests, grasslands, and cultivated land. The forest area increased from 5220.42 km^2 to 5297.56 km^2, while the grassland area decreased from 4414.82 km^2 to 4339.46 km^2. 2) From 2000 to 2020, net primary productivity showed a "U" shape change; soil conservation increased from 6.73 $\times 10^9$ t to 8.66 $\times 10^9$ t, and water conservation increased by 10.06%, indicating an overall improvement in the level of ecosystem services in the Minshan area of the Giant Panda National Park. 3) Different ecosystem services respond significantly differently to the landscape pattern, and the spatial heterogeneity characteristics are evident. Habitat quality is significantly positively correlated with the aggregation index and the largest patch index, while net primary productivity is significantly negatively correlated with these two indices. The research results are beneficial for adjusting the landscape pattern optimization of the Giant Panda National Park and for formulating ecological environment governance and protection measures tailored to local conditions.

Keywords

Landscape Pattern, Ecosystem Services, Giant Panda National Park

1. Introduction

Ecosystem services are all the benefits that humans obtain directly or indirectly from ecosystems and ecological processes, providing essential environmental conditions and utilities for human survival and development (Daily et al., 1997; Ouyang et al., 1999). However, due to the combined effects of natural and human factors, changes in the landscape pattern within a region occur, indirectly affecting its material cycles and energy flows, thereby impacting the ecosystem services to a certain extent (Zheng et al., 2021; Chen et al., 2023). Therefore, identifying the relationship between landscape patterns and ecosystem services can help reduce the potential impacts of human disturbances on ecosystems and promote the sustainable development of ecosystem services within the region.

The correlation between landscape patterns and ecosystem services has become a focus of interest in recent years (Zhang et al., 2024; Kang et al., 2024; Ayituxun et al., 2024), but most studies have concentrated on the impact of landscape patterns on the comprehensive value of ecosystem services, with few examining the response mechanisms of various ecosystem services to changes in landscape patterns. For instance, Wang Liqun (Wang et al., 2018) and others systematically studied the impact of landscape pattern changes on ecosystem services in the fringe areas of Beijing; Wen Jianghui (Wen et al., 2022) and others found that adjusting the spatial distribution pattern of landscape patterns in Guizhou Province helps to enhance the value of ecosystem services; Zheng Bofu (Zheng et al., 2021) and others discovered that the value of ecosystem services in the southern region of Jiangxi is positively correlated with the contagion index and negatively correlated with the Shannon diversity index. However, in terms of technical methods, the current approach often involves using Pearson or Spearman rank correlation analysis to explore the interrelationships between landscape patterns and ecosystem services. These methods can only determine the significance of the correlation between the two and fail to reflect their spatial information. In summary, further research is needed on the response mechanisms of ecosystem services in typical areas to changes in landscape patterns.

The Minshan section of the Giant Panda National Park is a typical forest ecosystem, playing a significant role in ecosystem service provision, protection of rare species, and sustainable development of ecosystems (Li et al., 2022; Xu et al., 2020b). However, due to frequent natural disasters and increasing human activities, the land use landscape pattern within the region has undergone significant changes, which may affect the ecosystem service capabilities. Therefore, studying the relationship between the landscape pattern and ecosystem services in this area is crucial for the sustainable development of ecosystem services. Given that the Minshan section of the Giant Panda National Park is dominated by forest vegetation and has complex terrain conditions, it is necessary to comprehensively consider the spatial heterogeneity of the correlation between the two. Thus, this paper builds upon Person's correlation analysis and employs a bivariate local spatial autocorrelation analysis method to explore the response mechanisms of ecosystem services in the Minshan section of the Giant Panda National Park to changes in the landscape pattern. The aim is to provide theoretical guidance for the future optimization of the landscape pattern, enhancement of ecosystem services, and sustainable development of the Giant Panda National Park.

2. Method and Materials

2.1. Study Area

The Minshan section of the Giant Panda National Park (103˚28' - 105˚34' E, 31˚2' - 34˚11' N) encompasses 12 counties and districts including Jiuzhaigou, Songpan, and Maoxian, covering an area of approximately 10,013 km^2 (**Figure 1**). The region exhibits a topography of higher elevations in the west and lower in the east, characterized by significant relief changes, a well-developed water system, and

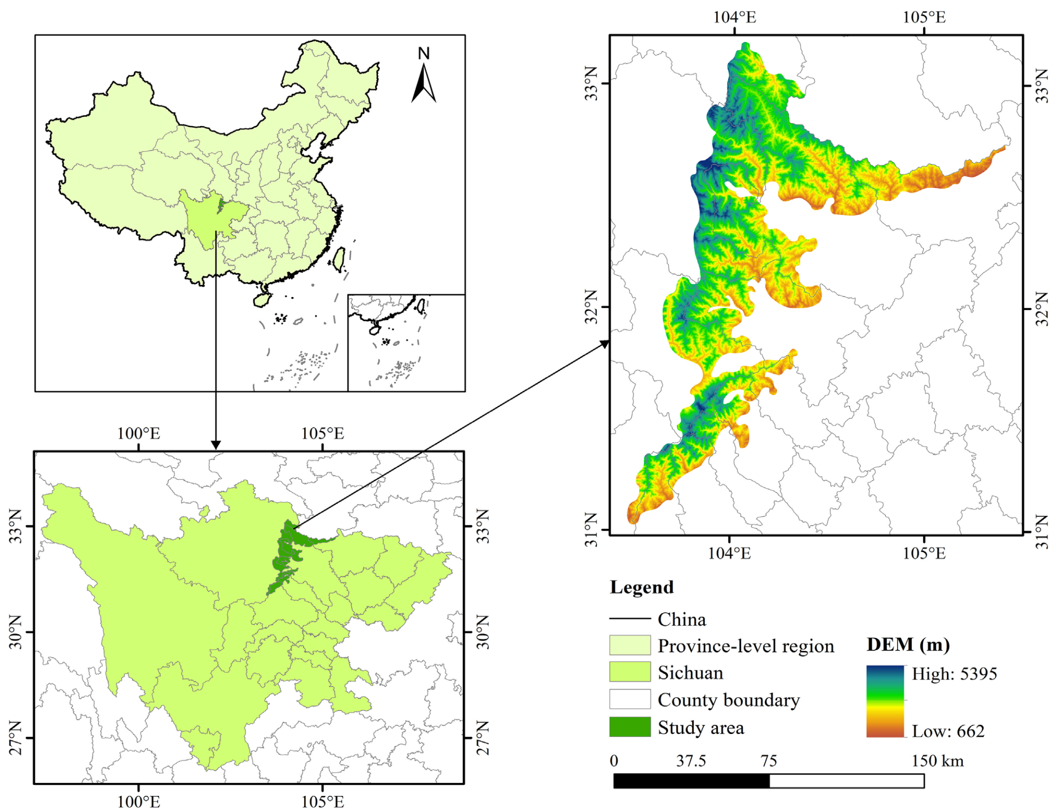

Figure 1. Geographical location diagram of the study area. (Source: Ministry of Natural Resources of China, http://bzdt.ch.mnr.gov.cn/).

high forest coverage. It holds significant ecological value in terms of carbon storage, water conservation, soil retention, and biodiversity maintenance. However, due to frequent natural disasters within the study area and the increasing intensity of human activities, changes in land use and landscape patterns are affected, leading to increased landscape fragmentation and compromised landscape connectivity, threatening the structure and function of ecosystem services.

2.2. Data Collection and Processing

The land use/cover data, meteorological data, topographic data, vegetation data, soil data, and socio-economic data used in this article are sourced from six types of data as shown in Table 1. To simplify the subsequent ecosystem service assessment process and reduce experimental errors, all data were resampled to a resolution of 30 meters using the WGS_1984_UTM_Zone_48N coordinate system.

