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Spatiotemporal Dynamics and Obstacle Factor Diagnosis of Social-Ecological System Resilience in Qilian Mountain National Park

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ABSTRACT

Scientifically assessing social-ecological system resilience (SESR) in national parks in alpine-arid regions is crucial for to balancing ecological conservation with sustainable development. As a vital ecological security barrier and a sensitive zone for human-nature coupling in western China, the Qilian Mountain National Park (QMNP) necessitates a systematic research of its SESR trends and driver factors. Based on the social-ecological system (SES) framework, this study constructed a multi-criteria indicator system encompassing social, economic, and ecological dimensions. Employing the CRITIC method, three-dimensional Kernel Density Estimation, and the Obstacle Degree Model, we analyzed the temporal evolution, spatial differentiation, and key obstacle factors of SESR in QMNP from 2010 to 2024. The results show that: (1) The comprehensive social-ecological system resilience index (SESRI) of QMNP steadily increased from 0.3645 to 0.4308 from 2010 to 2024, exhibiting a consistent upward trajectory. (2) The spatial pattern evolved from an initially low-level homogeneity to a pronounced "high-west, low-east" differentiation, featuring a high-resilience cluster in the northwest driven and a resilience-lagging zone in the southeast constrained."(3) Population density, per capita GDP, and net primary productivity (NPP) persisted as the core obstacle factors inhibiting the enhancement of SESR. This study provides a scientific basis and decision-making reference for hierarchical adaptive management and the optimization of sustainable development pathways for national parks in alpine and arid regions.

KEYWORDS

Social-ecological system resilience; Spatiotemporal dynamics; Obstacle factors; Qilian Mountain National Park

1. INTRODUCTION

As core components of the global nature conservation system, national parks not only fulfill fundamental roles in biodiversity conservation and landscape preservation but also serve as critical spatial units within which complex coupled human–nature systems address climate change and achieve global sustainable development goals [1-4]. Functioning as adaptive governance instruments for responding to climate change, national parks effectively enhance the carbon sequestration capacity and climate resilience of forest, grassland, wetland, and marine ecosystems through strict ecological protection and systematic ecological restoration [5]. Specifically, Healthy national park ecosystems significantly bolster regional resilience to adverse impacts of climate change [6] by regulating water supplies during droughts, mitigating flood risks during extreme precipitation [7], and serving as effective buffers against sea-level rise and storm surges [8]. Furthermore, the establishment of national parks constitutes a critical pathway for realizing the UN 2030 Sustainable Development Goals (SDGs). Their relevance extends beyond SDG 14 (Life Below Water) and SDG 15 (Life on Land), permeating comprehensive social, economic, and ecological dimensions [9]. In this context, China's national park system represents a significant advancement in global protected area governance. Fundamentally, these parks serve as typical social-ecological system units characterized by high conservation value and environmental sensitivity [10]. Therefore, analyzing social-ecological system resilience in national parks and exploring their formation processes and evolutionary patterns are essential for formulating sustainable development pathways and achieving the SDGs.

The concept of resilience originated in the fields of physics and engineering, describing the ability of a material to return to its original state after being subjected to external forces, emphasizing system stability and the rate of recovery [11, 12]. In 1973, this concept was introduced into ecology by Holling in 1973 as "ecological resilience." With the subsequent advancement of systems science, the concept has gradually evolved into social-ecological system resilience [13]. Within this framework, it is emphasized that in the face of complex uncertainties, systems possess not only the capacity to withstand shocks but also the potential for dynamic evolution toward sustainable development facilitated by self-organization, learning, and transformation [14, 15]. To data, a mature framework for SESR research has been established, spanning from theoretical construction to quantitative empirical analysis. Regarding research frameworks, evaluation models are predominantly constructed based on the process dimension of "Resistance-Adaptability-Recovery," the structural dimension of "Pressure-State-Response", or the system dimension of "Social-Economic-Ecological." [16-18]. Methodologically, the indicator system approach, integrated with CRITIC weighting and the entropy weight method, is widely employed to quantify resilience levels [19]. In terms of research scales and objects, the academic focus has gradually extended from macro-scale units such as watersheds and provinces to meso- and micro-scale units such as municipalities, counties, nature reserves, and communities [20-23], the research objects have expanded to encompass diverse regions characterized by acute human-environment conflicts, including tourism destinations, oases in arid regions, and resource-based cities [18, 24, 25].

Current research on SESR in national parks exhibits a pronounced bias towards the ecological dimension. A substantial body of literature concentrates on assessments within the natural science dimension, such as changes in vegetation indices, improvements in habitat quality, and the evolution of ecological resilience [26-28]. Through remote sensing monitoring and ecological modeling, these studies have confirmed the significant effectiveness of national park establishment in mitigating ecological degradation [29]. However, national parks are not merely natural protected areas but complex coupled human-nature systems. Their resilience depends not only on the stability of natural habitats but is also significantly constrained by the dynamic feedbacks of socioeconomic systems [30]. Under the rigid constraints of the Ecological Conservation Redline, the pressure of community livelihood transition and the intervention of social capital have generated complex mutual feedback mechanisms within the system [31-32]. This characteristic necessitates a shift in research perspective from a singular focus on natural succession to a holistic social-economic-ecological perspective, aiming to elucidate the evolutionary dynamics of national parks as complex SES units [33]. Despite significant advancements in analytical frameworks, methodologies, and research content regarding SESR, several critical challenges remain to be addressed specifically for national parks: (1) There is a scarcity of integrated multi-system research on the SESR of national parks. (2) Insufficient attention has been paid to the long-term, continuous, and dynamic evolutionary processes of SESR, making it difficult to reveal its evolutionary patterns and regularities. (3) The identification of obstacle factors for SESR remains at the level of static description, lacking exploration into their temporal evolution patterns. (4) There is a deficiency in revealing the spatial differentiation mechanisms of resilience at the county scale, which hinders the guidance of precise policy implementation at the micro-management level.

The pilot program for the Qilian Mountain National Park system was officially launched in 2017 [34]. Situated at the intersection of the Qinghai-Tibet, Loess, and Mongolian Plateaus, QMNP serves not only as a critical ecological security barrier and a key water conservation area in western China but also as a priority region for biodiversity conservation and a representative area for the evolution of social-ecological systems in alpine desert and ecologically fragile zones [20,35]. However, driven by the dual forces of global climate change and human activities, this region faces severe natural background constraints, including cryosphere retreat, fluctuations in vegetation coverage, and permafrost degradation. The resulting fragility of ecological functions has become a core bottleneck restricting high-quality regional development [36-37]. During the pilot reform of the national park system, QMNP is undergoing a profound structural transition from traditional pastoral livelihoods to eco-conservation-based livelihoods [38]. However, the misalignment between administrative boundaries and natural geographic units has triggered intense conflicts arising from the overlap of the Ecological Conservation Redline and community livelihood spaces. This scenario provides a critical empirical window for examining the trade-offs between social adaptability and ecological protection [39]. Given the representativeness of its geographical unit, the acuteness of human-environment conflicts, and the urgency of policy responses, QMNP constitutes an exemplary case for exploring the formation processes and spatiotemporal evolution of SESR.

Accordingly, grounded in the theoretical framework of the SES, this study takes QMNP as the research subject. By integrating multi-source, long-term spatiotemporal data spanning 2010–2024, it systematically evaluates the spatiotemporal evolutionary characteristics of SESR, reveals its spatial distribution patterns and dynamic features, and further diagnoses the obstacle factors hindering resilience. The specific objectives are as follows:(1) To construct a multi-criteria evaluation system encompassing social, economic, and ecological dimensions, thereby systematically measuring the SESR of the national park. (2) To analyze the temporal evolutionary characteristics and spatial distribution patterns of SESR within the national park. (3) To identify the obstacle factors affecting SESR and propose targeted policy recommendations, providing a scientific basis for promoting the sustainable development of QMNP.

