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Evaluation of Ecological Sensitivity and Spatial Correlation Analysis of Landscape Patterns in Sanjiangyuan National Park

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Abstract: The Sanjiangyuan region, situated on the Qinghai–Tibetan Plateau, constitutes an exceptionally delicate ecological environment. Alterations in the region's ecological landscape stem not only from natural factors but also from significant anthropogenic influences, exerting a notable impact on the sustainable economic and social development of the region's middle and lower reaches. Consequently, investigating changes in the landscape pattern of Sanjiangyuan National Park holds paramount importance for comprehending the formation mechanism of spatial landscape distribution in the area. This study analyzes the ecological sensitivity and landscape pattern of Sanjiangyuan National Park in Qinghai Province, China, utilizing ArcGIS 10.8 and Fragstats 4.2. Employing the bivariate spatial autocorrelation analysis method, the research uncovers the spatial distribution characteristics between ecological sensitivity and landscape pattern, along with their aggregated change traits. The findings reveal that ecological sensitivity areas within the park encompass varying degrees, ranging from extremely sensitive to insensitive. The area of moderately sensitive zones in the Yellow River source region is 7279.67 km^2 (39.17%), whereas the corresponding area in the Yangtze River source region is 32,572.34 km^2 (36.30%). The eastern and northern parts of the Sanjiangyuan National Park exhibit significant landscape fragmentation. Ecological sensitivity varies markedly across different regions, with the southern and some northern areas showing higher sensitivity. In the Lancang River source park and the southern part of the Yellow River source park, the Largest Patch Index (LPI) and Ecological Sensitivity Index exhibit a high–high (HH) clustering pattern, indicating strong ecological connectivity in these areas. These regions also feature high Total Edge (TE), Number of Patches (NP), Patch Density (PD), and Edge Density (ED), indicating a complex landscape structure and abundant habitat edge areas. The study recommends restoring ecological connectivity in highly fragmented areas and implementing strict protection measures in sensitive regions to maintain ecosystem health and biodiversity. These findings provide a foundation for developing targeted ecological protection measures to enhance ecosystem health and biodiversity conservation in the area. This research aligns with several Sustainable Development Goals (SDGs), including Climate Action, Life on Land, and Clean Water and Sanitation, by promoting sustainable ecosystem management and biodiversity conservation.

Keywords: Sanjiangyuan National Park; ecological sensitivity; landscape pattern; ecological conservation strategy; landscape planning

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1. Introduction

The construction of national parks is closely related to the Sustainable Development Goals (SDGs). National parks contribute to achieving multiple SDGs through their roles in ecological conservation, promoting economic development, and enhancing social welfare [1–3]. National parks play a vital role in safeguarding the landscape resources of a nation, encompassing ecological conservation and the management of recreational scenic resources [4–6]. Landscape resource conservation stands as a pivotal component of national park establishment, involving various facets such as resource inventory, classification, environmental monitoring, and management [7]. The favorable ecological milieu and landscape structure within national parks form the cornerstone for effective landscape resource conservation. However, existing research predominantly concentrates on small- to medium-scale protected areas, with national parks being relatively underrepresented. These studies typically approach landscape resource conservation through assessment, management, and planning, alongside fundamental resource investigation, classification, grading, and value assessment and development [8,9]. Methodologically, research largely relies on GIS technology in conjunction with the Analytic Hierarchy Process (AHP) and landscape description methods. Sanjiangyuan National Park, the largest terrestrial national park in China, is also one of the highest-altitude, most geologically complex, and ecologically fragile nature reserves in the world. Conducting specific studies on land use change and ecological sensitivity in Sanjiangyuan National Park is crucial for guiding the implementation of conservation policies in the region. However, there are still relatively few studies that focus specifically on the protection of landscape resources in Sanjiangyuan National Park from the perspectives of ecological sensitivity and landscape pattern indices.

Ecological sensitivity denotes an ecosystem's capacity to withstand external pressures or changes while preserving environmental quality. Through in-depth analysis and assessment of a region's ecological sensitivity and its spatial distribution, scientific underpinning is provided for ecological management and policy formulation. This analytical framework finds wide application across various domains, encompassing nature reserve planning [10], wetland conservation and development planning [11–13], and urban environmental assessment [14,15]. Subsequently, scholars have directed attention towards integrating ecological sensitivity into tourism planning and development [16,17]. For instance, Fu et al. devised an ecological assessment framework for the Xandu Mountain Scenic Area in Jinyun County, Lishui City, Zhejiang Province, China. They utilized ecological sensitivity analysis and the minimum cumulative resistance model (MCR) to systematically categorize different construction suitability zones [18]. Similarly, Liu et al. proposed a functional zoning method for the Qianjiangyuan National Park based on ecological sensitivity. This approach aims to foster the sustainable development of the park's natural ecosystem [19].

Landscape pattern constitutes a pivotal aspect in studying the interactions between ecosystems and their surroundings, encompassing the spatial distribution and configurations of diverse land use types within the landscape [20,21]. Through the analysis of landscape patterns, a deeper comprehension of the interrelations among biodiversity [22], ecological processes [23], and ecological services [24,25] can be attained. The calculation methods of various landscape pattern indices and their respective implications vary according to the landscape analysis paradigm. Fei et al. elucidated the correlation between these indices and water quality parameters by computing landscape indices such as the continuity index, patch density, and neighborhood interspersion index in the Jinghe River Basin of Northwest China [26]. Similarly, Xiao et al. examined the Shannon diversity index in these areas through monthly monitoring of 28 subtropical ponds in central China [27]. Furthermore, they analyzed the Shannon diversity index, the number of patches, and the landscape shape index in these areas, revealing distinct contributions to the variation of chlorophyll α concentration across different temporal clusters [27].

The further integration of ecology and tourism through additional analysis using the ecological sensitivity impact factor and landscape pattern index aims to provide a scientific basis and reference for ecological environmental protection and sustainable development of recreation in national parks. This is achieved by systematically and comprehensively analyzing and evaluating the impacts of natural resources, environmental conditions, and human activities on the ecosystem. Therefore, this study meticulously examined the spatial distribution characteristics of ecological sensitivity and landscape pattern in Sanjiangyuan National Park, Qinghai Province, China, utilizing Geographic Information System (GIS) and Fragstats 4.2. Employing bivariate spatial autocorrelation analyses, the study investigated the spatial correlation characteristics between landscape patterns and changes in habitat quality, along with the evolution of their aggregation characteristics, thus shedding light on habitat connectivity and ecological integrity. The study aims to address three key issues: (1) analyzing the spatial distribution characteristics of habitat sensitivity in Sanjiangyuan National Park; (2) exploring the spatial distribution characteristics of the landscape pattern in the region; and (3) assessing the correlation between landscape pattern and habitat sensitivity, as well as the evolution of its aggregation characteristics in Sanjiangyuan National Park. Based on these analyses, the study will furnish a scientific basis and practical guidance for regional ecological protection policy formulation, biodiversity conservation, and regional sustainable development strategies.

