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Original Research

Spatial and Temporal Dynamic Correlation Analysis of Landscape Fragmentation and Ecological Sensitivity in Hainan Tropical Rainforest National Park and its Surrounding Areas

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Abstract

Hainan Tropical Rainforest National Park (HTNP) prioritizes preserving its tropical rainforest ecology, requiring careful balance between conservation and surrounding development. This study utilized ArcGIS 10.8, Fragstats 4.2, and GeoDa 1.20 to analyze landscape fragmentation and ecological vulnerability in HTNP and its surroundings from 2002 to 2022, providing a basis for conservation and development zoning. Results showed a higher Largest Patch Index (LPI) within HTNP. At the same time, Patch Density (PD) was greater in urbanized coastal areas but declined in the western, northeastern, and southern outskirts, indicating reduced landscape degradation. Low Landscape Shape Index (LSI) and Shannon's Evenness Index (SHEI) suggested minimal human impact. Between 2002 and 2007, PD, LPI, LSI, Contagion Index (CONTAG), and SHEI decreased, reducing fragmentation. From 2017 to 2022, PD and LSI declined further, improving landscape integrity, though CONTAG increased due to coastal urbanization. Spatial autocorrelation analysis showed LPI and CONTAG positively correlated with habitat quality, while PD, LSI, and SHEI were negatively correlated, with LPI having the strongest association. Moran's Index indicated declining PD and CONTAG but increasing LPI, LSI, and SHEI from 2002 to 2022, reflecting landscape and habitat quality changes. These findings support conservation zones, development belts, and buffer zones in HTNP.

Keywords: Hainan Tropical Rainforest National Park, ecological sensitivity, landscape pattern, conservation and development zone, buffer zone construction

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Introduction

National parks form the cornerstone of China's nature reserve system, playing a crucial role in safeguarding animal diversity, ecological services, and advancing ecological civilization [1]. HTNP was selected as part of the inaugural group of national parks on October 12, 2021. It is renowned as China's premier continental island-style tropical rainforest, boasting the highest concentration of flora, the most exteFnsive variety of species, optimal preservation, and a vast, uninterrupted expanse [2-3]. However, rapid human development in surrounding areas poses challenges such as habitat isolation and degradation for national parks and nature reserves. In recent years, heightened ecological sensitivity has been observed in these surroundings, largely due to changes in land use and intensified human activities. Peripheral zones, serving as ecological buffer zones for national parks, mitigate direct human impacts on core protected areas, thus preserving ecosystem originality and integrity and ensuring effective biodiversity conservation. Nonetheless, the intricate relationship between landscape patterns and ecological processes remains complex and uncertain. Therefore, it is crucial to explore the environmental responsiveness of the HTNP's surrounding area and its association with land division patterns to steer future conservation initiatives.

Landscape patterns encompass the varieties, quantities, spatial arrangements, and structures of landscape elements that define the spatial layout of a landscape and the dispersion of its patches [4-5]. Optimizing landscape patterns is recognized as a crucial land use management strategy that enhances regional ecological protection and promotes sustainable development [6-8]. Exploring the intrinsic correlation between landscape patterns and ecological vulnerability, as well as establishing links between landscape characteristics and regional ecological responses, enables broader and deeper analysis and evaluation of regional environmental issues. This approach also fosters innovative research methods and perspectives for enhancing regional ecological environments [9]. Liang et al. demonstrated that urban landscape evolution significantly influences long-term PM2.5 pollution trends, varying with city scale and development stage [10]. Shi et al. utilized 19 sampling sites within the Tumen River basin to investigate how various landscape metrics affect river water quality differently. The results suggested that the extent of landscape composition at spatial scales significantly affects the quality of river water [11]. Zhang et al. examined the changes in land use in the Pingshuo open-pit mining area between 1986 and 2015, noting unstable heterogeneity in the mining landscape due to natural and anthropogenic factors, and highlighting how increased landscape fragmentation impacts ecological functions [12]. Synthesizing previous studies underscores landscape fragmentation as a key indicator for assessing landscape ecological risks [9-12]. Effective ecological protection of the national park surroundings is vital for their long-term sustainability. Therefore, studying the spatial and temporal dynamics of landscape patterns around HTNP holds significant implications for ecological conservation, sustainable development, tourism resource management, and policy formulation.