Table 1. Data sources and processing.

Data	Resource and description
Land use/land cover (LULC)	LULC data were from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn/). Land use types include six types such as cultivated land, woodland, grassland, water area, construction land, and unused land (Liu et al., 2018). Processes such as clipping, mask extraction, and resampling are performed in ArcGIS.
Meteorological data	Meteorological data includes annual precipitation, annual temperature, solar radiation, and annual potential evapotranspiration data, sourced from the China Meteorological Data Network (http://data.cma.cn/). Data from the years 2000, 2010, and 2020 for these four categories were selected and processed with spatial interpolation and resampling at the ANULSPIIN station.
Digital elevation model (DEM)	The data primarily originates from the Geospatial Data Cloud (http://www.gscloud.cn/), where resampling is performed in the ArcGIS software, and terrain data such as slope and slope length are extracted based on research requirements.
Normalized difference vegetation index (NDVI)	The data originates from the Google Earth Engine (GEE) cloud processing platform (https://earthengine.google.com/) using Landsat series data from 2000 to 2020, with a temporal resolution of 8 days, obtained through the maximum value compositing method.
Soil data	The data includes maximum root depth, soil sand, silt, clay, organic carbon content, etc., sourced from the Harmonized World Soil Database (version, HWSD).
The statistical data	The data represents grain production figures, sourced from the "Sichuan Statistical Yearbook".

2.3. Selection of Landscape Pattern Indices

Landscape pattern indices can effectively reflect landscape pattern information and are widely used in studies of landscape composition and configuration changes

(Li et al., 2020; Yang et al., 2022; Liao et al., 2025). Based on the actual conditions of the study area and referring to relevant literature (Zhang et al., 2023; Ma et al., 2022; Tang et al., 2021; Zhou et al., 2023a), landscape pattern indices that characterize patch aggregation, fragmentation, shape complexity, diversity, and other features were selected from two levels: class level and landscape level (**Table 2**). These indices are used to reflect the characteristics of landscape pattern changes in the Minshan area of the Giant Panda National Park. All landscape pattern indices are based on land use/cover data and were calculated using the Fragstats software.

Table 2. Definitions of landscape pattern metrics.

Landscape metrics	Abbreviation	Level	Definition
Edge Density	ED	Class	Refers to the ratio of the total edge length of all patches in the landscape to the total area of the landscape, which can reflect the degree of landscape fragmentation to some extent.
Largest Patch Index	LPI	Class/ Land	Refers to the percentage of the largest patch area in the landscape unit to the total area, which simply measures the dominance of the landscape and helps to determine the dominant landscape type.
Average plaque area	AREA_MN	Class/ Land	Reflects the average size of the patches, a smaller average patch area indicates a higher degree of fragmentation.
Landscape Shape Index	LSI	Class/ Land	The index reflects the complexity of the landscape shape, with a higher value indicating a greater degree of patch separation.
Aggregation Index	AI	Class/ Land	Used to measure aggregation degree or agglomeration condition of similar patches in the landscape.
Spreading Degree Index	CONTAG	Class	The aggregation degree or spread trend of different patch types in the landscape can be characterized by the contagion index. A high contagion index indicates better connectivity between dominant patches.
Patch Density	PD	Class/ Land	Number of patches in the landscape per unit area, which measures the degree of fragmentation of the landscape.
Shannon's Diversity Index	SHDI	Land	Used to reflect the richness and complexity of landscape types.

2.4. Calculation of ESs

The Giant Panda National Park is an important forest ecosystem. By consulting relevant literature (Xu et al., 2020a; Wang et al., 2020) and combining field conditions, soil and water conservation (SC), water conservation (WC), habitat quality (HQ), and net primary productivity (Net Primary Productivity, NPP) services were selected as the focus of ecosystem service research. This study primarily quantitatively assesses six ecosystem services through the use of ArcGIS software, the InVEST model (Wang et al., 2021), and the CASA (Li et al., 2025) model.

1) Soil Conservation

This article utilizes the sediment delivery ratio module (Sediment Delivery Ratio model, SDR) within the InVEST model to calculate the difference between the actual soil erosion amount and the potential soil erosion amount in the region, estimating the soil conservation capacity of the Minshan area. The calculation formula is as follows:

$$SEDRET = RKLS - USLE \tag{1}$$

$$RKLS = R \times K \times L \times S \tag{2}$$

$$USLE = R \times K \times L \times S \times C \times P \tag{3}$$

In the formula: *SEDRET* represents the soil conservation amount in the study area (t), obtained by modifying the Universal Soil Loss Equation (*RUSLE*); *RKLS* and *USLE* are the potential soil erosion amount (t) and the actual soil erosion amount (t), respectively; R is the rainfall erosivity factor; K is the soil erodibility factor; L is the slope length; S is the slope factor; C is the vegetation cover factor; P is the soil and water conservation factor.

2) Water Retention Capacity

This study, based on the principle of the water cycle, utilizes the annual water yield module of the InVEST model to calculate the water resource retention within the region by subtracting soil and vegetation evapotranspiration from precipitation, thereby obtaining the water yield within the area. The specific calculation process is as follows:

$$Yjx = \left[1 - \left(AETx \div Px\right)\right] \times Px \tag{4}$$

$$AETx \div Px = \left(1 + \omega x \times Rxj\right) \div \left[1 + \omega x \times Rxj + 1/Rxj\right] \tag{5}$$

$$\Omega x = Z \times AWCx \div Px \tag{6}$$

$$Rxj = Kxj \times ETx \div Px \tag{7}$$

In the formula: *Yjx* represents the annual water yield (mm); *AETx* represents the annual average evapotranspiration (mm); *Px* represents the annual average precipitation (mm); ωx represents the ratio of the modified vegetation annual available water to precipitation; *Rxj* represents the aridity index; Z represents the Zhang coefficient; *AWCx* represents the available soil water content (mm); *Kxj* represents the vegetation evapotranspiration coefficient; *ETx* represents the reference crop evapotranspiration.

Based on the obtained water production data, combined with the topographic index, surface flow velocity coefficient, and soil saturated hydraulic conductivity data, the water conservation capacity of the area can be calculated. The specific calculation method (Zhou et al., 2023b) is as follows:

$$\mathrm{Re}ntention_{xj} = \min\left(1, \frac{249}{Vel_{xj}}\right) \times \min\left(1, \frac{K_{sat_x}}{300}\right) \times \left(1, \frac{0.9 \times TI_x}{3}\right) \times Y_{xj} \tag{8}$$

$$TI_x = \lg\left(\frac{drainagearea}{soil_{depth_x} \times slope_x}\right) \tag{9}$$

In the formula, $Retention_{xj}$ represents the water retention capacity (mm) of the raster cell x of land type j; Vel_{xj} is the flow velocity coefficient of the raster cell x of land type j, obtained from the model parameter table. K_{satx} is the soil saturated hydraulic conductivity (mm/d) of the raster cell x; TI_x is the topographic index of the raster cell x; $drainagearea$ is the number of catchment raster cells; soildepthx is the soil depth (mm) of the raster cell x; and $slope_x$ is the percentage slope of the raster cell x.

3) Habitat Quality

The Habitat Quality module in the InVEST model is based on landscape type data and calculates the Habitat Quality Index according to the sensitivity of landscape types and the intensity of external threats. The better the habitat quality in a region, the higher the biodiversity will be.

$$Q_{xj} = H_j\left(1 - \frac{D_{xj}^Z}{D_{xj}^Z + K^Z}\right) \tag{10}$$

In the formula: Q_{xj} represents the habitat quality of grid x in land use type j; H_j is the habitat suitability of land use type j; D_{xj} is the habitat degradation degree of grid unit x in land use type j; k is the semi-saturation constant, and z is the normalization constant.