2. Materials and Methods

2.1. Research Area

The Sanjiangyuan National Park, situated in the core region of the Tibetan Plateau, stands as a vital ecological reserve and biodiversity conservation center in China. Spanning from 32°22′36″ to 36°47′53″ north latitude and 89°50′57″ to 99°14′57″ east longitude, with an average elevation exceeding 4500 m above sea level, the park serves as the source of the Yangtze, Yellow, and Lancang Rivers, contributing an average multi-year runoff of 49.9 billion cubic meters [28]. Characterized by towering mountains, deep-cut canyons, and numerous lakes, the park's topography has been shaped by freeze–thaw erosion, resulting in distinctive landforms and ecosystems. Encompassing a planned area of approximately 123,100 square kilometers, it comprises three main sections: Yangtze River Source, Lancang River Source, and Yellow River Source. These areas not only play a pivotal role in ecological preservation but also serve as crucial sanctuaries for biodiversity conservation. The protection of Sanjiangyuan National Park holds paramount importance in safeguarding national ecological security and advancing the development of ecological civilization. The study area is depicted in Figure 1.

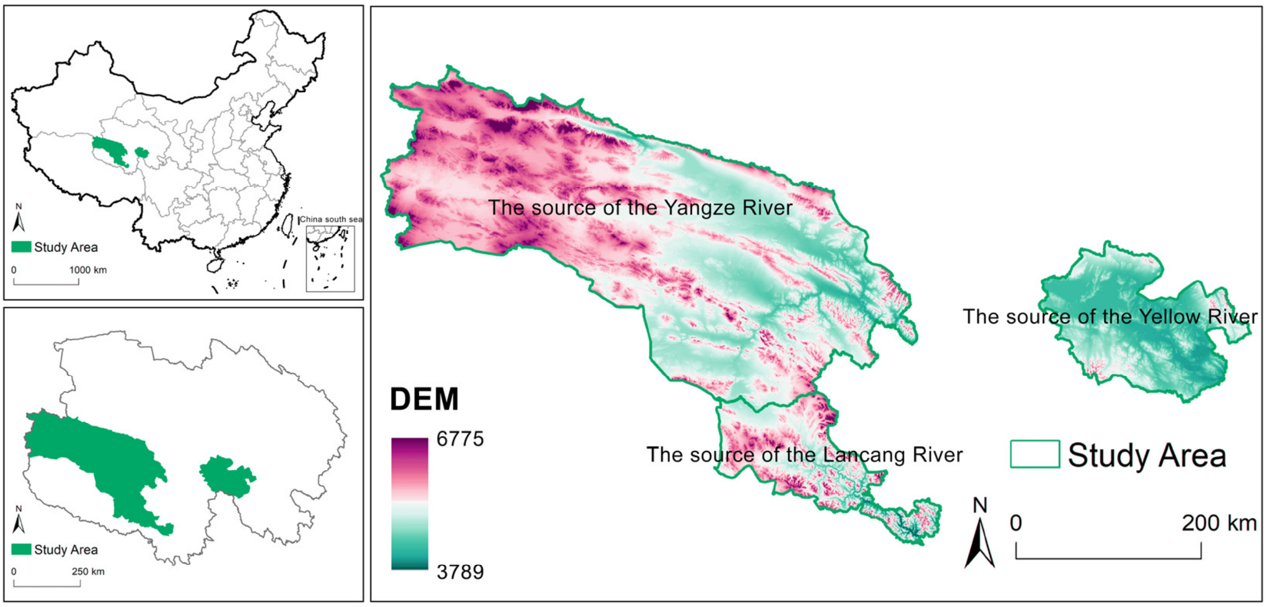

Figure 1. Location of the study area.

2.2. Data Sources

Land use data (LUCC) with a spatial resolution of 30 m for Sanjiangyuan National Park for 2022 were acquired from the ZENODO database [29], as shown in Figure 2. Vector boundary data were sourced from the Resource and Environment Science Data Center. Environmental data collection encompassed MOD13A2 Normalized Difference Vegetation Index (NDVI) [30] and SRTM Digital Elevation Model (DEM) data provided by National Aeronautics and Space Administration (NASA) [31]. The data processing involved data clipping and setting all data to a spatial resolution of 1000 m by 1000 m in the Krasovsky

1940 Albers coordinate system. Using the Create Fishnet tool in ArcGIS 10.8, we divided the region into square grid cells measuring 10 km by 10 km, resulting in a total of 1428 grid cells. Landscape pattern characteristics were then calculated for each grid cell. Subsequently, using ArcGIS 10.8, we assigned centroids to each cell and conducted ordinary kriging interpolation. Finally, after reclassification, we obtained the spatial distribution map. As shown in Table 1.

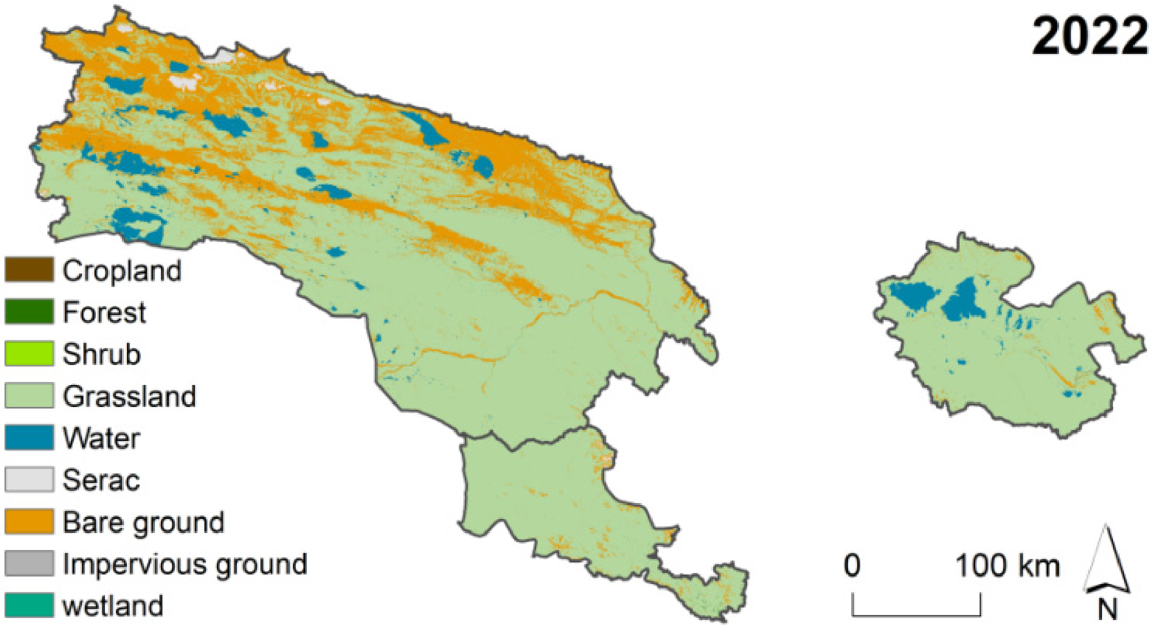

Figure 2. Land use map of Sanjiangyuan National Park.