2. MATERIALS AND METHODS

2.1. Study Area

The QMNP is situated at the northern foot of the Qilian Mountains, spanning the intersection of the Qinghai-Tibet, Inner Mongolia-Xinjiang, and Loess Plateaus across Gansu and Qinghai Provinces. The study area is characterized by a narrow, elongated northwest-southeast orientation, with a terrain dominated by high mountains and an average elevation ranging between 4000 and 5000 m [40].A typical plateau continental climate is observed, featuring distinct vertical zonality in both temperature and precipitation [35].Synchronized periods of heat and rain are recorded, with precipitation primarily concentrated in the summer; the mean annual precipitation is approximately 400 mm, and the mean annual temperature remains consistently below 4°C [36].Abundant water resources are found within the Qilian Mountains, where significant complexity and diversity are exhibited in both habitat types and vegetation cover [38].Driven by the three-dimensional zonality of climate, hydrology, soil, and geomorphology, a composite ecosystem has been formed within the study area. This complex system encompasses a variety of natural ecosystems, including forests, grasslands, water bodies, glaciers, alpine deserts, and arid deserts, as well as agricultural ecosystems [41].

The QMNP was established as one of the first ten pilot sites for China's national park system, covering a total area of 5.02×104km^2, the park is partitioned into the Gansu section (3.44 ×10^4 km^2)

and the Qinghai section (1.58×10^4 km^2). The Gansu section primarily encompasses eight counties (district), including Yongchang, Liangzhou, Sunan, and Subei across the cities of Jinchang, Wuwei, Zhangye, and Jiuquan; the Qinghai section involves four counties (city) such as Delingha, Tianjun, Menyuan, and Qilian within the Haixi and Haibei Prefectures [42]. The resident population is predominantly composed of nomadic ethnic groups, including the Tibetan, Mongol, and Yugur peoples. Regarding the industrial structure, a long-term reliance on traditional agro-pastoral production models has been maintained across the pilot counties, resulting in a relatively singular economic structure where production methods urgently require transformation and upgrading [42]. Furthermore, public infrastructure construction is characterized as relatively weak, and the urbanization process is noted to be comparatively slow [44]. With the deepening of national park systemic reforms, the regional social-ecological system is undergoing a profound transition from resource-dependent models toward ecological protection and adaptive governance.

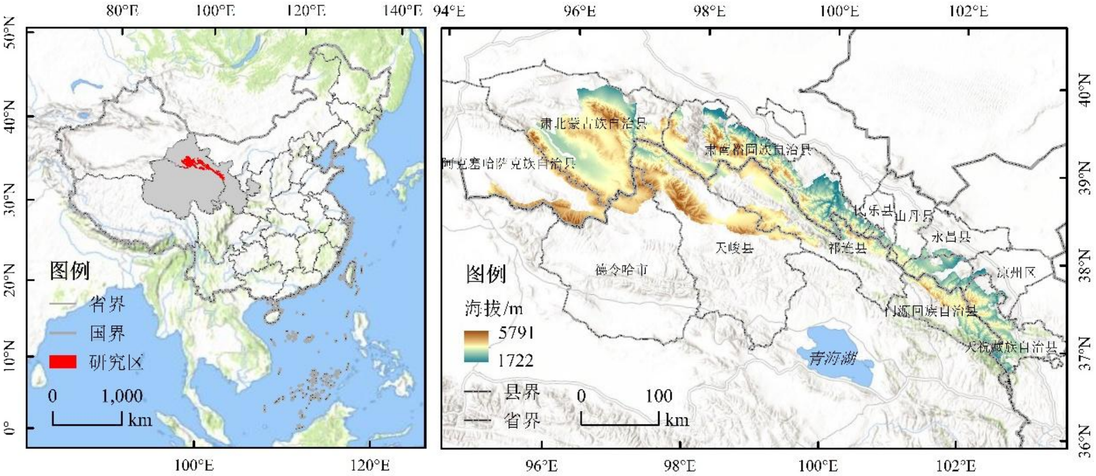

Figure 1. Location of the study area

2.2. Data Source

The continuous time-series dataset required for this study primarily encompasses remote sensing imagery, geospatial data, and socioeconomic statistical data integrated from multiple platforms from 2010 to 2024. To ensure data continuity, linear interpolation was employed to supplement missing values for specific years in the socioeconomic statistics. Detailed descriptions of the data sources and their attributes are provided in Table 1.

Table 1. Data source

Data	Data Source	Data Type	Resolution
Land Use	Zenodo (https://zenodo.org/)	TIFF	30m
FVC	National Tibetan Plateau Data Center (https://data.tpdc.ac.cn)		250m
NPP	NASA Earth Data, MOD17A3HGFv061 dataset (https://search.earthdata.nasa.gov)		500m
NSDI	National Snow and Ice Data Center (NSIDC), MOD10A1 dataset (https://nsidc.org/)		500m
PD	Oak Ridge National Laboratory (ORNL)(https://landscan.ornl.gov/)		1km
Vector Boundary Data	Official website of the National Forestry and Grassland Administration (National Park Administration)(https://www.forestry.gov.cn/)	SHP	-
Socio-economic data	Gansu Development Yearbook (2010–2024) Qinghai Statistical Yearbook (2010–2024) and local statistical yearbook	Statistical Data	-

* FVC: Fractional Vegetation Cover; NPP: Net Primary Productivity; NSDI: Normalized Difference Snow Index; PD: Population Density.

2.3. Index of the SESR

Based on the theory of SES and drawing upon established research findings [20, 45, 46], a resilience indicator system for the QMNP was constructed. This framework integrates the specific regional characteristics of the park and is structured across three primary dimensions: the social, economic, and ecological subsystems. The detailed composition of the indicator system is presented in Table 2.

Social Resilience reflects the demographic characteristics, resident well-being, infrastructure levels, and the potential of the social system to cope with risks, primarily manifesting through population carrying capacity, social security capability, and residents' adaptability to ecological policies. Population density characterizes the degree of population agglomeration and potential labor supply within the national park, where higher values indicate more sufficient labor resources [47-48]. Conversely, the proportion of employment in agriculture, forestry, animal husbandry, and fishery reflects the direct dependence of social livelihoods on natural resources; a higher proportion suggests a singular livelihood model, which reduces social system resilience [20]. The urbanization rate, Engel’s coefficient, and the urban-rural income gap (URIG) serve as core indicators characterizing socio-economic adaptability and social equity. An increase in the urbanization rate implies better access to public services and non-agricultural employment opportunities [21]; while a reduction in Engel’s coefficient and the urban-rural income gap significantly enhances the social system's ability to withstand risks [17]. Furthermore, average years of education and the number of hospital beds per thousand people represent social public service capacity; higher values indicate a stronger regional cognitive level regarding sudden disaster events and greater emergency medical capabilities, thereby contributing to higher social resilience [25].

Economic resilience characterizes the material buffering capacity of the regional economic system against external shocks, integrating considerations of economic development level, structure, and quality. Specifically, the GDP growth rate and per capita GDP serve as metrics for the speed of regional economic development and overall output capacity, respectively [49]; The per capita savings deposit balance of urban and rural residents characterizes the capacity to withstand economic risks, where higher levels of economic accumulation provide the necessary financial guarantees for post-shock recovery [50]; the proportion of the tertiary industry and the share of tourism revenue directly quantify the efficiency with which core natural capital (landscapes and ecology) is transformed into sustainable livelihoods and green benefits; these serve as positive indicators reflecting the quality of economic transformation within the national park [24, 38].

Ecological resilience reflects the capacity of an ecosystem to maintain structural integrity, stabilize core functions, and resist or absorb external disturbances, encompassing dimensions such as natural endowments, landscape patterns, cryosphere responses, and anthropogenic interference. In this study, FVC and NPP were selected to characterize the ecosystem's structural and functional status [51]. Regarding landscape patterns, LPI and CONTAG were utilized; a higher LPI indicates greater integrity of core ecological patches and stronger resistance to disturbance, while a higher CONTAG value signifies enhanced landscape connectivity [23, 52]. NSDI was included as a critical indicator specific to the Qilian Mountains' function as an "alpine solid water reservoir," directly linking to watershed hydrological regulation and the sustainability of downstream water supplies. Conversely, the proportion of land used for human activities quantifies the encroachment of construction and cultivated land upon natural spaces, serving as a core negative indicator that measures the intensity of anthropogenic stress on the ecological baseline [20].

2.4. Methods

2.4.1. Data Standardization

Due to differing units of measurement across indicators, the raw data was normalized to comparable units ranging from 0 to 1. Additionally, the selected indicators have varying impacts (positive and negative) on each sub-objective layer. This study employs the range standardization method for data standardization [24], The calculation formulas are as follows:

$$\text{Positive indicators: } X_{ij} = \frac{x_{ij} - x_{i,min}}{x_{i,max} - x_{i,min}} \tag{1}$$

$$\text{Negative indicators: } X_{ij} = \frac{x_{i,max} - x_{ij}}{x_{i,max} - x_{i,min}} \tag{2}$$

Where x_{ij} is the original value of indicator for *j* county *i*, $x_{i,max}$ and $x_{i,min}$ are the maximum and minimum values of indicator *j*, and X_{ij} is the standardized value of the indicator.