4) Net Primary Productivity

This article is based on the NDVI data, total solar radiation data, temperature data, precipitation data, and vegetation type data of the Minshan area from 2000 to 2020, using the CASA model to estimate the NPP values within the region. The calculation process is as follows:

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t) \tag{11}$$

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5 \tag{12}$$

$$\varepsilon(x,t) = T\varepsilon 1(x,t) \times T\varepsilon 2(x,t) \times W\varepsilon 1(x,t) \times \varepsilon\max \tag{13}$$

In the equation, x represents the spatial location, t represents time, $APAR(x, t)$ and $\varepsilon(x, t)$ are the photosynthetically active radiation (g C/m^2/month) and the actual light energy use efficiency (g C/MJ) at location x in the month of t, respectively; $SOL(x, t)$ is the total solar radiation at location x in the month of t (MJ/m^2/month); $FPAR(x, t)$ is the absorption ratio of the vegetation layer for photosynthetically active radiation; 0.5 refers to the proportion of solar effective radiation that vegetation can utilize relative to the total solar radiation; $T\varepsilon 1(x, t)$ and $T\varepsilon 2(x, t)$ represent the stress effects of low and high temperatures on light energy use efficiency, respectively; $W\varepsilon 1(x, t)$ represents the water stress influence coefficient.

2.5. Landscape Index Correlation Analysis with Ecosystem Services

This study employs the Person correlation analysis method to analyze the interrelationship between landscape pattern indices and ecosystem services, judging the strength of the correlation between the two based on the absolute value of the correlation coefficient "*r*", and determining the significance of the correlation based on the size of the coefficient "*p*" (Chen et al., 2023), to reflect the response degree of the overall regional ecosystem services to changes in landscape patterns in the study area.

Spatial auto-correlation analysis includes global and local spatial auto-correlation and is widely used in the study of the interrelationship between two variables, which can intuitively reflect the characteristics of spatial heterogeneity (Li et al., 2024; Chen et al., 2021; Meng et al., 2023). This study uses local spatial auto-correlation analysis to explore the interrelationship between the two in local areas, revealing the characteristics of spatial heterogeneity. Based on this, the study explores the impact mechanism of changes in the landscape pattern in the Minshan area of the Giant Panda National Park on ecosystem services.

3. Results

3.1. Landscape Pattern Dynamic Changes

3.1.1. Changes in Landscape Composition

As can be seen from **Figure 2**, the landscape types in the Minshan area of the Giant Panda National Park are mainly dominated by woodland, which is mainly distributed in the southeastern region of Songpan County, the southern region from Pengzhou to Wenchuan, and the border area between Pingwu and Qingchuan; grassland is the second largest, distributed from Maoxian to Jiuzhaigou County. According to the landscape composition from 2000 to 2020 (**Table 3**), the area and changes in three types of landscapes—cultivated land, woodland, and grassland—are significant. Specifically, the woodland area increased from 5220.42 km^2 to 5290.68 km^2, an increase of 70.26 km^2; unused land increased by 76.65 km^2, while cultivated land and grassland decreased by 81.41 km^2 and 76.37 km^2, respectively. In contrast, the area and changes in water bodies and construction land are minimal, with increases of 6.35 km^2 and 4.51 km^2, respectively. Considering the effects of landscape pattern changes, subsequent analyses will focus on the impact of changes in four types of landscapes—cultivated land, woodland, grassland, and unused land—on ecosystem services. Specifically, within the study area from 2000 to 2020, the area of cultivated land and grassland has been in a slow decline, while the area of unused land has shown an opposite trend of change, with woodland area first increasing slowly and then decreasing slowly (**Table 4**). Among these, during the period from 2000 to 2010, the change trend index P_s for cultivated land and grassland was less than 0, indicating a decreasing trend in their area, while the change trend index P_s for woodland and unused land was greater than 0, indicating an increasing trend in their area. From 2010 to 2020, the change trend index for the area of grassland, woodland, and cultivated land was less than 0, indicating a decreasing trend in their area. From 2000 to 2020, the change trend index P_s for cultivated land, woodland, grassland, and unused land was very small, at −0.02588, 0.00135, −0.00173, and 0.13591, respectively, with no significant changes observed.

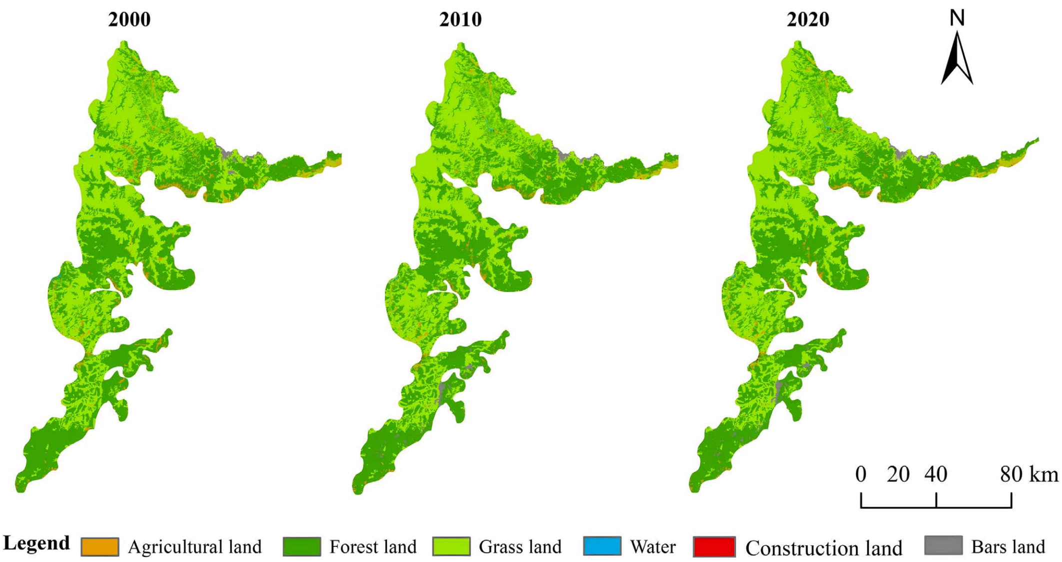

Figure 2. Spatial distribution of landscape composition from 2000 to 2020.

Table 3. Landscape composition from 2000 to 2020.

Landscape type	2000		2010		2020	
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Agricultural land	314.60	3.14	237.44	2.37	233.19	2.33
Forest land	5220.42	52.14	5297.56	52.91	5290.68	52.84
Grass land	4414.82	44.09	4339.46	43.34	4338.45	43.33
Water	4.50	0.04	10.66	0.11	10.85	0.11
Construction land	2.41	0.02	4.09	0.04	6.92	0.07
Bars land	56.39	0.56	123.93	1.24	133.03	1.33

Table 4. Trend index (P_s) of landscape composition from 2000 to 2020.