Ecological sensitivity denotes the capacity of ecosystems to adapt to natural environmental changes and human-induced disturbances without compromising ecosystem quality [13]. It assesses the types, challenges, and likelihood of ecological issues arising from disturbances to local ecosystems [14]. Ecological sensitivity assessments are crucial for identifying potential ecological risks in natural environments [15]. Widely recognized as an effective tool for maintaining regional ecological stability and promoting sustainable development, ecological sensitivity assessments are integral to landscape planning and management practices [16-17]. Hu et al. utilized the AHP-PSR model to evaluate the ecological sensitivity of Weifang City [18], while Kang et al. analyzed the spatial distribution of ecological sensitivity in the Jiaodong Peninsula, employing ecological resistance surfaces and the least cumulative resistance model to delineate ecological corridors and buffer zones [19]. Therefore, assessing the ecological sensitivity of cities surrounding HTNP is imperative for establishing ecological protection buffer zones and ensuring the integrity of the tropical rainforest ecosystem.

Analyzing how landscape fragmentation patterns and ecological vulnerability evolve over time in HTNP and its neighboring areas is crucial for the park's ecological restoration and the establishment of protective buffers. The investigation explores how landscape patterns are distributed spatially and the ecological sensitivity observed between 2002 and 2022, utilizing GIS alongside Fragstats 4.2. The primary objectives are: 1) to assess how environmental responsiveness varied spatially and temporally in HTNP and its adjacent regions between 2002 and 2022; 2) to examine the spatial arrangement features of landform patterns in the area; 3) to assess and examine the correlation between landform configurations and environmental responsiveness in HTNP and their transformations from 2002 to 2022; 4) to research offers a scientific rationale for establishing an ecological buffer area in HTNP.

Materials and Methods

Research Area

HTNP (108º44'-110º04′E, 18º33′-19º14′N) is situated in the central mountainous core of Hainan Province, encompassing approximately thirteen percent of the island's land area, or about 4,400 square kilometers [20]. The area encounters a tropical maritime monsoon climate, marked by mean yearly temperatures varying from 22.5ºC to 26.0ºC and a yearly precipitation averaging 1,760 mm. Within its boundaries lie numerous national and provincial nature reserves, highlighting its integral role in regional ecological protection policies. The park boasts a diverse ecosystem shaped by its complex topography, rich biodiversity of endemic species, and abundant mountainous rivers and water resources. Consequently, utilizing HTNP as a research area is crucial for generating high-quality data to support scientific research, ecological resource management, and ecotourism initiatives.

Data Sources

The digital elevation model (DEM) data utilized in this research were obtained from the Geospatial Data Cloud (https://www.gscloud.cn/) at a spatial resolution of 30 meters. Normalized vegetation index data from 2002 to 2022 were sourced from NASA MOD13A2 (https://www.nasa.gov), while land use data were acquired from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences, specifically the Multi-stage Land Use and Land Cover Remote Sensing Monitoring Dataset in China [21]. To ensure consistency in data processing and accuracy in analysis, all datasets were standardized to the Krasovsky 1940 Albers projection system following specific transformations. The research methodology is illustrated in Fig. 1.

Methods

Ecological Sensitivity Calculations

The selection of ecological sensitivity factors in HTNP should consider the area's unique ecological environment and distinctions from other regions, ensuring the chosen factors are representative [22]. As a result, this research establishes a holistic index framework to evaluate the environmental responsiveness of the park's surrounding regions, structured around three primary categories: topographic situation, natural environment, and human activities. Five key sensitivity factors – elevation, slope, aspect, NDVI, and LUCC – were selected to construct this index system. The Analytic Hierarchy Process (AHP) was employed to calculate the weightings for these factors [23]. This involved creating a judgment matrix to subjectively evaluate each factor's importance on a scale from 1 to 5, with 1 being of equal importance and 5 being of utmost importance [24]. Subsequently, the geometric mean of each row in the judgment matrix was calculated, summed, and normalized to derive the weight for each factor. Finally, consistency testing was conducted to validate the derived weight values.