Table 1. Detailed description of data.

Data Name	Format	Spatial Resolution	Temporal Resolution	Data Source
Sanjiangyuan National Park boundary data	shp	/	/	RESDC [a]
MOD13A2 NDVI	HDF	1000 m	Annual	NASA [b]
LUCC	TIFF	30 m	Annual	ZENODO [c]

Note: [a] RESDC: Resource and Environment Science Data Center https://www.resdc.cn/ (accessed on 5 February 2024). [b] NASA: National Aeronautics and Space Administration https://www.nasa.gov/ (accessed on 6 February 2024). [c] ZENODO: https://doi.org/10.5281/zenodo.8176941 (accessed on 5 February 2024).

2.3. Methods

2.3.1. Ecological Sensitivity Calculations

The ecological sensitivity assessment of Sanjiangyuan National Park encompasses an indicator system comprising three primary aspects: terrain conditions, natural environment, and human activities. Drawing from the Interim Regulations on Ecological Functional Areas issued by the State Environmental Protection Administration of China, and considering the ecological context of Sanjiangyuan National Park, this study selected six factors across four categories—geological geomorphology, surface water system, vegetation cover, and human activities—to formulate an ecological sensitivity evaluation index system. The classification criteria were based on existing research findings and local regulations. Single-factor ecological sensitivity was divided into five levels: insensitive, mildly sensitive, moderately sensitive, highly sensitive, and extremely sensitive, assigned values of 1, 2, 3, 4, and 5, respectively [32,33]. The specific classification criteria are shown in Table 2.

Table 2. Ecological sensitivity assessment index grading for Sanjiangyuan national park [32,33].

Criterion Layer	Evaluation Factors	Evaluation Standards					Weight
		Extremely Sensitive	Highly Sensitive	Moderately Sensitive	Mildly Sensitive	Insensitive	
Geological Feature	DEM (m)	>5054	4834–5054	4633–4834	4421–4633	<4421	0.104
	Slope (°)	45–90	30–45	25–30	15–25	0–15	0.062
	Aspect	True North	Northwest, Northeast	True West, True East	Southwest, Southeast	True South, Flat Ground	0.137
Surface water system	Water Body Buffer Zone (m)	0–100	100–600	600–1200	1200–1800	>1800	0.265
Surface vegetation	NDVI	0.75–1	0.65–0.75	0.5–0.65	0.35–0.5	0–0.35	0.306
Human activity	Land Use	Wetland, Forest	Water body	Shrub, Grassland	Cropland	Others	0.125
value		5	4	3	2	1	

The study utilized the AHP to determine the weights of each evaluation factor based on their respective impacts on ecological sensitivity. The weight determination process proceeds as follows [15,32,34,35]:

A pairwise comparison matrix was constructed for each indicator based on its relative importance:

$$A = (a_{ij})_{n\times n} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} \tag{1}$$

where: a_i, a_j $(i,j = 1,2,\ldots,n)$ represents the element, and since matrix A is a positive reciprocal matrix, $a_{ij} > 0, a_{ij} = 1, a_{ij} = \frac{1}{a_{ij}}, (i,j = 1,2,\ldots,n)$.

Using the set average method, the average value was calculated based on the judgment matrix:

$$a_i = \sqrt[m]{M_i}(i = 1,\ldots,n) \tag{2}$$

The calculation results were normalized to obtain the average weight for each item:

$$w_i = \frac{a_i}{\sum_{i=1}^{m} a_i} \tag{3}$$

Calculate the maximum eigenvalue of the matrix (λ_{max}):

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{A_{Wi}}{W_i} \tag{4}$$

where A_{Wi} represents the ith component of vector A_W, and n represents the order:

Check its average consistency indicator as shown in Equation (1):

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

where RI represents the consistency indicator, CI stands for the consistency ratio, and n denotes the value corresponding to the judgment moment evaluation scale. Ensuring the scientific accuracy of results necessitates conducting a consistency test on the calculated outcomes. If matrix A's $CR \leq 0.1$ or $\lambda_{max} = n$, the consistency test is deemed successful; otherwise, it fails. Following the consistency test, yielding CR = 0.0774 < 0.1, indicates the validity of the judgment's weight assignment. Thus, the ecological sensitivity evaluation factors' weights in this study are reasonably allocated [36–38].

Calculation of the ecological sensitivity evaluation index involves standardizing the selected indicators due to their varying value ranges, units, and attributes, thus ensuring uniformity in measurement. The ecological sensitivity evaluation index can be computed using the following formula, as presented in Equation (3):

$$ES = \sum_{i=1}^{6} E_i \cdot w_i \tag{7}$$

where ES is the ecological sensitivity index; E_i represents the data assigned to each evaluation factor; and w_i represents the weight corresponding to each evaluation factor. The ecological sensitivity index of Sanjiangyuan National Park was finally calculated [36–38].

2.3.2. Landscape Pattern Index

In landscape ecology, "pattern" denotes a spatial arrangement, encompassing patch type, patch count, and patch spatial distribution. The landscape pattern index, a quantitative measure, synthesizes landscape pattern information, reflecting both pattern structure and spatial configuration. Utilizing landscape pattern indices enables data to acquire statistical properties and unveil meaningful regularities within seemingly disordered patch mosaic landscapes. Landscape fragmentation typically manifests as a surge in patch count accompanied by a reduction in patch size, leading to increased patch complexity, truncated corridors, and patch isolation. After reviewing numerous articles by scholars both domestically and internationally and considering the landscape fragmentation characteristics along with the specific conditions of the project area, the following landscape indices were chosen based on the actual landscape structure within the study area: Largest Patch Index (LPI), Edge Density (ED), Mean Patch Area Per Hectare, Number of patches (NP), Total Edge (TE), Mean Shape Index, Patch Density (PD), and Patch Richness (PR). These indices were selected to conduct the study, and the Landscape Pattern Index of the study area was computed with the assistance of Fragstats 4.2 software [39–41]. In this study, the grid method was selected to investigate the spatial distribution of ecological environmental quality within the study area, drawing upon the grid division approach employed in prior research. Considering the area and research scale of the Yangtze River Economic Zone, as well as data accuracy, research objectives, and computational burden, the study area was partitioned into 10 km × 10 km grid cells. The landscape pattern index was spatially analyzed through evenly spaced sampling, resulting in a total of 1428 analytical spatial units. Subsequently, the landscape pattern index for each grid was calculated, and the value was assigned to the center point of each grid. Interpolation was then conducted using the ordinary kriging interpolation method in ArcGIS 10.8 to obtain the landscape pattern index for the entire study area. The specific formula is shown in Table 3.