Landscape type	2000-2010	2010-2020	2000-2020
Agricultural land	−0.02453	−0.00179	−0.02588
Forest land	0.00148	−0.00013	0.00135
Grass land	−0.00171	−0.00002	−0.00173
Bars land	0.11978	0.00734	0.13591

From the landscape composition transfer from 2000 to 2020 (**Table 5**), it is known that the landscape types in the Minshan area of the Giant Panda National Park mainly shift between cultivated land, woodland, and grassland. Specifically, during 2000-2010, the area of landscape type transfer in the study area reached 653.35 km^2, accounting for 6.62% of the total area, showing characteristics of a large amount of transfer out of cultivated and grassland and a large amount of transfer into woodland. Among them, grassland and cultivated land transferred out 214.11 km^2 and 28.82 km^2, respectively, and the woodland was mainly transferred in from grassland and cultivated land, accounting for 71.57% of the total transferred area into woodland, while the conversion rate between unused land and grassland and other three types of landscapes was low. During 2010-2020, the conversion of landscape types showed that grassland transferred into woodland by 240.08 km^2, accounting for 84.61% of the total transferred area; other land use types had varying degrees of conversion rates, but the conversion rates were low. From 2000 to 2020, a large amount of grassland was transferred out, with a transferred area of 453.1 km^2; woodland was transferred in on a large scale, with the main sources being cultivated land and unused land, transferring in 310.29 km^2 and 70.26 km^2, respectively.

Table 5. Transfer of landscape composition from 2000 to 2020 (area: km^2).

Transfer time	Transfer-out situation	Transfer situation					
		Grass land	Agricultural land	Construction land	Forest land	Water	Bars land
2000-2010	Grass land	4125.35	52.27	0.02	159.64	1.52	0.64
	Agricultural land	13.01	208.62	0.32	15.48	0.01	0.00
	Construction land	0.81	0.78	1.75	0.76	0	0.00
	Forest land	262.92	48.58	0.07	4975.72	0.06	10.20
	Water	3.89	2.02	0.24	1.60	2.90	0
	Bars land	8.84	2.33	0	67.22	0	45.55
2010-2020	Grass land	4068.73	22.04	0.45	242.56	1.33	3.34
	Agricultural land	19.87	186.18	0.22	26.48	0.40	0.04
	Construction land	0.64	0.76	3.15	2.30	0.07	0
	Forest land	240.08	28.02	0.22	5013.79	0.64	7.92
	Water	1.17	0.29	0.05	1.14	8.19	0
	Bars land	8.95	0.144	0	11.29	0.03	112.63
2000-2020	Grass land	3961.72	24.74	1.71	406.77	4.10	15.77
	Agricultural land	62.85	177.76	1.40	68.42	1.88	2.29
	Construction land	0.18	0.43	1.40	0.18	0.22	0.00
	Forest land	310.29	30.18	2.39	4805.22	2.08	70.26
	Water	1.79	0.06	0.02	0.05	2.58	0.00
	Bars land	1.62	0.03	0.00	10.04	0.00	44.71

3.1.2. Landscape Configuration Changes

At the type level, the trend of landscape pattern index changes from 2000 to 2020 is shown in **Figure 3**. The AI, ED, LPI, and LSI indices are all larger in grasslands and forests; while the AREA_MN is slightly larger in grasslands than in forests, the PD value in grasslands is lower than in forests, but the values of both indices are still significantly larger than those of other landscape types. This indicates that grasslands and forests have a high degree of patch aggregation, strong edge effects, good landscape connectivity, complex shapes, and low fragmentation, making them the dominant landscape types in the area. Therefore, the changes in landscape pattern indices on grasslands and forests are mainly discussed. During the study period, the AI, ED, LPI, and LSI values on grasslands and forests remained relatively stable with no significant changes; the AREA_MN value in forests slightly increased from 805.62 to 838.46, while the AREA_MN value in grasslands continuously decreased from 1038.78 to 852.34, with a relatively large reduction; the PD value in forests showed a slight inverted "U" shape change, that is, the PD value in forests first increased from 0.0647 to 0.067 and then decreased to 0.063, while the PD value in grasslands showed a slow upward trend, increasing from 0.0424 to 0.0508. This indicates that the overall landscape pattern of the dominant landscape types in the study area is relatively stable, the degree of fragmentation in local forests has decreased, but the degree of fragmentation in local grasslands has slightly increased.

At the landscape level, as can be seen from Figure 4, between 2000 and 2020, the AI and LPI values were relatively high throughout the study area, while the

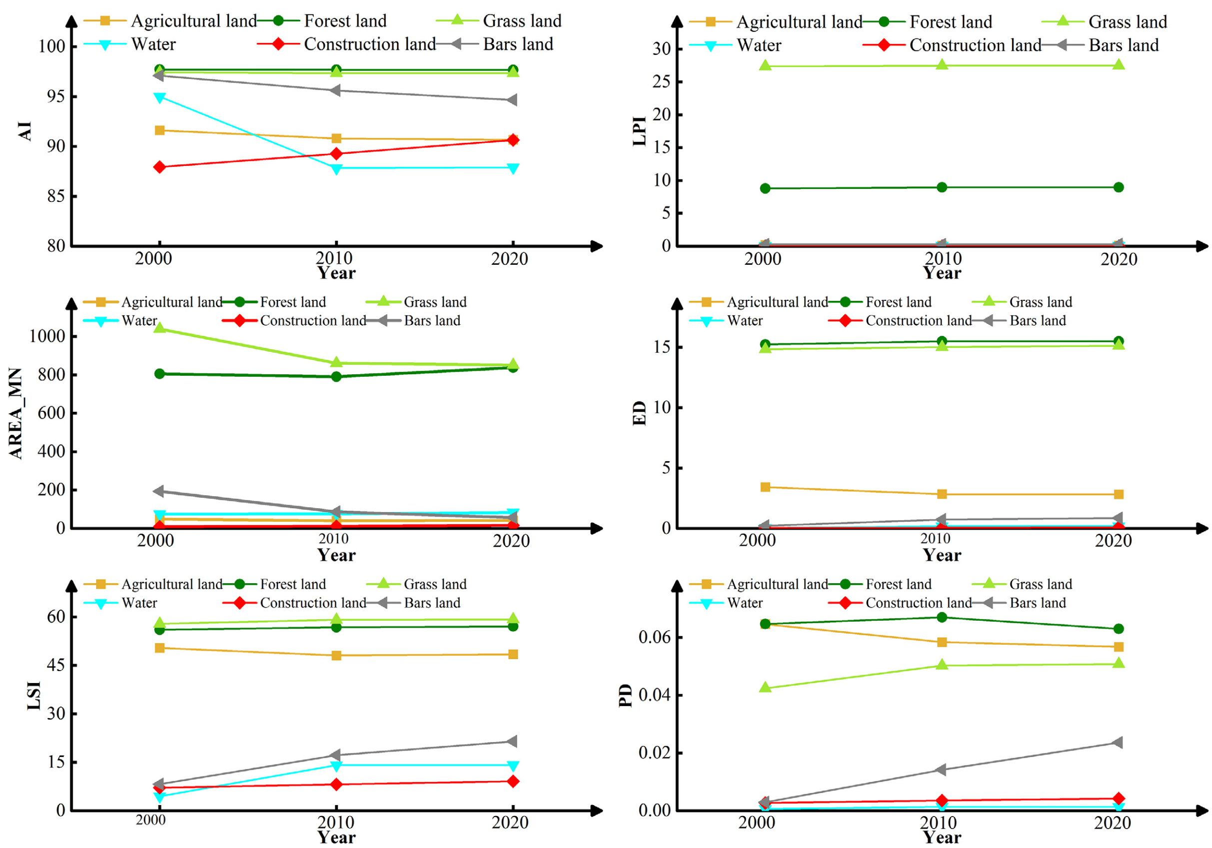

Figure 3. Change of landscape type index from 2000 to 2020.