2.4.2. CRITIC Weighting Method

CRITIC (Criteria Importance Through Intercriteria Correlation) method, as an objective weighting technique, determines the objective attributes of indicator weights by utilizing contrast intensity (represented by standard deviation) and conflict (represented by correlation coefficients) [49]. In comparison to other methods such as the entropy method, the CRITIC approach simultaneously accounts for the correlation and variability among indicators. This effectively mitigates weight distortion caused by extreme data outliers, thereby demonstrating superior robustness and system coupling [18]. Given the significant physiographic and socio-economic disparities across the counties within the QMNP, and the strong coupling correlations among indicators within the social-ecological subsystems, this method is particularly effective in eliminating information redundancy. Consequently, the CRITIC method was adopted to assign weights to each indicator. Subsequently, the SESRI for the QMNP from 2010 to 2024 was calculated via the linear weighting method. The calculation formulas are as follows:

$$S_j = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(z_{ij} - \bar{z}_j)^2} \tag{3}$$

$$c_j = \sum_{k=1,k=j}^{n}(1 - |r_{jk}|) \tag{4}$$

$$C_j = S_j \times c_j \tag{5}$$

$$W_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{6}$$

Where S_j is the standard deviation of the indicator; n represents the total number of indicators; $\overline{z}_j$ denotes the mean value of the standardized indicator; c_j represents the conflict measure between indicators; $|r_{jk}|$ is the correlation coefficient between j and k indicators; C_j signifies the information content of j indicator; W_j is the weight.

Table 2. The indicator system for evaluating SESR in the QMNP.

System	Criteria	Indicator	Weight	Property
Socio-ecological System Resilience	Social System Resilience	Population Density (A1)	0.1861	+
		Proportion of employment in agriculture, forestry, animal husbandry, and fishery (A2)	0.1743	-
		Urbanization Rate (A3)	0.1495	+
		Engel's Coefficient (A4)	0.1322	-
		Urban-Rural Income Gap (A5)	0.1186	-
		Average Years of Education (A6)	0.1220	+
		Number of Hospital Beds per Thousand People (A7)	0.1173	+
	Economic System Resilience	Local GDP Growth Rate (B1)	0.1886	+
		Per Capita GDP (B2)	0.2035	+
		Per Capita Savings Deposit Balance of Urban and Rural Residents (B3)	0.1597	+
		Proportion of Tertiary Industry (B4)	0.2298	+
		Proportion of Tourism Revenue (B5)	0.2184	+
	Ecosystem Resilience	FVC (C1)	0.2760	+
		NPP (C2)	0.1927	+
		LPI (C3)	0.1549	+
		CONTAG (C4)	0.1517	+
		NSDI (C5)	0.1007	+
		Proportion of Land Used for Human Activities (C6)	0.1240	-

2.4.3. Social-ecological system resilience index

The SESRI is calculated using a weighted summation formula, incorporating the economic resilience index and the ecological resilience index. Based on scholars' understanding and calculation of resilience, social-ecological system resilience is defined as a function of social, economic, and ecological factors [45]. The specific formula is as follows:

$$SSRI = \sum_{i=1}^{n} W_i X_i \tag{7}$$

$$ESRI = \sum_{i=1}^{n} W_i X_i \tag{8}$$

$$ERI = \sum_{i=1}^{n} W_i X_i \tag{9}$$

$$SESRI = \sum_{i=1}^{n} W_i X_i \tag{10}$$

Where W_i and X_i represent the weight and normalized value of i indicator within each dimension, respectively; SSRI, ESRI and ERI denote the social, economic, and ecological system resilience indexes; and SESRI stands for the social-ecological system resilience index.

2.4.4. Three-dimensional kernel density function estimation

Three-dimensional Kernel Density Estimation (3D KDE) is a non-parametric statistical method that uses kernel functions to transform discrete data into continuous smooth surfaces, reflecting the degree of aggregation and distribution patterns of data in three-dimensional space. Due to its superior robustness and minimal reliance on prior model assumptions, this method has become a crucial tool for analyzing the evolutionary characteristics of dynamic data distributions [49, 53]. Generally, a higher kernel density value indicates a higher concentration of the data distribution. The calculation formula is as follows:

$$f(X) = \frac{1}{N\rho}\sum_{i=1}^{n} K\left(\frac{X_i - \bar{x}}{\rho}\right) \tag{11}$$

$$K(X) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{x^2}{2}\right) \tag{12}$$

Where X represents a random variable; N denotes the count of observations; $K(X)$ signifies the kernel function; X_i represents observations that are independently and identically distributed, and x stands as the central tendency; ρ embodies the bandwidth, the narrower the bandwidth, the greater the precision in estimation, and the smoother the curve becomes.

2.4.5. Obstacle degree model

The Obstacle Degree Model is a quantitative method used for system diagnosis and analysis. It calculates the obstacle degree from two dimensions: factor deviation and indicator weight. It is primarily employed to identify key constraints that hinder the achievement of objectives within complex systems [25, 54]. Therefore, this study introduces the Obstacle Degree Model to identify the primary limiting factors hindering the SESR of the QMNP. The calculation formula is as follows:

$$F_{ij} = W_{ij} - R_j \tag{13}$$

$$I_{ij} = \left|1 - Y_{ij}\right| \tag{14}$$

$$y_{ij} = \frac{F_{ij} \times I_{ij}}{\sum_{j=1}^{n} F_{ij} \times I_{ij}} \tag{15}$$

Where F_{ij} is the factor contribution degree; W_{ij} represents the weight of i indicator to which j sub-indicator belongs; R_j is the weight of j sub-indicator; I_{ij} denotes the indicator deviation; Y_{ij} is the normalized value of each individual indicator; and y_{ij} represents the obstacle degree of j indicator at level i.

3. RESULTS

3.1. Spatio-temporal Distribution Pattern of SESR in QMNP

3.1.1. Temporal variation characteristics of SESR

Taking the 12 counties (district/city) of the QMNP as the basic units, the results show that from 2010 to 2024, the SSRI, ESRI, ERI, and the comprehensive SESRI of QMNP all exhibited an overall upward trend (Fig. 2). However, the resilience of different counties showed significant disparities due to the influence of subsystem interactions. From 2010 to 2024, the SSRI of most counties exhibited a clear growth trend. Aksai County recorded the highest and most significant growth in SESRI, rising from 0.4164 to 0.6167. Although its ERI fluctuated considerably with an overall slight decline (from 0.6074 to 0.5857), its ESRI remained the highest in the entire region and grew rapidly (surging from 0.2757 to 0.6383). Simultaneously, its SSRI also improved substantially (from 0.3662 to 0.6261), which effectively offset the negative impact of ecological subsystem fluctuations and drove a leapfrog growth in overall resilience. In contrast, Tianzhu County's comprehensive SESRI was initially the lowest in the region (0.2486). Although its SSRI and ESRI both more than doubled over the 15-year period (SSRI from 0.1798 to 0.4203; ESRI from 0.1802 to 0.3461), it was constrained by an extremely low ecological resilience baseline (ERI consistently hovered around 0.40). As a result, while its overall resilience level recovered to 0.3928 by 2024, it remained within the lower range of the entire region for a long period. Additionally, other areas such as Delingha, Liangzhou, and Subei all showed a steady upward trend in their resilience indexes.