Additionally, sensitivity was categorized into five levels based on existing literature and assigned numerical values ranging from 1 to 5 [25-26], detailed in Table 1. The calculation of the ecological sensitivity index revealed variations in units, attributes, and value ranges among the selected indices, necessitating standardization for accurate calculation.

Landscape Pattern Index

The landscape pattern index provides insights into spatial distribution characteristics such as composition and structure, as well as detailed landscape pattern information. This index evaluates landscape complexity by analyzing patch shape, size, number, and spatial arrangement. In this study, five key indices – LSI, LPI, SHEI, PD, and CONTAG – were chosen based on pertinent literature and the distinct geographical layout of the research site. Land-use data were resampled to a pixel size of 1000×1000 and exported in TIFF format, and the LPI was computed using Fragstats 4.2 software [27-28]. To accurately assess ecological quality across the study area, a grid division method was applied. Considering the accuracy of the data, with a focus on research goals and the complexity of computations, the study region was segmented into 2 km x 2 km grids with the national park at the center.

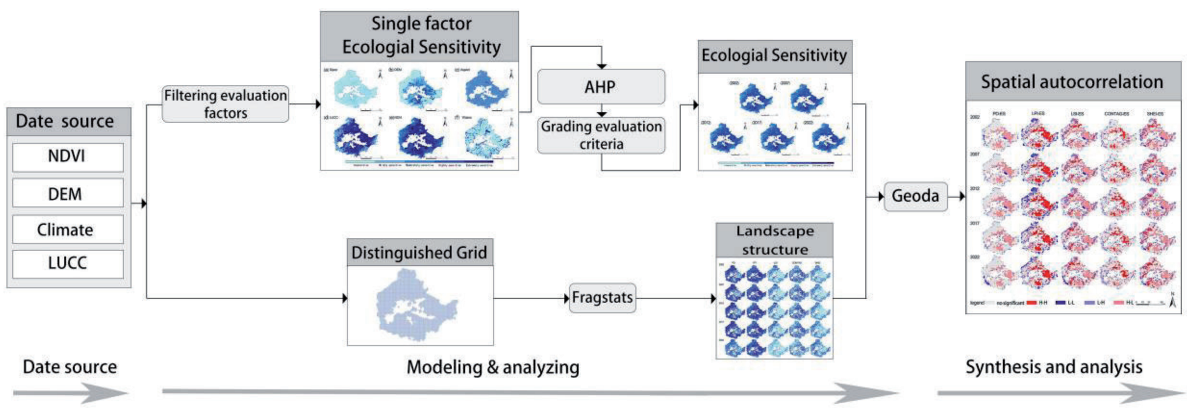

Fig. 1. Research Flowchart.

Table 1. Evaluation System and Weighting of Ecological Sensitivity in the Surrounding Areas of HTNP.

Normative layer	Evaluation factor	Ecological sensitivity classification					Factor weight
		Extremely sensitive	Highly sensitive	Moderately sensitive	Mildly sensitive	Insensitive	
Geological feature	DEM (m)	0-20	20-40	40-60	60-80	>80	0.3064
	Slope (°)	45-90	30-45	25-30	15-25	0-15	0.0626
	Aspect	Due North	Northeast, northwest	Due east, Due west	Southeast, southwest	Due south, Flat land	0.1367
Underground water system	Waters	0-200	200-500	500-800	800-1000	>1000	0.2652
Surface vegetation	NDVI	0.75-1	0.65-0.75	0.5-0.65	0.35-0.5	0-0.35	0.1043
Human activity	Lucc	Wetlands, forests	water bodies	Shrubs, grass	Cropland	Other	0.1247
Value		5	4	3	2	1	