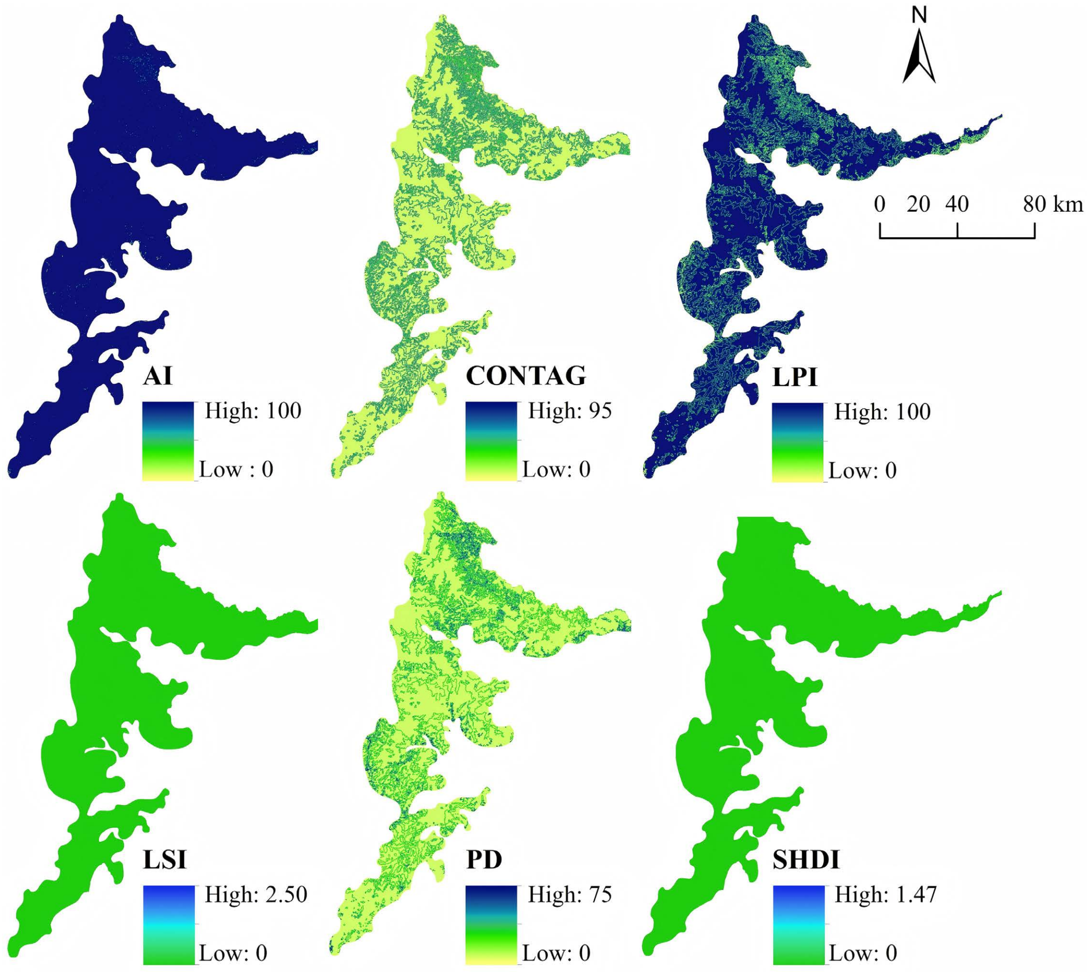

Figure 4. Spatial distribution of landscape pattern index.

LSI and SHDI values were relatively low across the entire region; the CONTAG values were distributed in the counties of Jiuzhaigou, Qingchuan, Pingwu, and Maoxian, with lower values in the remaining areas; the PD values were lower in most parts of the region, only slightly higher in the marginal areas of Jiuzhaigou, Qingchuan, Pingwu. This indicates that the degree of landscape fragmentation in areas such as Jiuzhaigou is slightly higher than in other areas, but the overall landscape condition of the study area remains good. The changes in landscape pattern indices over time are shown in **Table 6**, and from 2000 to 2020, the absolute values of the change rates of AI, CONTAG, LPI, LSI, PD, and SHDI were all less than 1%, indicating that the overall landscape pattern of the giant panda national park Minshan area is relatively stable.

Overall, the overall landscape level of the study area is high and stable, and the landscape characteristics of the dominant landscape types have not changed, that is, the landscape configuration of the study area is less affected by external disturbances and has not changed significantly. This is mainly related to a series of ecological protection measures carried out in the area, such as afforestation and returning farmland to forests.

Table 6. Changes of landscape level index from 2000 to 2020.

Landscape Pattern Index	Exponential value			Change rate		
	2000	2010	2020	2000-2020	2010-2020	2000-2020
AI	97.392	97.346	97.320	−0.005%	−0.003%	−0.004%
CONTAG	72.874	72.543	72.388	−0.045%	−0.021%	−0.033%
LPI	27.367	27.464	27.466	0.035%	0.0002%	0.018%
LSI	46.303	47.081	47.516	0.0168%	0.092%	0.131%
PD	0.178	0.195	0.212	0.955%	0.870%	0.955%
SHDI	0.844	0.853	0.857	0.107%	0.047%	0.771%

3.2. Ecosystem Services Changes

The changes in ecosystem services from 2000 to 2020 are shown in **Table 7** and **Figure 5**. Except for water conservation, the other three types of ecosystem services have very small changes in magnitude. Habitat quality distribution is relatively stable, with the habitat quality index in most areas of the study area fluctuating between 0.819 and 0.826, and the absolute value of the change rate does not exceed 0.1%; Net primary productivity decreased from 5.70 × 109 t to 5.14 × 109 t and then increased to 6.21 × 109 t, with the change rates in the three periods being only −0.982%, 2.082%, and 0.448% respectively, and the change areas are mainly concentrated in Pengzhou, Mianzhu, Shifang, and Anzhou; Soil conservation gradually and slowly increased from south to north and from west to east by 1.93 × 109 t, with a growth rate of only 1.434%; Water conservation shows a significant upward trend, with the amount of water conservation increasing from 2.55 × 108 m^3 to 7.68 × 108 m^3, and the growth rate is 10.061%, especially in Maoxian and Pingwu, where the increase is relatively large.

Table 7. Changes in ecosystem services from 2000 to 2020.

Ecosystem Services Indicators	Ecosystem service quantity			Change rate		
	2000	2010	2020	2000-2020	2010-2020	2000-2020
HQ	0.819	0.827	0.826	0.098%	−0.012%	0.043%
NPP	5.70 × 109 t	5.14 × 109 t	6.21 × 109 t	−0.982%	2.082%	0.448%
SC	6.73 × 109 t	7.80 × 109 t	8.66 × 109 t	1.590%	1.103%	1.434%
WC	2.55 × 108 m^3	7.20 × 108 m^3	7.68 × 108 m^3	18.235%	0.667%	10.059%

3.3. Ecosystem Services' Response to Landscape Patterns

The correlation between landscape pattern indices and ecosystem services in the three periods of 2000, 2010, and 2020 is similar, hence this article only presents the correlation heatmap for 2020. From the analysis of the correlation between landscape indices and ecosystem services (**Figure 6**), it is evident that AI and five other indices have an extremely weak correlation with soil conservation and water