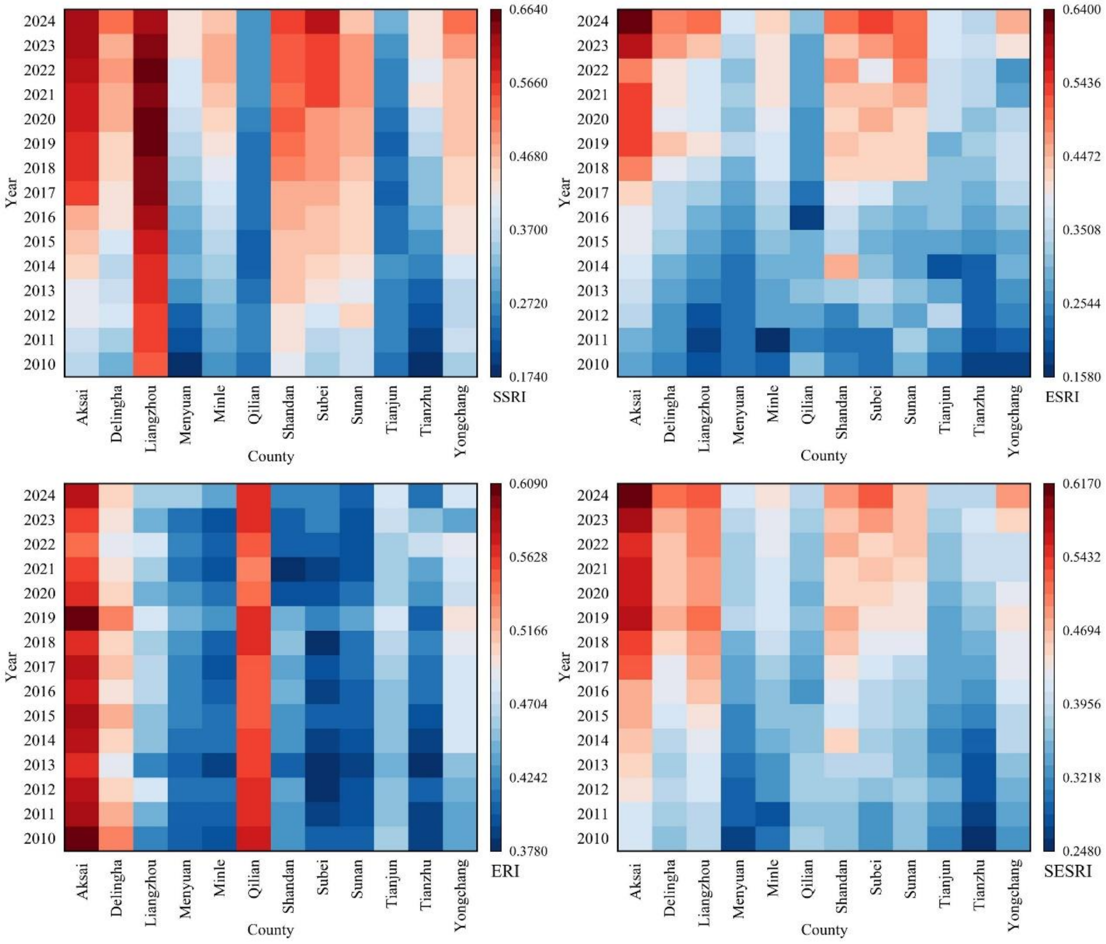

Figure 2. Temporal variation of SESRI in QMNP from 2010 to 2024

3.1.2. Spatial Distribution Pattern of Resilience

To better investigate the spatial disparities and overall patterns among regions, this study utilized ArcGIS and employed the Natural Breaks method to classify the SSRI, ESRI, ERI, and SESRI from 2010 to 2024. The resilience indexes were categorized into five levels (Levels I–V) and spatially visualized to generate spatial distribution maps of resilience.

From 2010 to 2024, the SSRI of QMNP transitioned from low-level homogenization to high-level differentiation (Fig. 3). In 2010, the SSRI was generally low across the national park, with low-to-medium level counties (Levels I–III) accounting for 92% of the total, exhibiting significant low-level homogenization; only Liangzhou was in the high-value Level V zone. By 2015, Level IV counties had expanded in a point-like diffusion toward Aksai and Shandan, while Level III counties saw largescale contiguous growth in Delingha, Subei, and Sunan, leading to a rapid contraction of low-value areas (Levels I and II) toward the southern mountainous regions. After 2018, the number of Level V counties increased to two, forming a dual-growth-pole pattern centered on Liangzhou and Aksai County. From 2021 to 2024, the number of Level V counties grew steadily, quadrupling compared to 2010. By 2024, counties at Level III and above had formed a contiguous high-value belt along the Hexi Corridor axis, with low-resilience counties confined only to Qilian County. This reflects the rapid growth of social system resilience in the national park driven by infrastructure development and regional collaborative governance.

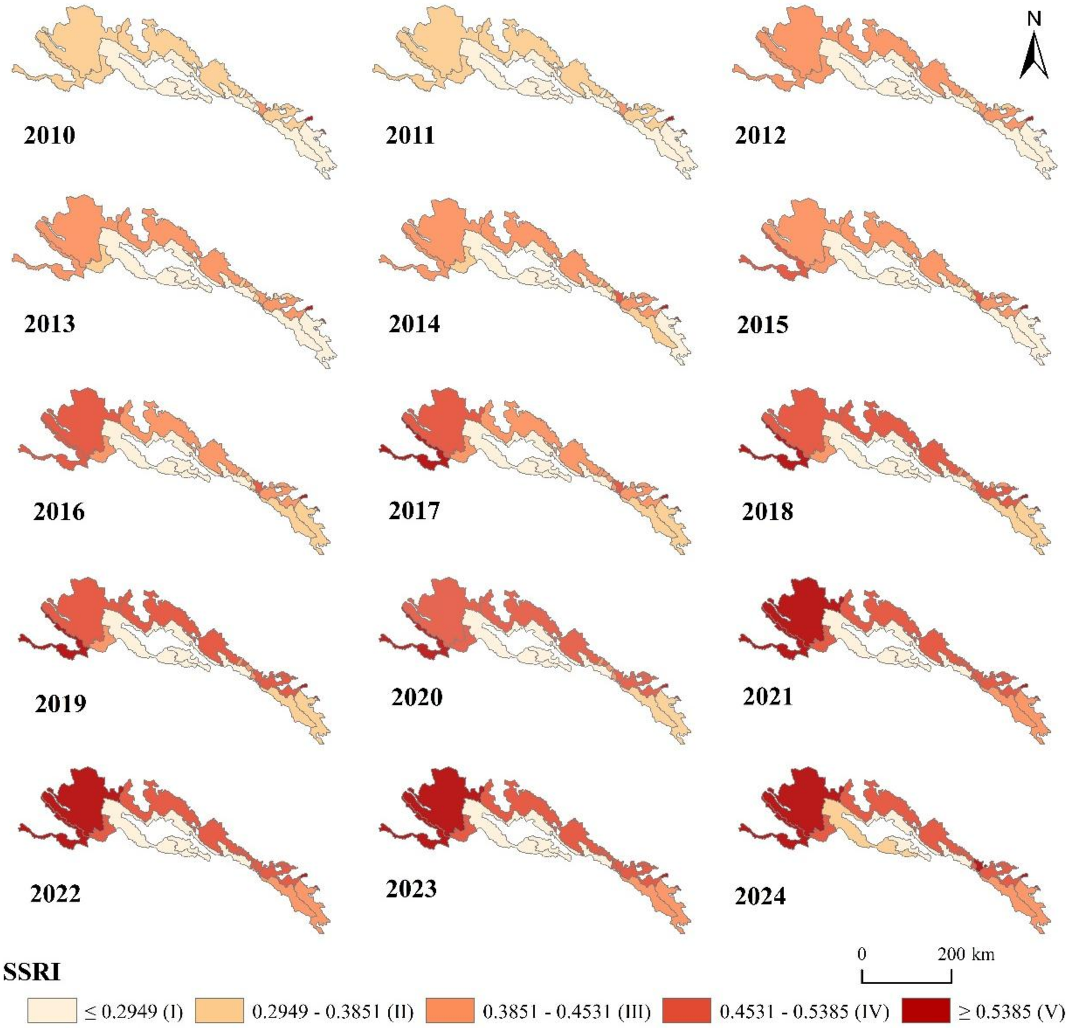

Figure 3. Spatial pattern of SSRI in QMNP from 2010 to 2024

From 2010 to 2024, the spatial pattern of ESRI in QMNP transitioned from low-level homogenization to a prominent "core-periphery" structure (Fig. 4). During the 2010–2012 period, economic resilience across the national park was generally fragile, with Level I counties accounting for as much as 58% (7 counties), and no Level IV or higher counties existed in the entire region. Leveraging its resource endowment and industrial advantages, Aksai developed rapidly and became the first to reach Level IV in 2014. Meanwhile, the Level I low-value areas contracted rapidly until they were completely eliminated by 2018. Medium-to-high value areas gradually expanded, forming a spatial agglomeration pattern led by Aksai as a single core, supported by multiple points such as Delingha and Shandan. After 2019, Level V counties experienced explosive growth. By 2024, this level covered seven counties (over 55% of the total), including Aksai, Delingha, and Liangzhou, and the number of Level IV and above counties increased to nine. This marks that the economy of the national park has entered a new stage of high-resilience development.