Global Spatial Autocorrelation

This study utilizes bivariate Moran's I to examine the relationship between landscape composition within HTNP and the ecological sensitivity index. Unlike traditional univariate Moran's I, which assesses clustering of individual variables in local space, bivariate Moran's I evaluates correlations between variables in neighboring spatial units [29]. Spatial autocorrelation analysis was employed to detect geographic dependencies, including global and local spatial autocorrelation between these two components [30-31]. The specific calculation formula is provided below:

Results

Monoecological Sensitivity

Using elevation, slope, slope direction, watershed sensitivity, NDVI sensitivity, and LUCC sensitivity data spanning from 2002 to 2022, the region surrounding the Hainan Tropical Rainforest National Park was categorized into five sensitivity classes: Insensitive, mildly sensitive, moderately sensitive, highly sensitive, and extremely sensitive. This classification was performed using ArcGIS and is illustrated in Fig. 2 and 3.

As illustrated in Fig. 2, the analysis of elevation sensitivity reveals that most surrounding areas exhibit

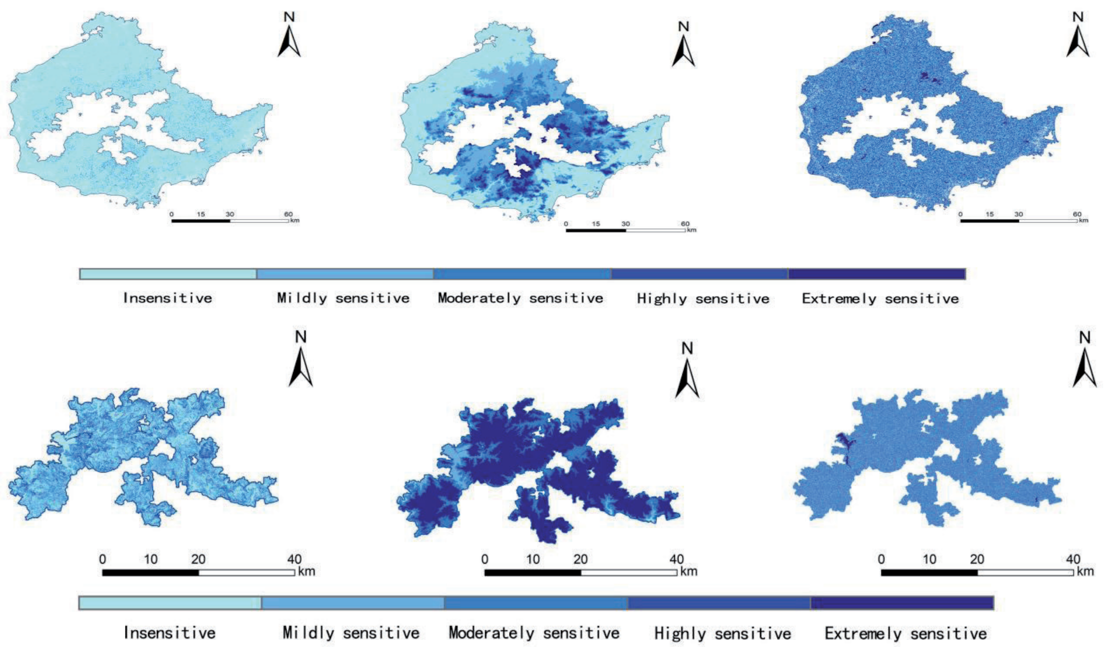

Fig. 2. Characteristic maps illustrating the spatial distribution of incline, altitude, and orientation sensitivities in the National Park and its environs. a. Spatial distribution of slope sensitivity b. Spatial distribution of altitude responsiveness c. Sensitivity to slope orientation's spatial distribution.