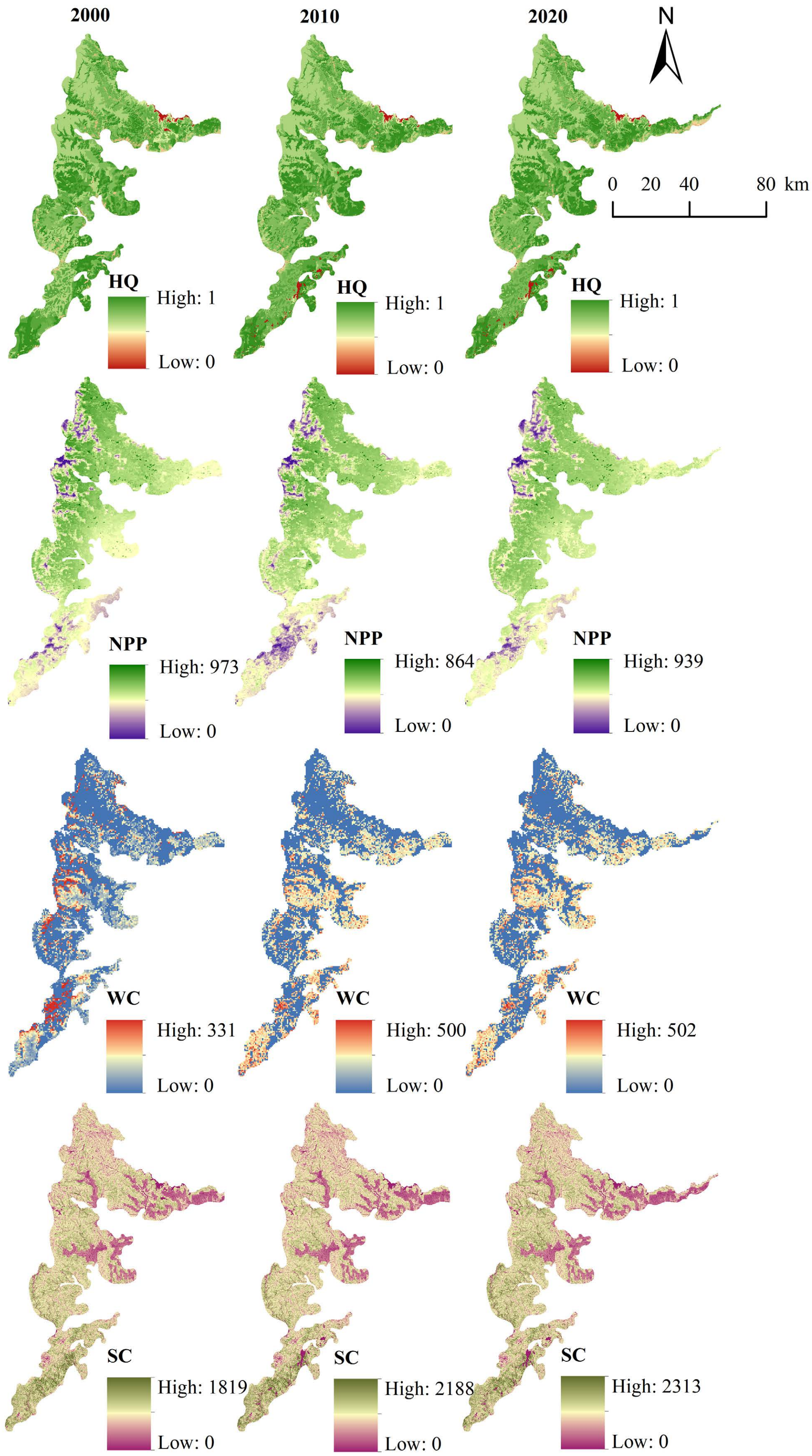

Figure 5. Spatial distribution of ecosystem services from 2000 to 2020.

retention, with the absolute value of the correlation coefficient R not exceeding 0.1. This indicates that the response of soil conservation and water retention to the six landscape indices is not significant. AI and LPI are significantly positively correlated with habitat quality and significantly negatively correlated with net primary productivity; the remaining four indices, including CONTAG, are significantly negatively correlated with habitat quality and significantly positively correlated with net primary productivity. The absolute values of the correlation coefficients between the six indices and habitat quality, as well as net primary productivity, are all between 0.1 and 0.2, suggesting a lower response level of habitat quality and net primary productivity to the six indices.

Although the overall impact of landscape pattern changes within the study area on ecosystem services is relatively small, the extent of their response in local areas remains unclear. Therefore, it is still necessary to explore the response of ecosystem services to landscape pattern changes from the perspective of spatial heterogeneity. From Figure 7, it is evident that the spatial heterogeneity of the correlation between landscape pattern indices and ecosystem services is significant. AI and LPI show a "low-low" clustered distribution with habitat quality and soil conservation in the northern part of Qingchuan, while LSI, CONTAG, PD, and SHDI exhibit a "high-low" clustered distribution with habitat quality and soil conservation in the same area. This indicates that the supply level of habitat quality and soil conservation services in the northern part of Qingchuan is relatively low, with a low degree of aggregation of dominant patches and weak connectivity, whereas the patch types are complex and diverse with a high degree of fragmentation. The "high-low" clustered phenomenon of AI, LPI, and net primary productivity is concentrated at the junction of Songpan, Pingwu, and Jiuzhaigou. The remaining four indices and net primary productivity in this area have a "low-low" clustered spatial distribution, revealing that the net primary productivity in this region is low, with poor patch aggregation, weak connectivity, strong landscape heterogeneity, and a high degree of patch fragmentation. AI, LPI, and CONTAG show a "high-high" clustered distribution with water conservation in Dujiangyan and Wenchuan, while the remaining three indices have a "low-high" clustered distribution with it in this area. This suggests that water conservation services in Dujiangyan and Pengzhou are strong, with better connectivity of dominant patches and a low degree of patch fragmentation.

Overall, the degree of patch aggregation and the connectivity of dominant patches have a positive impact on habitat quality, soil conservation, and water conservation, while patch density, Shannon diversity, contagion, and patch type complexity have a negative effect. The six landscape pattern characteristics, including the degree of patch aggregation, have an opposite effect on net primary productivity. Landscape types characterized by high aggregation, strong heterogeneity, strong edge effects, good connectivity, and rich diversity are more stable and conducive to enhancing the ecosystem service capacity within the region. It is necessary to strengthen ecological protection in the northern part of Qingchuan to improve landscape fragmentation issues, thereby enhancing the overall ecosystem service level within the region.

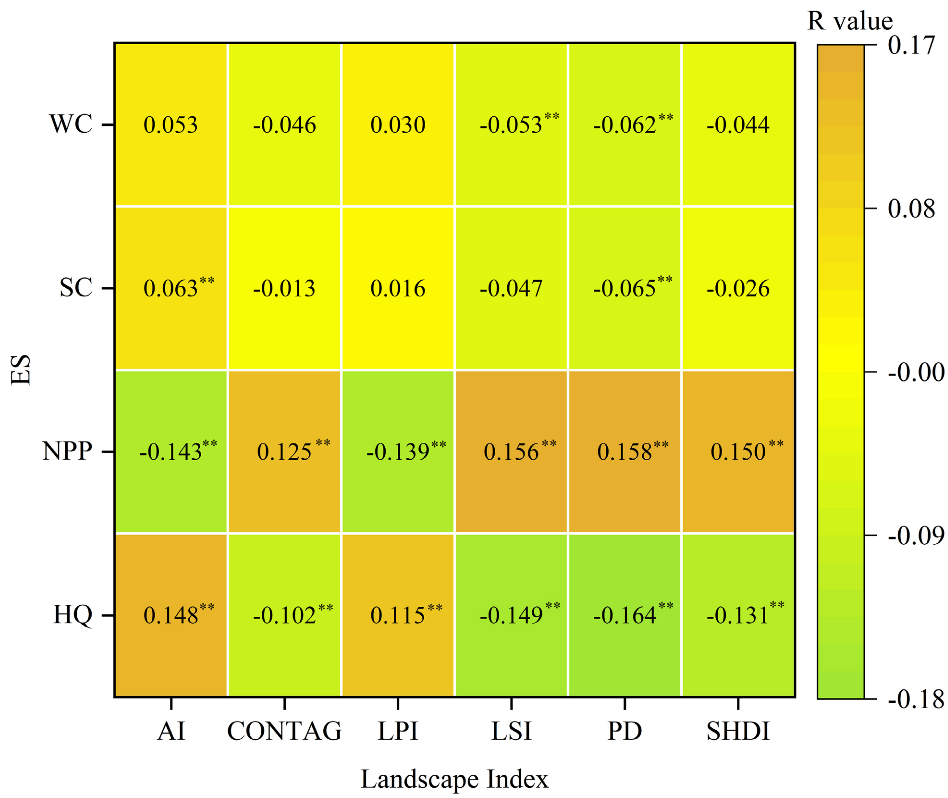

Figure 6. Correlation between landscape index and ecosystem services.