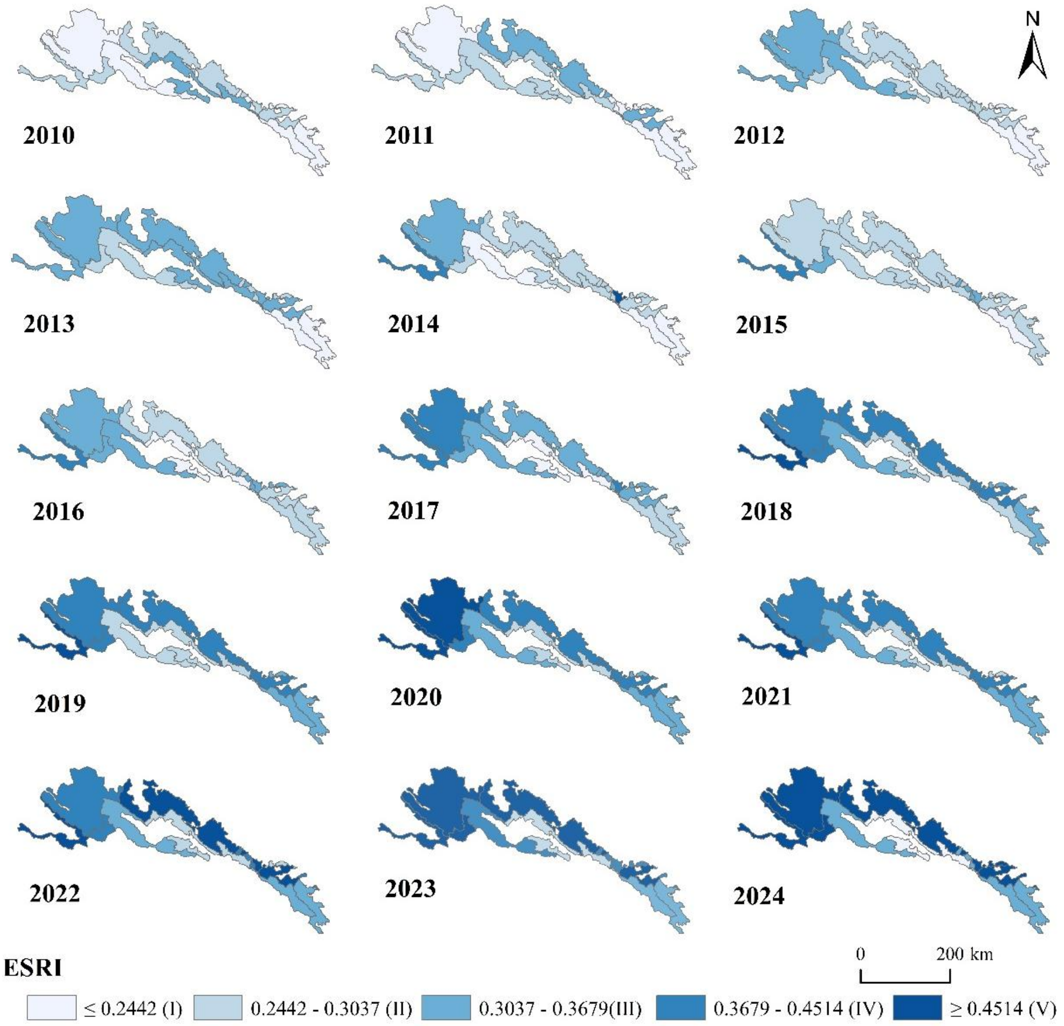

Figure 4. Spatial pattern of ESRI in QMNP from 2010 to 2024

From 2010 to 2024, the ERI of QMNP exhibited a distinct spatial differentiation pattern characterized by high in the center and low at both ends (Fig. 5). In 2010, the ERI in Aksai and Qilian counties demonstrated extremely strong stability, consistently remaining at Level V. Level I areas were widely distributed across five counties in the central region, including Menyuan, Minle, and Subei. After 2018, the ERI levels evolved from Level I toward Levels II and III. By 2024, Level I counties had completely disappeared from the entire region. Furthermore, transitional counties such as Delingha and Yongchang exhibited significant fluctuations in their ERI levels.

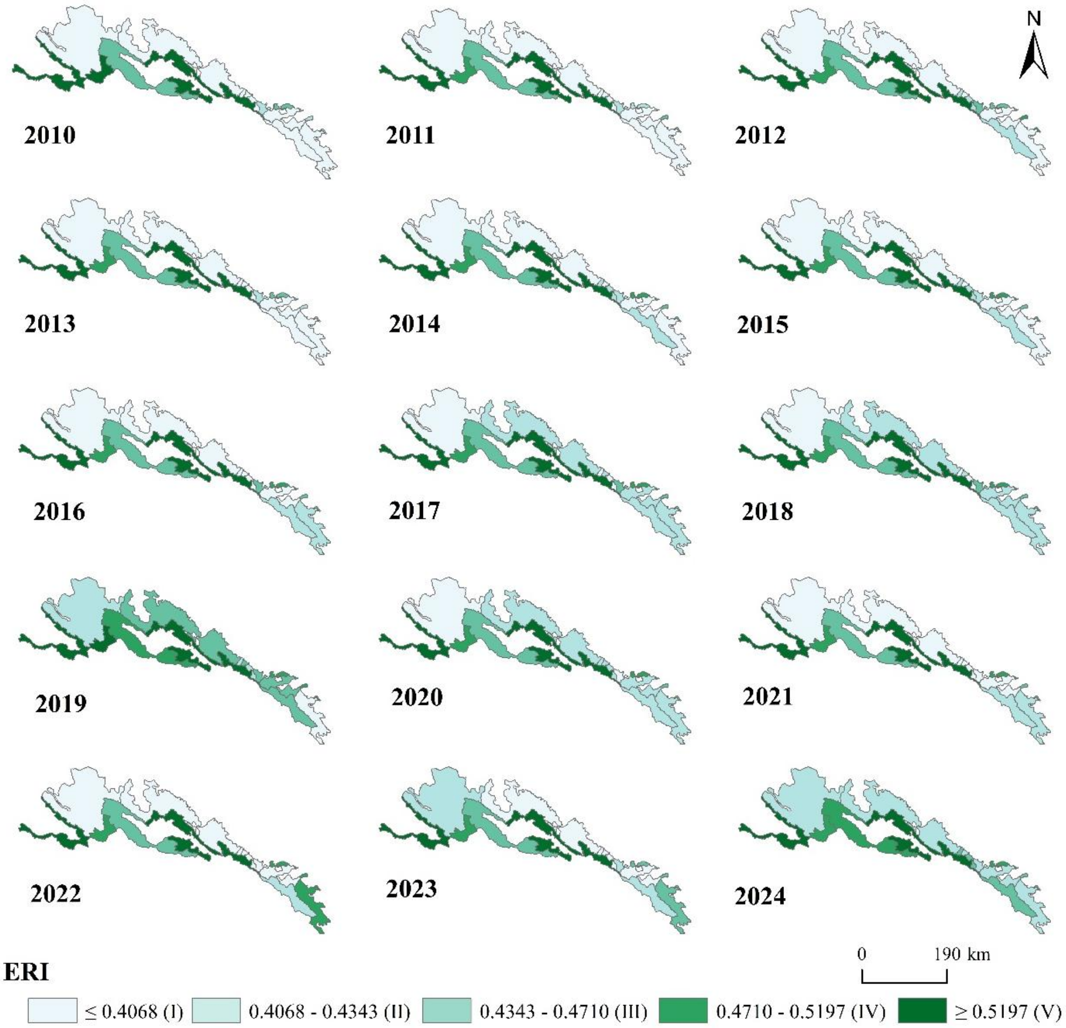

Figure 5. Spatial pattern of ERI in QMNP from 2010 to 2024

From 2010 to 2024, the spatial pattern of SESRI in QMNP transitioned from initial low-level homogenization to a pattern characterized by high in the west and low in the east (Fig.6). In 2010, Level I counties of SESRI were distributed contiguously, covering six counties, with no Level IV or V counties in the entire region, reflecting generally low resilience. Leveraging its dual advantages in both economic and ecological dimensions, Aksai was the first to leap to Level IV in 2012. Since 2018, Level I counties across the region have achieved dynamic zeroing-out, and Level V high-value counties have emerged from scratch and expanded rapidly, exhibiting a diffusion trend from west to east. By 2024, the number of counties with high-level resilience (Level IV and above) had increased to eight, indicating a significant enhancement in the social-ecological system resilience of the national park.