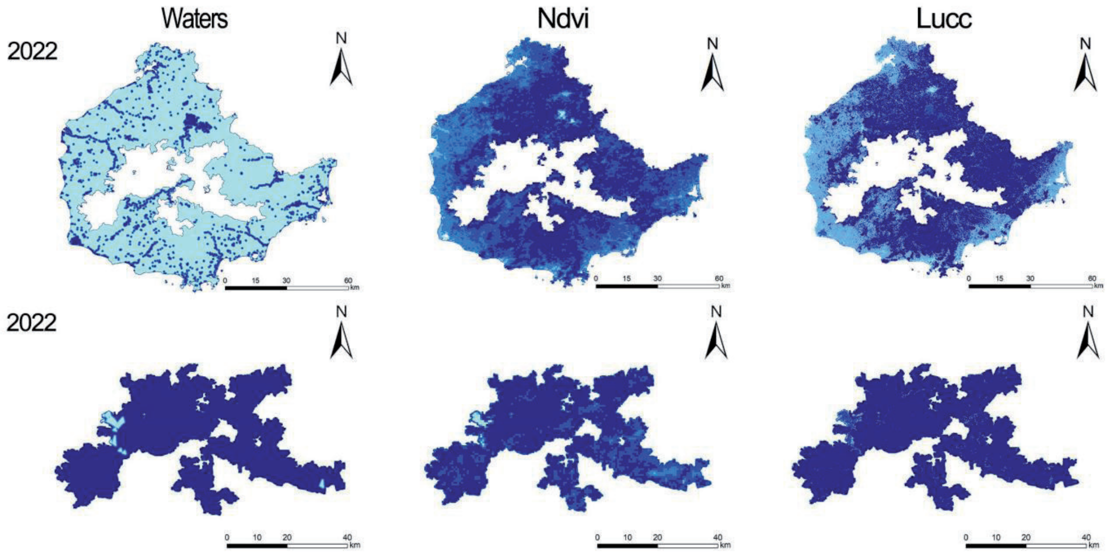

Fig. 3. Spatial and temporal dynamics of watershed sensitivity, NDVI sensitivity, and LUCC sensitivity in Hainan Tropical Rainforest National Park, 2002-2022.

moderate sensitivity to elevation, indicating some level of responsiveness but not excessively high. In contrast, the study areas demonstrate extreme sensitivity to elevation, suggesting a high degree of responsiveness and increased potential for development in mountainous regions. A few peripheral areas, primarily in the center and south, show high sensitivity, which highlights their greater responsiveness to elevation. Meanwhile, the study areas mostly show mild to moderate sensitivity, implying lower sensitivity overall.

Overall, there is considerable variation in elevation sensitivity across both the surrounding and study areas. The distribution of incline and its susceptibility remain relatively constant. The spatial distribution map analysis indicates that slope has a minimal effect on ecological sensitivity. The surrounding areas exhibit mainly low sensitivity, interspersed with some mildly sensitive areas, while the study area is predominantly characterized by moderate sensitivity, with a few insensitive regions. Given that slope is a crucial factor influencing geological hazards such as avalanches, landslides, and severe erosion, and significantly affects land use, it indirectly impacts plant growth and distribution.

Analyzing the spatial distribution map of slope sensitivity, we find that both the study and surrounding areas are largely moderately sensitive, with some highly sensitive regions. Particularly, areas with elevated sensitivity are situated in the northeastern portion of the surrounding regions and certain zones in the northwest of the research area. Slope orientation, a key factor in mountain ecosystems, affects solar radiation intensity and daylight duration, which in turn influences vegetation distribution and ecosystem structure and function.

The study found that water sensitivity in the peripheral area was predominantly low, with some regions exhibiting very high sensitivity. In contrast, the study area generally exhibited very high sensitivity, with occasional areas of low sensitivity. The NDVI (Normalized Difference Vegetation Index) sensitivity in both regions primarily displayed a pattern of internal-to-external diffusion. This pattern showed very high, high, and medium sensitivity at the core, gradually decreasing outward, accompanied by some insensitive zones. LUCC sensitivity decreases in the surrounding area, mainly centred on very high sensitivity and moderate sensitivity in all directions. In the study area, LUCC sensitivity was predominantly very high, with a small proportion of medium sensitivity interspersed.

Integrated Ecological Sensitivity

Ecological sensitivity analysis involved evaluating each factor, followed by a weighted overlay analysis and reclassification, resulting in the classification of the area into five sensitivity categories: sensitive, mildly sensitive, moderately sensitive, highly sensitive, and extremely sensitive. The spatial distribution of these combined sensitivities across the study area is depicted in Fig. 4.