4. Discussion

4.1. Changes in Ecosystem Services across Different Landscapes

Studies have shown that there are certain differences in the changes of ecosystem services across different landscape types (as shown in **Figure 8**). The quantity of six ecosystem services is significantly greater in forest and grassland areas than in other landscape types, indicating that forests and grasslands are the key landscape types in this region. Therefore, this article mainly discusses the changes in the quantity of six ecosystem services in forest and grassland areas. Habitat quality has not changed significantly over the past 20 years across the six landscape types, mainly because the study area is located within a nature reserve where forests and grasslands are predominant, leading to high vegetation coverage. The changes in the area of different landscape types identified by remote sensing images are not significant, resulting in no significant changes in carbon storage and habitat quality services, which rely mainly on land use data. This is similar to the results of Xu Jianying et al. (Xu et al., 2020a). The NPP values in forest and grassland areas have a similar trend of first decreasing and then increasing, but the magnitude of change is different, consistent with the research results of Yahui Wang et al. (Wang et al., 2020). This may be due to the predominance of forest land in the study area and the lush vegetation, which enhances the carbon sink capacity of plants. The quantity of soil conservation and water conservation in forest and grassland areas has been increasing, but the rate of increase is different. This is due to the significant effects of ecological protection measures taken in this area, which have improved the soil and vegetation conditions in forests and grasslands, enhancing the resistance to water erosion (Ma et al., 2022; Wei et al., 2024),

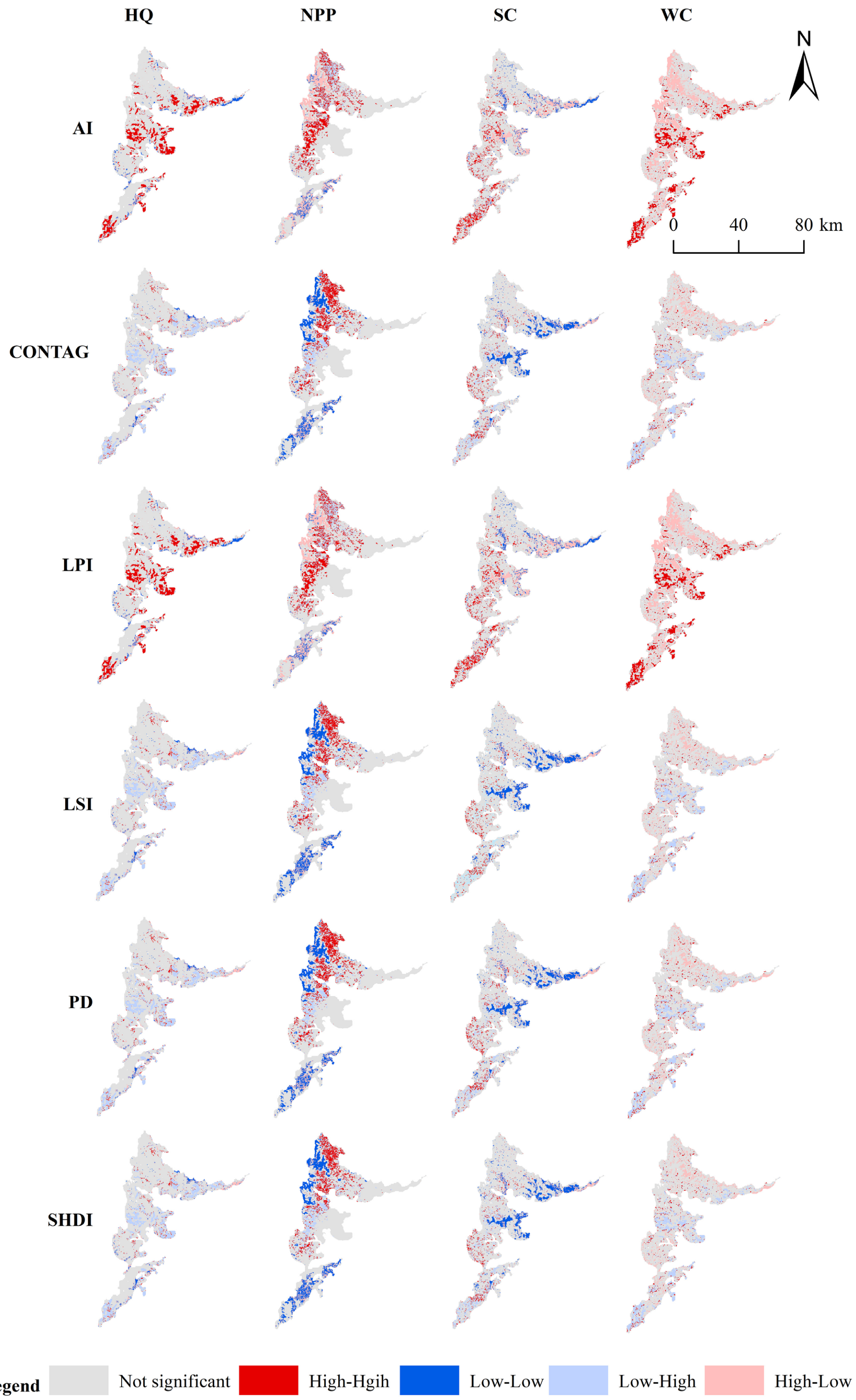

Figure 7. Spatial distribution of correlation between landscape pattern index and ecosystem services.