Table 3. Interpretation table for landscape metrics.

Metric Name	Formulas	Explanations
Largest Patch Index (LPI)	$LPI = \frac{A_{max}}{A_{total}} \times 100$	In the formula, A_{max} represents the area of the largest patch, and A_{total} represents the total area of the landscape.
Edge Density (ED)	$ED = \frac{E}{A} \times 10,000$	In the formula, E represents the total length of all patch edges within the landscape, measured in meters, and A represents the total area of the landscape, measured in hectares.
Mean Patch Area Per Hectare	$MPA = \frac{A_{total}}{N}$	In the formula, A_{total} represents the total area of the landscape, and N represents the total number of patches.
Total Edge (TE)	$TE = \sum_{i=1}^{N} E_i$	In the formula, E_i represents the perimeter of the i-th patch, and N represents the total number of patches.
Mean Shape Index (MSI)	$MSI = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{P_i}{2\sqrt{\pi A_i}}\right)$	In the formula, P_i represents the perimeter of the i-th patch, A_i represents the area of the i-th patch, and N represents the total number of patches.

Table 3. *Cont.*

Metric Name	Formulas	Explanations
Patch Density (PD)	$PD = (NP/A)$	In the formula, NP represents the total number of patches, and A represents the total area of the landscape, measured in hectares.
Patch Richness (PR)		PR represents the number of different types of patches in the landscape, serving as an indicator of landscape diversity.
Number of Patches (NP)		NP represents the total number of patches in the landscape, serving as an indicator of landscape fragmentation.

2.3.3. Local Spatial Autocorrelation

In this study, we employed both global bivariate Moran's I and local bivariate Moran's I to evaluate the spatial relationship between ecological sensitivity and landscape pattern indices [42]. The global bivariate Moran's I assesses the linear association between ecological sensitivity and landscape pattern indices across the entire study area, yielding values ranging from −1 to 1. These values denote varying degrees of spatial autocorrelation, from very strong negative to strong positive spatial autocorrelation. Calculation of this index enabled determination of significant spatial correlation between the two variables. Conversely, the local bivariate Moran's I was utilized to examine spatial correlation at local levels, producing cluster maps that categorized spatial units into four types: high–high, low–low, high–low, and low–high. These classifications unveiled diverse spatial correlation patterns, aiding in the identification of areas with heightened ecological integrity. GeoDa 1.14 software was utilized for the computations and visualization of local spatial association maps, with a significance level set at 0.01 to ensure analytical reliability. The research framework is shown in Figure 3.

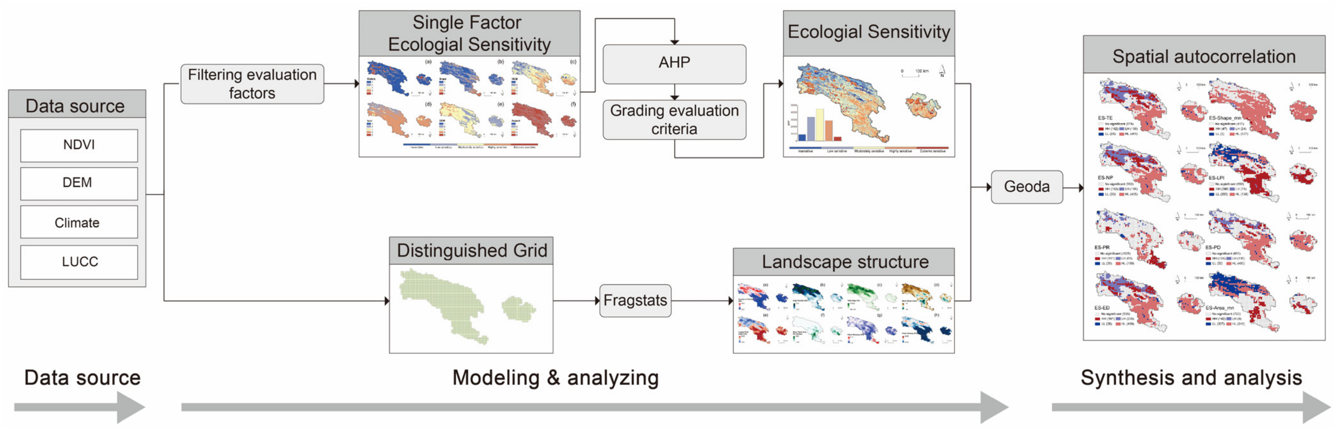

Figure 3. Research framework diagram.

3. Results

3.1. Single Ecological Sensitivity

Initially, we categorized the ecological sensitivity indicators of the Sanjiangyuan region into five levels: insensitive, mildly sensitive, sensitive, highly sensitive, and extremely sensitive areas using ArcGIS 10.8, as depicted in Figure 4. Geological features, including DEM, Slope, and Aspect, were considered, with Aspect exerting the most pronounced influence on ecological sensitivity. Notably, highly sensitive and extremely sensitive areas spanned nearly the entire Sanjiangyuan region. However, it is noteworthy that Slope, under the influence of Aspect, exhibited more extreme conditions. While some highly sensitive areas were observed in the southeast and other fragmented grids, the predominant areas were insensitive. Conversely, the influence of DEM was prominent in sensitive areas, with some highly sensitive areas scattered in the northeast, primarily dominated by mild sensitivity in our study. The remaining indicators, namely surface vegetation, groundwater system, and human activities, were replaced by NDVI, Water Body Buffer Zone, and LUCC, respectively. LUCC predominantly impacted the Sanjiangyuan area as highly sensitive, whereas the Water Body Buffer Zone was primarily insensitive, with sporadic highly sensitive areas. NDVI exhibited a ladder-like distribution, with sensitivity levels gradually increasing from northeast to southeast.