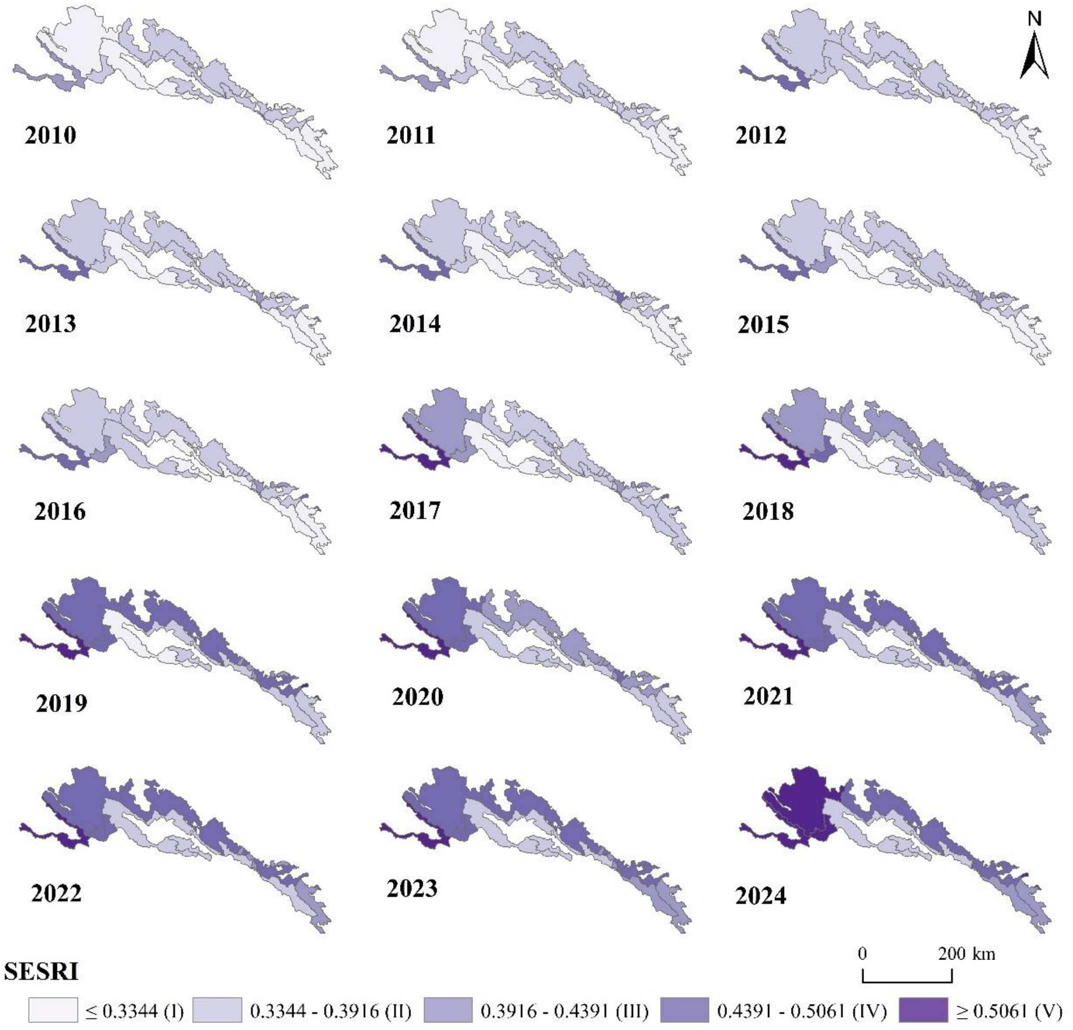

Figure 6. Spatial pattern of SESRI in QMNP from 2010 to 2024

3.2. Dynamic Evolution Characteristics of SESR

From 2010 to 2024, the 3D KDE curves of SESR in QMNP generally exhibited a significant rightward shift, though evolutionary trends across subsystems varied markedly.

The center of gravity of the SSRI kernel density curve showed a significant rightward movement (Fig. 7(a)), indicating an overall leap in the regional social resilience level. The peak value underwent a "decline-then-rise" process, and the width of the main peak gradually narrowed, implying that the spatial disparities in social resilience among counties are progressively converging after an initial expansion. The curve morphology evolved from early "multi-peak coexistence" to "single-peak dominance with a right-skewed tail," suggesting that low-value areas in the social system are rapidly disappearing and aggregating toward medium-to-high levels. The ESRI kernel density curve exhibited the most dramatic rightward shift (Fig. 7(b)), confirming the leapfrog growth of regional economic resilience. Unlike SSRI, the ESRI curve maintained a distinct "multi-peak" morphology over the long term, with a significantly elongated right tail. This reveals prominent multipolar polarization characteristics against the backdrop of overall growth. The ERI kernel density curve showed a slight rightward shift amidst fluctuations (Fig. 7(c)), indicating that the enhancement of ecological resilience is a gradual process marked by twists and turns. The curve morphology is the most unique, maintaining a significant "bimodal" structure over the long term with a wide gap between the two peaks, revealing a solidified phenomenon of ecological resilience polarization in the region. Driven by the integrated effects of the three subsystems, the SESRI kernel density curve exhibited a continuous and clear rightward trajectory (Fig. 7(d)). The evolutionary characteristics, marked by increasing peak height, narrowing bandwidth, and weakening lateral peaks, verify the steady enhancement of SESR in QMNP.