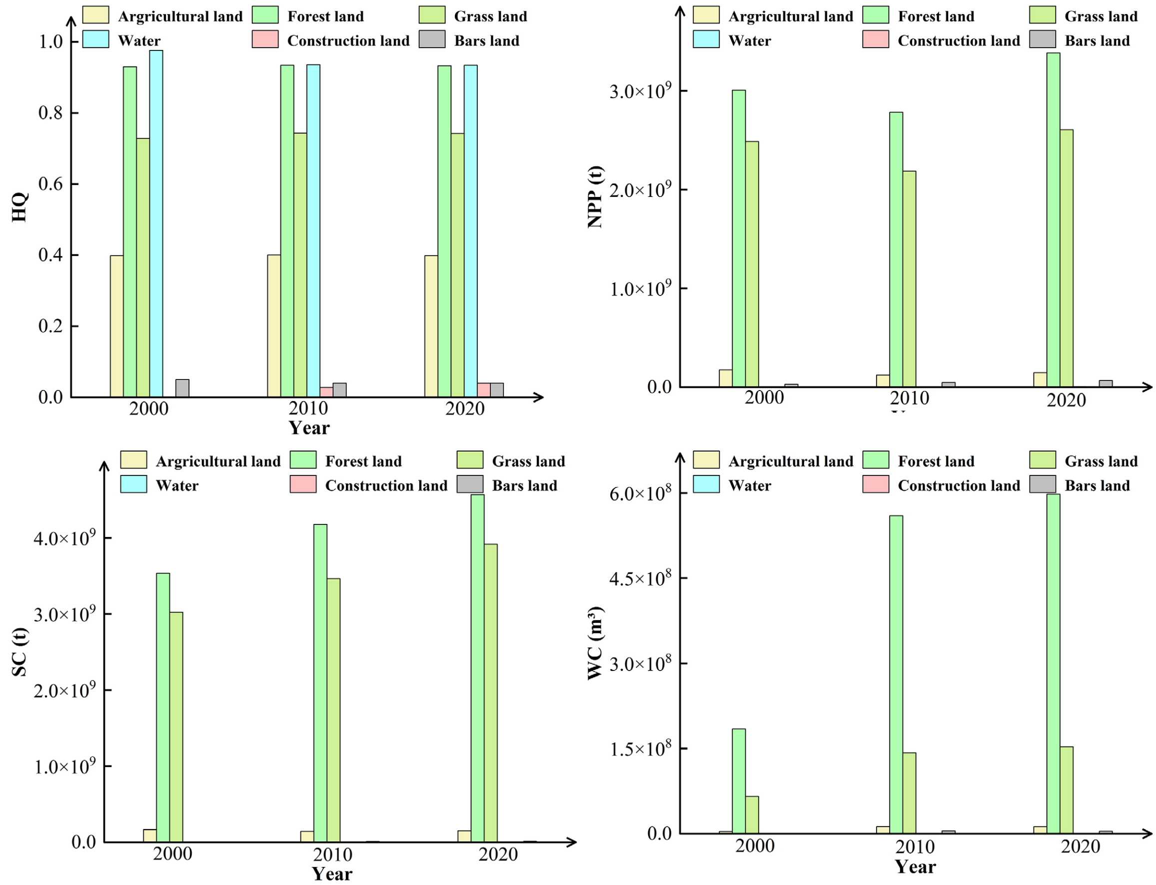

Figure 8. Changes of ecosystem services in different landscape types.

thereby increasing the capacity for soil and water conservation; studies have shown that water conservation is related to rainfall and evapotranspiration (Tao et al., 2025), and over the past 20 years, the temperature has not changed significantly, leading to no significant change in evapotranspiration, while the rainfall has increased significantly, thus promoting the increase in water conservation. However, studies have shown that agricultural activities can cause environmental pollution, threaten habitats, reduce aboveground biomass, and increase soil erosion, leading to a decrease in habitat quality and soil conservation services (Liao et al., 2025).

Therefore, measures such as returning farmland to forests and establishing national park systems can enhance the overall ecosystem service capacity within the region.

4.2. Ecosystem Services' Response to Landscape Patterns

Changes in landscape patterns affect ecosystem services by altering landscape composition and configuration (Ma et al., 2022; Zhang et al., 2023). Although this study shows differences in the changes of ecosystem services across different landscape compositions, some studies have shown that the response of ecosystem services to landscape configuration is greater than to landscape composition (Liu et al., 2020), so it is still necessary to discuss the response of ecosystem services to landscape configuration. This study found that the correlation between six landscape indices and water conservation, soil conservation is weak; AI, LPI are positively correlated with habitat quality and negatively correlated with net primary productivity; CONTAG, LSI, PD, SHDI are negatively correlated with habitat quality. The results are similar to those of Shuai Ma (Ma et al., 2022) and Xu Jianying (Xu et al., 2020a). Over the past 20 years, AI, LPI, CONTAG have existed at medium to high values and have not changed much, while LSI, PD, SHDI have been increasing, and habitat quality has always existed at high values and has not changed much; net primary productivity first decreased and then increased; water conservation and soil conservation have been continuously increasing. This indicates that high landscape aggregation and good connectivity of dominant landscapes are conducive to the provision of habitat quality services by ecosystems, while net primary productivity, water conservation, and soil conservation tend to be associated with heterogeneous, complexly shaped landscape configurations. Although the relationship between water conservation, soil conservation, and landscape configuration is not clear, the increase in LSI, PD, SHDI can lead to an increase in both services, suggesting that multiple other factors may jointly affect changes in ecosystem services. For example, although AI, LPI exist at high values throughout the study area, water conservation is at low values in Jiuzhaigou, Songpan, and Maoxian, areas with high altitude, indicating that factors affecting ecosystem services may also be related to topography (Zhang et al., 2025). LSI, SHDI exist at low values throughout the region, but water conservation is at high values in Qingchuan, as well as at the junction of Songpan, Pingwu, and Beichuan, while soil conservation is at low values in these areas, indicating that rainfall (Meng et al., 2023; Wei et al., 2024) will affect water conservation and soil conservation services. Habitat quality is at low values in a small area at the junction of Qingchuan and Jiuzhaigou, where construction land and cultivated land are concentrated, possibly due to frequent human activities in this area, indicating that human activities (Yan et al., 2025; Yuan et al., 2024) can have a certain impact on habitat quality.

In summary, although rational planning of landscape pattern space can help enhance ecosystem service levels and sustainable development, future management will still require differentiated strategies for different areas. For example, protecting connectivity in the core area and involving heterogeneous configurations in the ecological transition zone to balance multiple services.

4.3. Research Limitations and Management Implications

In this study, existing multi-source basic data were processed into 30m resolution grid cells, which may have overlooked small-scale landscape features. Future research could combine high-precision remote sensing data with field monitoring data such as soil and vegetation conditions, topographical conditions, to improve the assessment accuracy. Furthermore, the assessment framework proposed in this study can be extended to other nature reserves by calibrating local core parameters (such as precipitation thresholds, vegetation sensitivity). To enhance the regional adaptability of the model, it is recommended to supplement local socio-economic data (such as the intensity of ecological compensation investment, land use policy texts) in applications, to quantify the interaction effects of human activities and conservation measures. Future explorations could further integrate indicators such as GDP growth, community participation, to reveal the multi-dimensional driving mechanisms of ecosystem services. At the practical level, a management framework of "Primarily natural restoration, supplemented by artificial rehabilitation." should be established, focusing on monitoring the ecological chain reactions in areas where cultivated land is converted, and coordinating the contradictions between conservation and development through green infrastructure (such as ecological corridors). These measures can provide scientific references for the landscape planning of similar nature reserves.

5. Conclusion

This study, based on landscape pattern and spatiotemporal change data of ecosystem services, combined with Person correlation analysis and bivariate local spatial autocorrelation analysis methods, reveals the impact mechanism of landscape pattern changes on ecosystem services in the Minshan area of the Giant Panda National Park. The following main conclusions have been drawn:

1) From 2000 to 2020, the dominant landscape types in the Minshan area of the Giant Panda National Park were mainly forest and grassland, with slight changes in the area of grassland and forest; the overall characteristics of the landscape pattern did not change significantly.

2) From 2000 to 2020, the distribution of habitat quality was relatively stable, and only existed in the low-value areas at the junction of Qingchuan, Wenxian, and Pingwu counties, and at the junction of Mianzhu and Shifang; the net primary productivity service first decreased and then increased, while water conservation and soil conservation continuously increased, and the overall level of ecosystem services in the study area improved.

3) AI and LPI were significantly negatively correlated with the net primary productivity service, while CONTAG, LSI, PD, and SHDI were significantly positively correlated with the net primary productivity service. The correlation of the remaining three services with landscape indices was negative; and AI and LPI were less likely to exist in the study area as low-low phenomena with the four ecosystem services, while the spatial distribution pattern of the correlation between the remaining four landscape indices and ecosystem services was opposite.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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