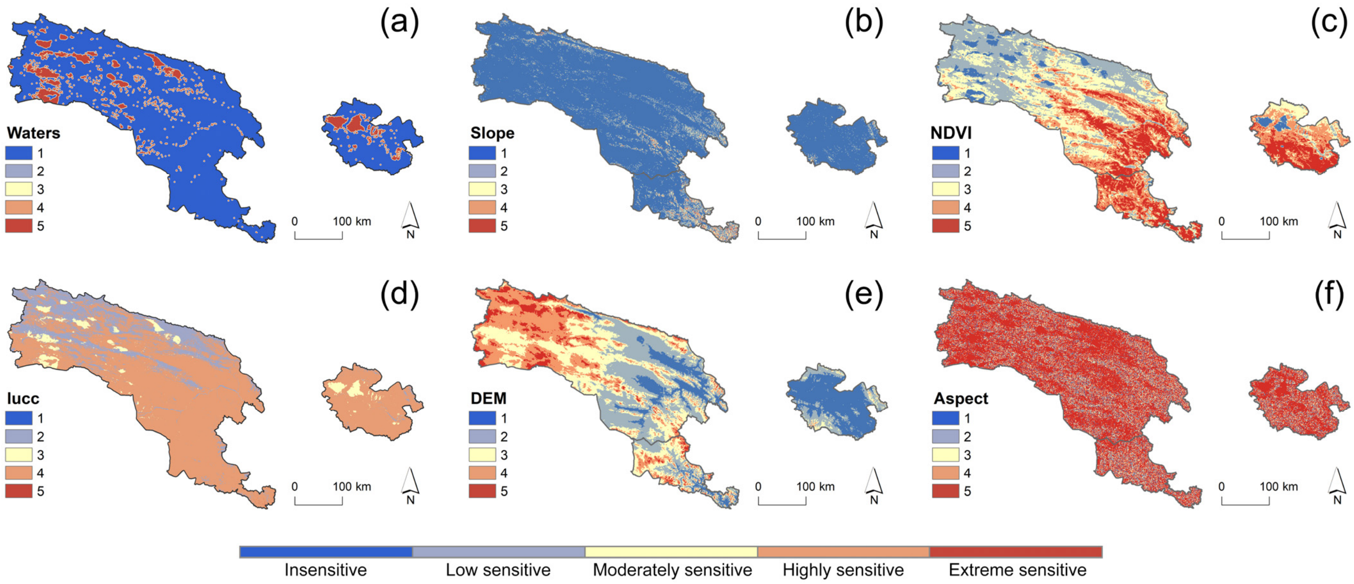

Figure 4. Single ecological sensitivity analysis map. (**a**) Watershed sensitivity analysis; (**b**) Slope sensitivity analysis; (**c**) Vegetation sensitivity analysis; (**d**) Land use type sensitivity analysis; (**e**) Elevation sensitivity analysis; (**f**), Aspect sensitivity analysis.

3.2. Integrated Ecological Sensitivity

According to the ecological sensitivity evaluation system, the Sanjiangyuan National Park underwent further analysis to comprehensively assess the factors influencing sensitivity in the study area. The findings delineate the park into five sensitivity categories: extremely sensitive, highly sensitive, moderately sensitive, mildly sensitive, and insensitive. As illustrated in Figure 5, the southern region of the Sanjiangyuan National Park exhibits higher ecological sensitivity compared to the northern region overall, with the Lancang River source region and the Yellow River source park displaying notably higher sensitivity than the Yangtze River source park. The Yellow River Source Park encompasses 7568.34 km^2 (41.18%) of moderately sensitive terrain, followed by 3627.47 km^2 (19.74%) of mildly sensitive areas, 5199.29 km^2 (28.29%) of highly sensitive zones, 758.71 km^2 (4.13%) of insensitive regions, and 1226.22 km^2 (6.67%) of very highly sensitive zones. Similarly, the Yangtze River Source Park is predominantly characterized by moderately sensitive terrain, covering 28,753.11 km^2 (32.21%), followed by 18,808.63 km^2 (21.07%) of highly sensitive areas, 23,798.29 km^2 (26.66%) of mildly sensitive zones, 3288.08 km^2 (3.68%) of extremely sensitive regions, and 14,621.13 km^2 (16.38%) of insensitive areas. In the Lancang River Source Park, the largest proportion is highly sensitive areas, covering approximately 4321.64 km^2 (32.56%), followed by moderately sensitive areas, also covering 4321.64 km^2 (32.56%), mildly sensitive areas covering 1430.36 km^2 (10.78%), extremely sensitive areas covering 638.68 km^2 (4.81%), and insensitive areas covering 267.94 km^2 (2.02%). The statistical data are shown in Table 4.

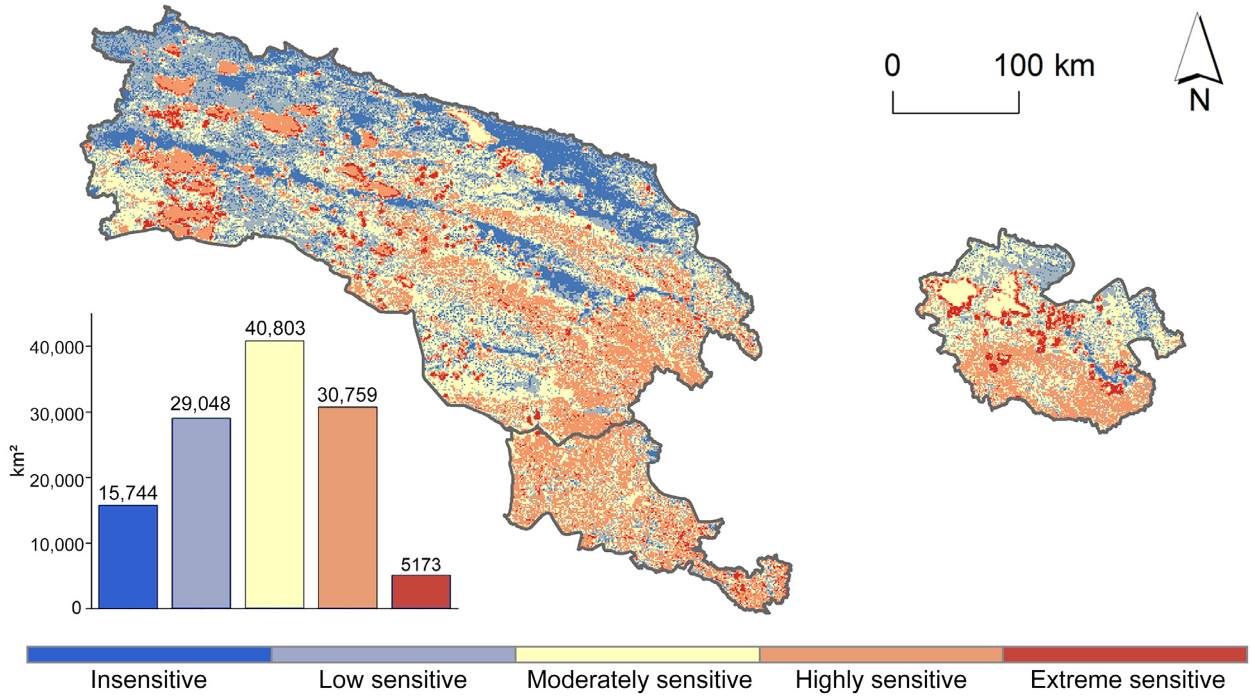

Figure 5. Integrated ecological sensitivity.

Table 4. Results of ecological sensitivity assessment.