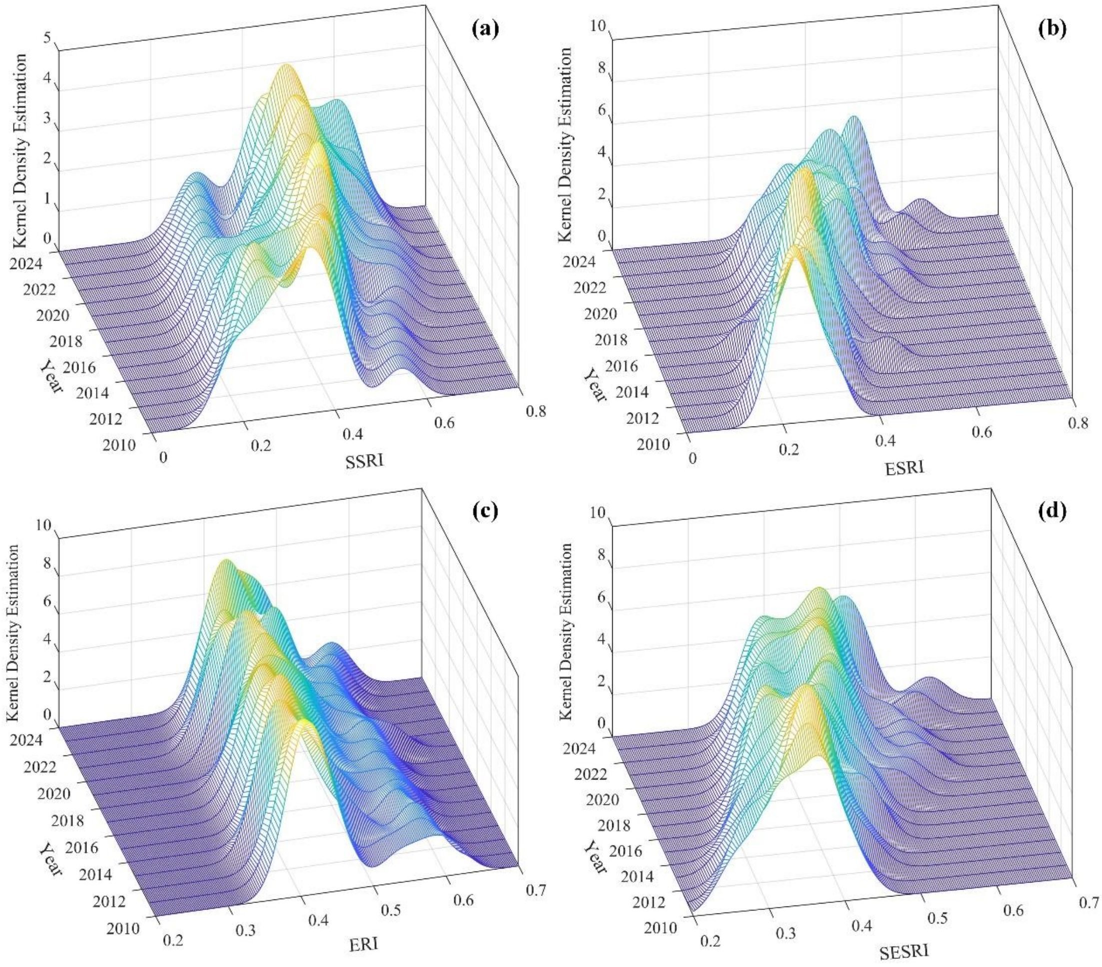

Figure 7. Dynamic kernel density curve of SESRI in QMNP. (a) Dynamic kernel density curve of SSRI; (b) Dynamic kernel density curve of ESRI; (c) Dynamic kernel density curve of ERI; (d) Dynamic kernel density curve of SESRI.

3.3. Analysis of Obstacle Factors for SESR

3.3.1. Identification of General Obstacle Factors for SESR

This study utilized the obstacle degree model to perform a systematic diagnosis of the SESRI across 12 counties (district/city) in QMNP from 2010 to 2024. The results indicate that population density (A1), per capita GDP (B2), proportion of tourism revenue (B5), GDP growth rate (B1), and NPP (C2) collectively constitute the primary obstacle factors for the SESRI of QMNP (Table 3). From 2010 to 2016, A1, B2, and B5 were the dominant obstacle factors, reflecting that resilience was primarily constrained by low levels of economic development and a simplistic industrial structure during the initial stage. In contrast, from 2017 to 2024, while the constraint of A1 remained prominent, the obstacle degree rankings for B1 and B2 surged further. This suggests that a structural shift may have occurred in the SESR of QMNP. Furthermore, in ecologically sensitive counties such as Aksai and Qilian, FVC (C1) and NPP (C2) consistently ranked among the top obstacle factors, forming the ecological baseline constraints for the resilience of the national park.

Table 3. Main obstacle factors of SESR from 2010 to 2024

Year	Ranking of obstacle factors				
	1	2	3	4	5
2010-2016	A1	B2	B5	C2	B1
2017-2024	A1	B1	B2	B5	C2
2010-2024	A1	B2	B5	B1	C2

3.3.2. Analysis of Disparities in County-level Obstacle Factors

From the perspective of primary obstacle factors, the SESRI of various counties in QMNP from 2010 to 2024 exhibited significant spatial heterogeneity and dimensional concentration (Table 4).

For half of the studied counties, including Liangzhou, Menyuan, Minle, Shandan, Tianzhu, and Yongchang, the primary obstacle factor was per capita GDP (B2). This highlights the fundamental supporting role of economic output levels and material wealth accumulation in the resilience of the national park system. These counties are mostly in a period of economic transition, where the lag in per capita GDP directly limits the system's recovery capacity when facing external risks. In Aksai, Delingha, Subei, and Tianjun, the primary obstacle factor was FVC (C1), while Qilian County was constrained by NPP (C2). This reflects that ecological baseline elements, such as vegetation cover and biological productivity levels, are common obstacle factors restricting resilience enhancement in alpine and arid counties. The primary obstacle factor for Sunan was population density (A1). Under the dual constraints of ecological functional positioning and the natural environment, low population density limits the efficiency of public services and the robustness of the social structure, becoming a key obstacle to the improvement of resilience in this county.

Table 4. Main obstacle factors of SESR in county-level from 2010 to 2024

County	Ranking of obstacle factors				
	1	2	3	4	5
Aksai	C1	A1	B1	B5	B2
Delingha	C1	A1	B5	B1	B2
Liangzhou	B2	C2	B1	B5	B3
Menyuan	B2	C2	A1	B5	C3
Minle	B2	C2	A1	B1	C4
Qilian	C2	B2	A1	B5	B1
Shandan	B2	C2	A1	B1	B5
Subei	C1	A1	B5	B1	C3
Sunan	A1	C2	B5	C1	B2
Tianjun	C1	A1	A2	B1	B5
Tianzhu	B2	B5	C2	A1	B1
Yongchang	B2	A1	B5	C2	B1

Combined with the analysis of obstacle evolution trends, the obstacle factors in various counties during the study period exhibited dynamic characteristics of baseline solidification and shifting focus (Fig. 8). In ecologically constrained counties such as Aksai, Delingha, Subei, and Tianjun, the obstacle factors showed extremely high stability. Their core obstacle factor, C1, remained consistently high with an increasing trend in obstacle degree year by year. In contrast, counties like Liangzhou, Menyuan, Minle, Shandan, and Yongchang were primarily hindered by B2 in the initial stage. However, after 2020, the rankings of C2 or C1 rose significantly, with C2 in Liangzhou and Minle even leaping to the primary position. This reflects a shift in obstacles from insufficient economic foundation support to ecological quality constraints.