Table 2 presents the fluctuations in environmental responsiveness levels surrounding HTNP from 2002 to 2022. Over the past two decades, the total peripheral area reached 16,012.36716 km², with ecological sensitivity primarily concentrated in moderately sensitive, highly sensitive, and extremely sensitive areas, with moderate sensitivity being predominant. Comparatively, the non-sensitive area was 0.944 km² in 2002, accounting for 0.006%, increased to 1.877 km² in 2007 (0.012%), and then stabilized around 0.943 km² in 2012, 2017, and 2022 (0.006%). The area of low sensitivity increased from 730.002 km² (4.559%) in 2002 to 909.761 km² (5.682%) in 2017, but decreased to 669.765 km² (4.183%) in 2022.

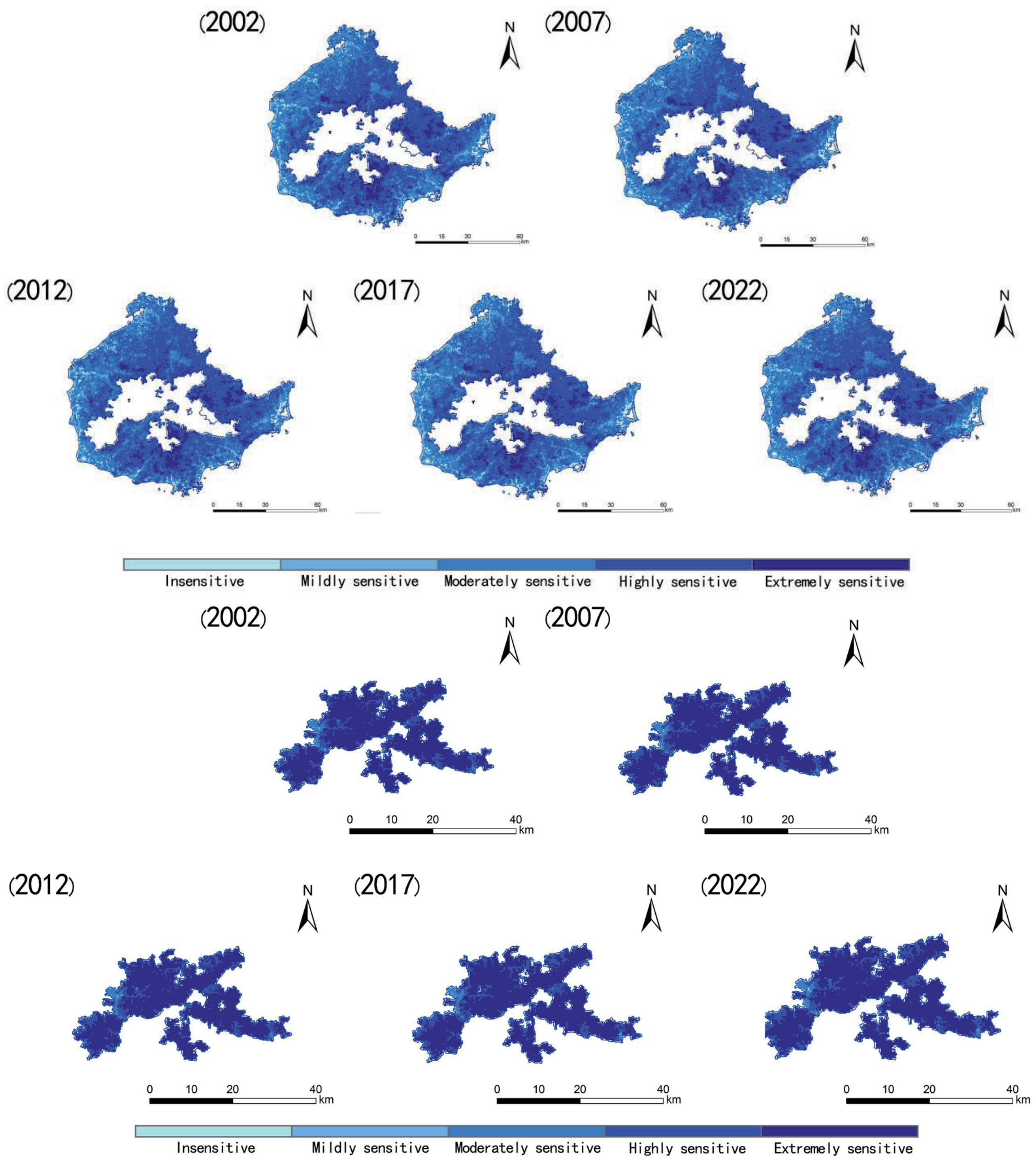

Fig. 4. Spatial and temporal distribution characteristics of sensitivity in tropical rainforest national parks and surrounding areas in Hainan Province, spanning 2002-2022.

Medium sensitivity areas decreased from 5,949.56 km² (37.156%) in 2002 to 5,268.69 km² (32.436%) in 2012, then rose to 5,754.32 km² (35.937%) in 2017, and slightly decreased to 5,707.20 km² (35.642%) in 2022. The area of highly sensitive zones increased from 8,170.06 km² (51.023%) in 2002 to 8,787.99 km² (54.103%) in 2012, decreased slightly to 8,526.34 km² (53.249%) in 2017, and further to 8,266.23 km² (51.624%) in 2022. Extremely Highly Sensitive Areas (EHSAs) were 1,373.76 km² (8.579%) in 2002, increased to 1,417.99 km² (8.730%) in 2012, significantly decreased to 1,155.34 km² (7.215%) in 2017, and then rebounded to 1,368.21 km² (8.545%) in 2022.

The area of very low sensitivity increased by 98.83% from 2002 to 2007, followed by a 49.76% decrease from 2007 to 2012, stabilizing thereafter. Low sensitivity areas saw a slight increase of 0.30% from 2002 to 2007, followed by rises of 4.82% from 2007 to 2012 and 18.54% from 2012 to 2017, but