Sensitivity Zoning	The Source of the Yellow River		The Source of the Yangtze River		The Source of the Lancang River	
	Area/km^2	Proportion	Area/km^2	Proportion	Area/km^2	Proportion
Extremely sensitive	1226.22	6.67%	3288.08	3.68%	638.68	4.81%
Highly sensitive	5199.29	28.29%	18,808.63	21.07%	6615.34	49.84%
Moderately sensitive	7568.34	41.18%	28,753.11	32.21%	4321.64	32.56%
Mildly sensitive	3627.47	19.74%	23,798.29	26.66%	1430.36	10.78%
Insensitive	758.71	4.13%	14,621.13	16.38%	267.94	2.02%

3.3. Landscape Pattern Index

We utilized the grid method in Fragstats 4.2 software to calculate the landscape pattern indices of eight types across the entirety of Sanjiangyuan National Park. Subsequently, we interpolated these indices to depict their spatial distribution using the ordinary kriging interpolation method in ArcGIS, as depicted in Table 5 and Figure 6. The number of patches (NP) represents the aggregate number of patches within the study area. Within Sanjiangyuan National Park, this count reached 359,626, indicating a prevalence of numerous small patches within the park's boundaries. This observation is corroborated by the patch density (PD), averaging 2.9173 patches per square kilometer, suggesting a high degree of landscape fragmentation characterized by numerous small, scattered patches rather than a few large, contiguous areas. Furthermore, the Landscape Trait Index (LSI) stands at 191.8188, signifying a high degree of complexity or irregularity in patch shapes within the park, potentially attributable to human activities impacting the landscape. This fragmentation is further evidenced by the larger values of total landscape edge length (TE), typically associated with smaller patches and intricate patch boundaries. Despite the elevated fragmentation index, the Edge Density (ED) value of 21.4671 suggests relatively stable edge environments within Sanjiangyuan National Park, critical for supporting diverse species and ecological activities. The shape index (Shape_MN) approximates 1, indicating that patch shapes within the park tend to be basic geometric forms, possibly indicating minimal anthropogenic disturbance, as human activities typically result in more irregular patch shapes. Finally, analysis depicted in Figure 6 reveals that the eastern and northern regions of Sanjiangyuan National Park exhibit higher landscape fragmentation indicators (NP, PD, LSI, TE), accompanied by a lower mean value of patch area (Area_MN). This pattern suggests that patches in these regions are smaller, more numerous, and exhibit more complex shapes with longer total edges, indicative of a highly fragmented and marginal environment. While such landscapes may support increased biodiversity, they may also exert pressure on species with specific habitat size requirements. The specific values for the different parks are shown in Table 6.

Table 5. Sanjiangyuan National Park Landscape Pattern Index.

NP	PD	LPI	TE	ED	Area_MN	Shape_MN
359,626	2.9173	53.1715	264,633,560.9	21.4671	34.2785	1.2457

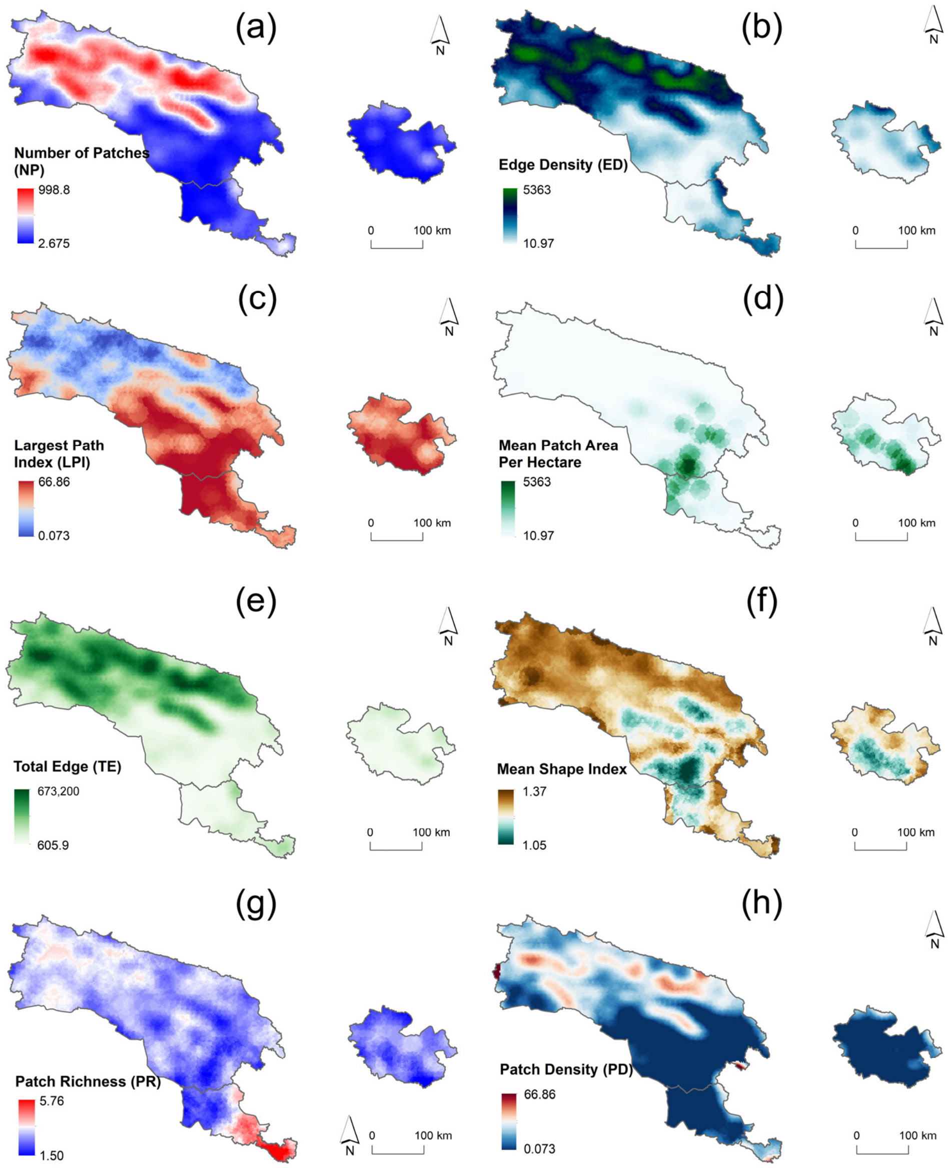

Figure 6. Spatial distribution map of landscape pattern indices. (**a**) NP visualisation map; (**b**) ED visualisation map; (**c**) LPI visualisation map; (**d**) Area_MN visualisation map; (**e**) TE visualisation map; (**f**) Shape_MN visualisation map; (**g**) PR visualisation map; (**h**) PD visualisation map.

Table 6. Landscape pattern indices of the three parks in Sanjiangyuan National Park.