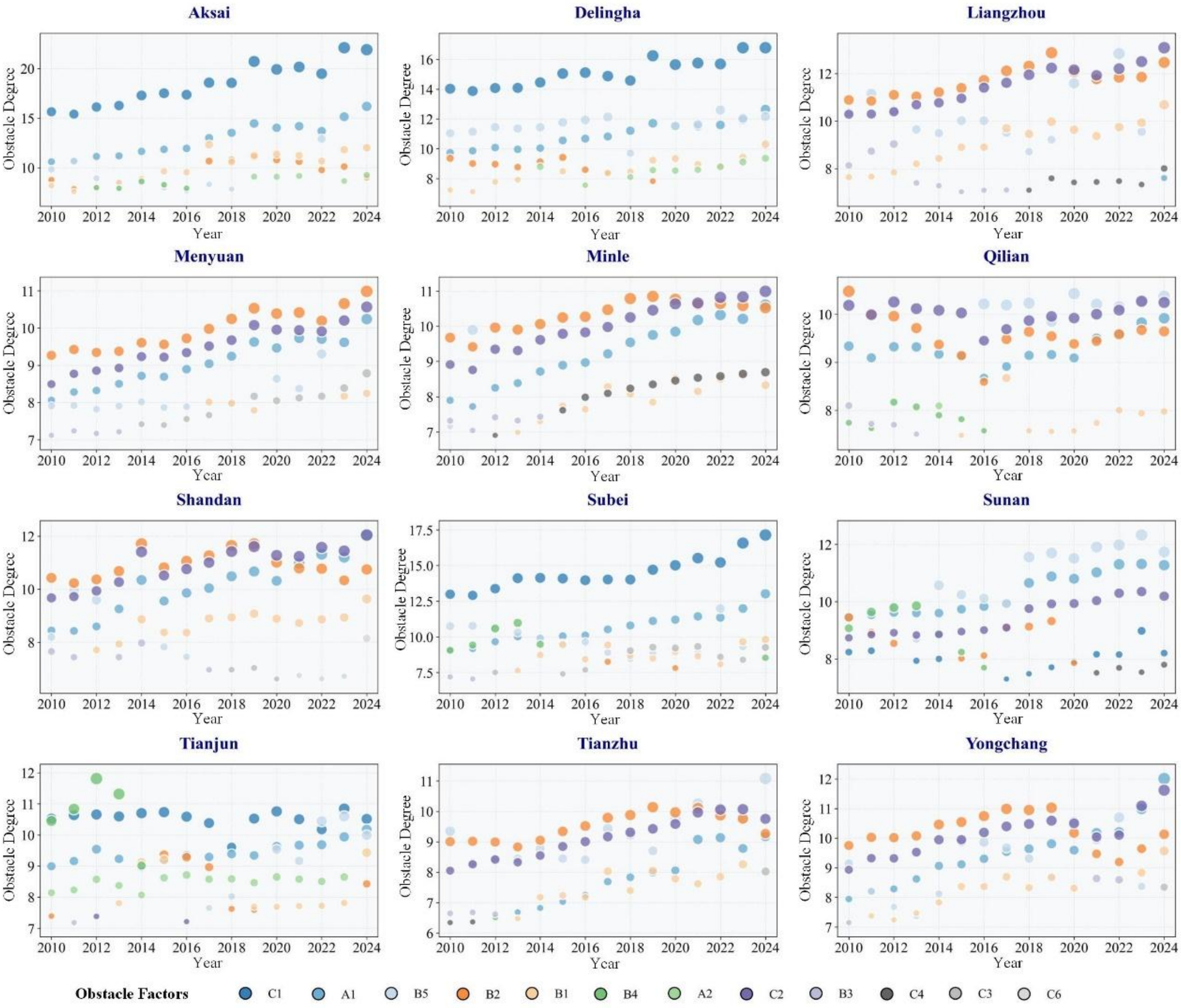

Figure 8. Obstacle factors of SESR at the county-level of QMNP from 2010 to 2024

4. DISCUSSION

4.1. Asynchronous Evolution of Social-Ecological Systems

From 2010 to 2024, the SES of QMNP exhibited significant asynchronous evolutionary characteristics, profoundly revealing the response mechanisms of alpine and arid regions under the dual constraints of policy intervention and natural baselines [33, 55]. Regarding the evolutionary path, the growth of the SESRI was primarily driven by the strong pull of economic resilience, whose growth rate was significantly higher than that of other systems. This reflects the powerful boost provided by tertiary industry transformation and tourism livelihood diversification to the system's material buffering and risk-hedging capabilities. Social resilience maintained steady growth driven by the combined effects of livelihood transformation and policy adaptation; however, there was a noticeable phase difference between its growth rate and that of the economic system. Meanwhile, constrained by the fragile natural baseline of the alpine and arid region, ecological resilience remained within a steady-state threshold of low-frequency fluctuations for a long period. The solidified characteristics of its 3D KDE distribution highlight the baseline constraint effect on ecological resilience enhancement. This uncoordinated evolution among systems essentially reflects the structural contradictions and functional trade-offs faced by internal elements during the reorganization process in the early stages of the national park system pilot. It represents an inevitable time-lag effect in the high-quality transformation process of social-ecological systems in alpine and arid regions [52].

4.2. Geographic Mechanisms of Spatial Differentiation in Resilience

The SESR of QMNP exhibits a significant "high in the west and low in the east" spatial pattern, which essentially represents the differentiated mapping of the man-land areal system under the dual constraints of resource endowments and policies. In the southeastern counties such as Tianzhu and Menyuan, relatively superior hydrothermal conditions have induced a high concentration of population and cropland, forming a typical resource competition mechanism. The intense overlap of high-intensity livelihood activities and ecological protection redlines within limited physical space leads to the advantages of the ecological baseline (NPP) being offset by resource consumption from high population density. Consequently, the system exhibits significant fragility due to the lack of resilience buffering space, making it highly susceptible to vulnerability when facing policy tightening or climate fluctuations [56,57]. In contrast, Aksai and Subei in the northwestern desert-oasis ecotone have developed long-term passive adaptation mechanisms due to harsh natural environments. Their maintained mode of low population density and wide-range nomadism reduces the intensity of anthropogenic interference. This low-stress state, formed through natural selection, results in statistically high resilience. Furthermore, the structural misalignment between current national park management boundaries and natural geographical units has severed the traditional integrity of nomadic space, leading to the physical separation of livelihood sources and residential spaces, which further exacerbates localized man-land conflicts [58]. This geographic process, driven by the synergy of natural baseline thresholds, anthropogenic pressure-stress, and management system misalignment, constitutes the deep mechanism underlying the spatial differentiation of regional resilience.

4.3. Adaptive Management Based on Obstacle Factors

Building upon the systematic diagnosis from the obstacle degree model, the resilience enhancement paths for counties in QMNP exhibit distinct characteristics of baseline solidification and shifting focus. To ensure the stability and sustainability of the SES in QMNP, this study proposes a set of targeted policy recommendations. First, for ecologically constrained counties such as Aksai, Subei, Delingha, and Tianjun, where FVC(C1) consistently ranks as the primary obstacle with an increasing annual trend, reflecting the rigid constraints of the natural baseline on system resilience. A passive intervention strategy centered on ecological conservation should be implemented. This involves strictly controlling ecological space usage and strengthening cryosphere monitoring to reduce anthropogenic interference and maintain the resilience baseline formed under natural selection. Second, for counties transitioning from economic to ecological constraints, such as Liangzhou, Minle, Yongchang, Shandan, and Menyuan, where the obstacle focus has shifted from per capita GDP (B2) to ecological quality (C2/C1). Efforts should focus on fostering high-value-added ecological product processing industries to mitigate over-dependence of livelihoods on natural resources, thereby facilitating the effective transmission of economic resilience into ecological restoration momentum. Finally, for social and industrial fluctuation-type counties like Sunan and Tianzhu, which face the dual pressures of population density (A1) constraints and tourism income (B5) fluctuations. Resilience should be strengthened by improving public service levels and developing low-disturbance ecotourism models to enhance the social system's adaptability to policy transitions. This hierarchical and categorized regulation based on obstacle factors is the key path to resolving structural contradictions and achieving a sustainable transformation for the SES of national parks in alpine and arid regions.

4.4. Limitations and Future Research

Although this study reveals the spatiotemporal dynamics characteristics and obstacle factors of the SESR in QMNP based on the social-ecological system framework, certain limitations remain that require further exploration in future research. First, due to the difficulty of obtaining long-term socio-economic data in alpine and arid regions, some county-level statistical indicators, while reflecting macro trends at a spatial scale, struggle to precisely characterize the micro-differences between internal functional zones (core protection area and general control area) of the national park. Future studies should attempt to incorporate high-resolution nighttime light data, multi-source geographic big data, and field survey data from farming and herding households to enhance the granularity of the research. Second, this study focuses on the long-term evaluation and spatio-temporal differentiation of resilience levels. However, the exploration of the complex, non-linear interactions and non-linear threshold characteristics among internal elements of the SES remains insufficient. Subsequent research could employ System Dynamics (SD) models or Structural Equation Modeling (SEM) to further analyze the trade-off and synergy mechanisms between subsystems. Finally, future efforts should strengthen the quantitative simulation of the long-term impacts of cryospheric elements (such as glacial retreat and permafrost degradation) on system resilience under the context of global climate change. This will provide more forward-looking decision support for the dynamic management and adaptive governance of national parks in alpine and arid regions.

5. CONCLUSIONS

Grounded in the theoretical framework of (SES), this study constructed an evaluation indicator system for the SESR of the QMNP. It systematically analyzed the spatio-temporal evolutionary characteristics and obstacle factors of the resilience from 2010 to 2024. The main conclusions are as follows:

(1) From 2010 to 2024, the SESR of QMNP exhibited asynchronous evolutionary characteristics, summarized as "overall improvement with dimensional imbalance." The SESRI of the national park increased steadily from 0.3645 to 0.4308, marking a significant enhancement in the overall resilience level. Specifically, the ESRI experienced leapfrog growth, becoming the core driving force of the system's evolution; the SSRI maintained steady growth; meanwhile, the ERI remained in a state of steady-state fluctuation for a long period due to the rigid constraints of the natural baseline.

(2) From 2010 to 2024, the spatiotemporal pattern of SESR in QMNP evolved from initial low-level homogenization to a differentiated "high-west, low-east" pattern. This transition resulted in the formation of high-resilience clusters centered in the northwestern "high baseline, low interference" zones, contrasted with resilience-lagging areas in the southeastern "high pressure, overlapping conflict" zones. Specifically, northwestern counties such as Aksai and Subei consistently remained in the high-value zone (Level V), whereas southeastern counties like Tianzhu and Menyuan remained at relatively low resilience levels over the long term.

(3) Population density, per capita GDP, and NPP consistently remained the core obstacle factors constraining the resilience of the entire region. From 2010 to 2024, the primary obstacle (FVC) in ecologically constrained counties such as Aksay and Delingha exhibited extreme stability with an increasing annual trend. In contrast, counties like Liangzhou and Menyuan underwent a shift in obstacle rankings, moving from insufficient economic foundation support (per capita GDP) to ecological quality constraints (FVC/NPP). Furthermore, Sunan and Tianzhu counties faced dual stresses from population concentration (population density) and fluctuations in the proportion of tourism income; their resilience pathways are currently undergoing profound adjustments, transitioning from scale expansion toward quality enhancement.

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