	LPI	ED	AREA_MN	NP	SHAPE_MN	PD	PR	TE
Source of the Yellow River	91.936	7.29	1021.48	89.367	1.221	1.311	2.838	53,395.95
Source of the Yangtze River	77.281	26.65	353.218	357.72	1.256	4.048	3.173	252,970.9
Source of the Lancang River	93.996	9.81	786.508	121.61	1.236	1.854	3.523	70,184.43

3.4. Spatial Autocorrelation Analysis

In the Sanjiangyuan region, Moran's index analyses of both the ecological sensitivity index and the landscape pattern index unveiled intriguing spatial relationships. These indices showcased varying degrees of spatial aggregation or dispersion, elucidating the intricate interplay between ecology and landscape across the region, as shown in Table 7. Negative Moran's indices, such as −0.344 for total edge length (TE), −0.330 for number of patches (NP), and −0.399 for edge density (ED), indicated a tendency for areas with higher attributes to border areas with lower attributes. This spatial distribution pattern may underscore the degree of fragmentation within the ecological landscape, where increased marginalization and dispersion in patch numbers might stem from human activities or natural geographic factors, potentially hindering ecological connectivity. Conversely, Moran's indices for maximum patch index (LPI) and average patch area (Area_mn) stood at 0.337 and 199, respectively, signaling a spatial aggregation trend. This suggests that sizable, contiguous patches and larger mean patch areas tend to cluster in specific regions, likely fostering better ecological connectivity and lower fragmentation, thus supporting biodiversity and ecosystem services. Regarding patch shape index (Shape_mn) and patch richness (PR), the Moran's index hovered around −0.192 and −0.01, respectively, with near-zero values indicating nearly random spatial distribution. This phenomenon may imply that these ecological features experience minimal anthropogenic or natural geophysical influences. Collectively, the spatial distribution characteristics of ecological and landscape pattern indices in the Sanjiangyuan region delineate both challenges and opportunities for ecological conservation and management. By pinpointing the spatial aggregation traits of these indices, tailored conservation strategies can be more effectively devised to bolster ecological connectivity and enhance overall ecosystem health and stability. Such analyses furnish a scientific foundation for ecological conservation efforts and furnish guidance for future ecological management and conservation strategies.

Table 7. Global Moran's I values of landscape pattern index.

	TE	Shape_mn	PR	PD	NP	LPI	ED	Area_mn
Moran's I	−0.344	−0.192	−0.010	−0.087	−0.330	0.337	−0.399	0.199

Through the interpretation of Moran index maps depicting the ecological sensitivity index and landscape pattern index in the Sanjiangyuan area, spatial aggregation patterns of landscape features become apparent. In the southern parts of the Lancang River Source Park and the Yellow River Source Park, the Largest Patch Area (LPI) and ecological sensitivity index exhibit a HH aggregation pattern, indicating robust ecological connectivity in these regions. Similarly, Total Edge (TE), Number of Patches (NP), Patch Density (PD), and Edge Density (ED) demonstrate comparable aggregation characteristics to the Landscape Sensitivity Index (LSI). High and low aggregation areas are predominantly concentrated in the southern regions of the Lancang River Source Park and the Yellow River Source Park, signifying that these ecologically sensitive areas feature longer total edge lengths and higher patch numbers. Moreover, both patch density and edge density are elevated, suggesting a complex landscape structure with abundant habitat edge areas, crucial for biodiversity and ecological processes. This comprehensive understanding of ecological and landscape patterns in the Sanjiangyuan region serves as a vital foundation for identifying conservation priorities and management measures, facilitating sustainable management and conservation of regional ecology.

4. Discussion and Limitation

4.1. Discussion

In evaluating the ecological sensitivity and landscape pattern of the Three-River-Source National Park, a diverse range of analytical methods is necessary to comprehensively understand the intricate interactions within the national park system and their dual impact on ecological and socio-economic development. National parks serve not only as repositories of biodiversity but also as crucial hubs for socio-economic activities. Planning and management efforts must strike a delicate balance between ecological conservation and economic development. This study employs ArcGIS 10.8, Fragstats 4.2, and GeoDa 1.20 to assess the ecological sensitivity of the Three-River-Source National Park and elucidate its impact on the overall landscape pattern stability and functionality.

In the study of landscape fragmentation in the Three-River-Source National Park, detailed data on landscape fragmentation were obtained through analysis using Fragstats 4.2 and ArcGIS 10.8. These data revealed the widespread presence of small and scattered patches within the park, particularly in the eastern and northern regions, where landscape fragmentation metrics such as NP, PD, LSI, and TE were high, while the average patch size was low. We found that the level of landscape fragmentation in the northern region of the park is high. However, based on land use data, we discovered that impervious surfaces within the park are rare, and the areas with high levels of landscape fragmentation are mainly composed of bare land, grassland, and lakes, indicating a lesser association with human activities. Therefore, priority should be given to restoring ecological connectivity by establishing ecological corridors and green belts in highly fragmented areas in the eastern and northern regions to maintain animal migration and ensure regional biodiversity [43–45]. Additionally, new development activities within areas with high landscape fragmentation should be restricted, especially those leading to further fragmentation, such as road construction and agricultural expansion. In contrast, conservation measures in less fragmented central and other regions will be relatively relaxed, allowing for moderate ecotourism and environmental education to raise public awareness. Supporting sustainable land use practices for traditional grazing and agriculture is crucial to ensure the sustainability of ecological quality [43–45].

In the ecological sensitivity assessment of the Three-River-Source National Park, the region is categorized into five sensitivity levels based on varying ecological requirements: extremely sensitive, highly sensitive, moderately sensitive, mildly sensitive, and insensitive. NDVI exhibits a gradual distribution, with sensitivity increasing from east to west. For areas with higher NDVI sensitivity, it is recommended to enhance the protection of grasslands, maintain the natural ecological processes of core conservation areas, implement strict closure measures, and limit various forms of human activities. Moreover, regions with higher water source sensitivity are primarily concentrated in the Yangtze River Source Park and Lancang River Source Park. Sustainable land use and resource management strategies, such as optimizing water resource utilization, should be prioritized for these areas to mitigate the adverse effects of human activities on the ecosystem [43–46]. The overall ecological sensitivity in the southern part of the Three-River-Source National Park is higher than that in the north, with the sensitivity in the Lancang River Source area and the Yellow River Source area being significantly higher than that in the Yangtze River Source area. The Yellow River Source Park is mainly classified as a moderately sensitive area (41.18%), followed by mildly sensitive areas (19.74%) and highly sensitive areas (28.29%). The Yangtze River Source Park is primarily a moderately sensitive area (32.21%), followed by highly sensitive areas (21.07%) and mildly sensitive areas (26.66%). The largest proportion in the Lancang River Source Park is highly sensitive areas (32.56%), followed by moderately sensitive areas (32.56%) and mildly sensitive areas (10.78%). Since the proportions of ecological sensitivity in the three parks are different, specific ecological restoration suggestions should be tailored to the different ecological characteristics of each park. The ecological sensitivity in the northern part of the Yangtze River Source Park is relatively low, so efforts should be made to enhance publicity and education, limit human production and operation activities around the snow-capped glaciers, and reduce the impact of human activities on the snow-capped glaciers within the park. The ecological sensitivity of the Lancang River Source Park and the Yellow River Source Park is relatively high; thus, protection of grasslands in these areas should be intensified. Implementing strict closure measures, gradually removing fences, and limiting or reducing human activities are essential to protect the natural ecological processes of core conservation areas [47–49].

According to Figure 7, the southern regions of the Yangtze River Source Park, the southern parts of the Lancang River Source Park, and the Yellow River Source Park exhibit lower degrees of landscape fragmentation and higher levels of ecological sensitivity. Therefore, we suggest that future corridor construction in these ecologically fragile areas of the Sanjiangyuan National Park should fully consider the landscape patterns and ecological sensitivity within the region to enhance corridor efficiency. Additionally, the three different zones of the Sanjiangyuan National Park demonstrate varying landscape ecological patterns. The Yangtze River Source region primarily exhibits low levels of ecological sensitivity but severe landscape fragmentation. The Yellow River Source Park demonstrates higher ecological sensitivity and lower levels of landscape fragmentation. In the northern region of the Lancang River Source Park, ecological sensitivity is low while landscape fragmentation is high; conversely, in the southern region, ecological sensitivity is high and landscape fragmentation is low. In areas with high levels of landscape fragmentation, such as the northern regions of the Yangtze River Source Park and the Lancang River Source Park, ecological corridors should be established to connect fragmented patches and protect wildlife habitats. Numerous studies indicate that roads directly obstruct species migration, with a stronger impact associated with higher road grades. Therefore, in the development and ecological protection of national parks, efforts should be made to protect the integrity of the landscape within the parks, mitigating excessive human construction that exacerbates landscape fragmentation. In areas with low landscape fragmentation but high ecological sensitivity, such as the southern regions of the Yellow River Source Park and the Lancang River Source Park, more comprehensive ecological protection policies should be implemented to preserve landscape continuity and environmental quality [44,45].

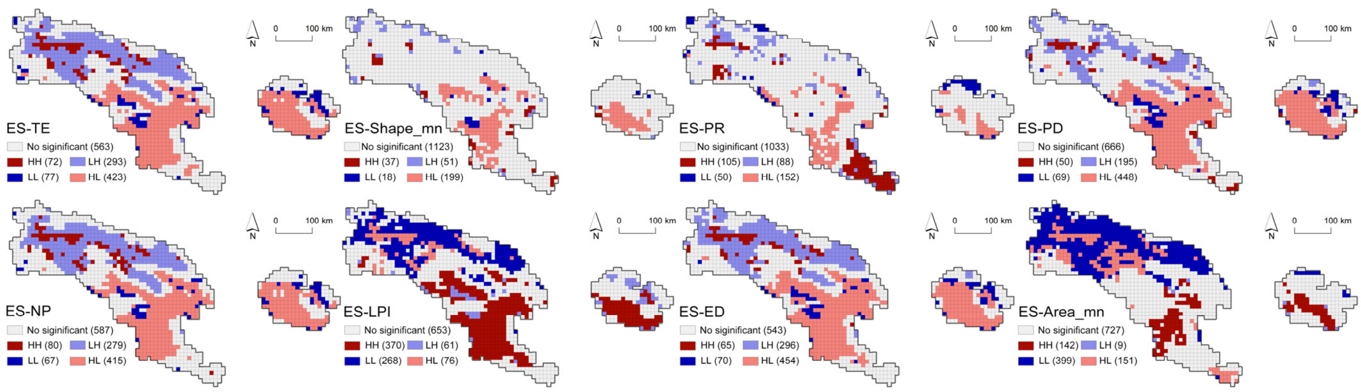

Figure 7. LISA plot of landscape pattern and ecological sensitivity in Sanjiangyuan National Park.

4.2. Limitation

This paper presents a preliminary investigation into the ecological sensitivity and spatial distribution characteristics of the landscape pattern in Sanjiangyuan National Park. However, the collected remote sensing data exhibit significant variation in spatial resolution due to limitations in data acquisition accuracy and spatial interpolation. Consequently, future research must employ higher-resolution data for analysis. Additionally, subsequent studies should analyze landscape patterns and ecological sensitivity at various grid scales. The scope of this study is confined to Sanjiangyuan National Park in China. Given the existence of numerous national parks worldwide, the applicability of these findings to other national parks is uncertain. Therefore, future research should examine and analyze other national parks globally to enhance the generalizability and robustness of the conclusions.

5. Conclusions

Over the past decades, China has made significant investments in the Sanjiangyuan National Park to preserve its originality and biodiversity. Assessing the effectiveness of conservation efforts in protected areas is essential for improving management practices and implementing targeted conservation strategies. The study revealed several key findings:

(1) Ecological Sensitivity Levels: The Sanjiangyuan National Park exhibits varying levels of sensitivity, categorized into extremely sensitive, highly sensitive, moderately sensitive, mildly sensitive, and insensitive areas. Notably, the moderately sensitive area of the Yellow River Source Park covers 7279.67 km^2 (41.18%), while the corresponding region in the Yangtze River Source Park spans 28,753.11 km^2 (32.21%), indicating a higher ecological sensitivity in the southern region compared to the northern region. This regional variation underscores the need for tailored resource management and conservation strategies, particularly focusing on highly sensitive and extremely sensitive areas.

(2) Fragmentation Analysis: Utilizing Fragstats 4.2 software and ArcGIS ordinary kriging interpolation, the study identified a high degree of fragmentation within the Sanjiangyuan National Park. The analysis revealed a total of 359,626 patches, with an average patch density of 2.9173 patches per square kilometer. While this fragmentation may promote biodiversity formation, it could also exert pressure on species requiring larger continuous habitats. Hence, measures to enhance ecological connectivity, such as establishing ecological corridors and limiting further fragmentation activities, are warranted.

(3) Moran's Index Analysis: The analysis of Moran's index elucidated the clustering or dispersing characteristics of the ecological sensitivity index and landscape pattern index in the Sanjiangyuan area. Negative Moran indices (−0.344 for TE, −0.192 for Shape_mn, −0.01 for PR, −0.087 for PD, −0.33 for NP, and −0.399 for ED) indicated a tendency for areas with higher attributes to adjoin those with lower attributes, signifying ecological landscape fragmentation. Conversely, positive Moran indices (0.337 for LPI and 0.199 for Area_mn) suggested spatial clustering, which supports biodiversity maintenance and ecosystem service provision. These findings underscore the importance of implementing targeted ecological conservation measures to bolster ecosystem health and stability.

(4) This study aligns with several SDGs, including SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 6 (Clean Water and Sanitation). By analyzing the ecological sensitivity and landscape pattern of Sanjiangyuan National Park, the research contributes to climate action, protection and restoration of terrestrial ecosystems and biodiversity, as well as ensuring sustainable management and availability of clean water and sanitation facilities. These findings provide valuable insights and support for achieving these SDGs.

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