a significant 26.40% decrease from 2017 to 2022. Medium sensitivity areas decreased by 2.10% from 2002 to 2007, then by 9.54% from 2007 to 2012, rose by 9.23% from 2012 to 2017, and slightly decreased by 0.82% from 2017 to 2022. High sensitivity areas experienced a slight 0.15% increase from 2002 to 2007, followed by rises of 7.41% from 2007 to 2012, and decreases of 2.98% from 2012 to 2017 and 3.05% from 2017 to 2022. Despite the overall decrease, this category still covers a significant portion of the area, underscoring continued ecological challenges in highly sensitive regions. There was a 1.68% increase in very

Table 2. The area and percentage of each class of ecological sensitivity in the area surrounding Hainan Tropical Rainforest National Park.

Level	2002		2007		2012		2017		2022	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
I	0.944	0.006	1.877	0.012	0.943	0.006	0.943	0.006	0.939	0.006
II	730.002	4.559	732.209	4.573	767.535	4.725	909.761	5.682	669.765	4.183
III	5949.56	37.156	5824.81	36.377	5268.69	32.436	5754.32	35.937	5707.20	35.642
IV	8170.06	51.023	8181.96	51.098	8787.99	54.103	8526.34	53.249	8266.23	51.624
V	1373.76	8.579	1396.83	8.723	1417.99	8.730	1155.34	7.215	1368.21	8.545

high sensitivity areas from 2002 to 2007, followed by a 1.51% rise from 2007 to 2012. Subsequently, there was a significant 18.49% decline from 2012 to 2017, followed by an 18.43% increase from 2017 to 2022.

From 2002 to 2022, the comprehensive sensitivity dynamics of counties in the study area exhibited distinct patterns, characterized by three stages of change: a rising pattern from 2002 to 2012, a decreasing trend from 2012 to 2015, and another increasing trend from 2015 to 2022 (Fig. 5). Danzhou City consistently showed an upward trend. Sanya City, Dongfang City, Baisha Li, Lingshui Li, Baoting Li and Miao Autonomous County, and Qiongzhong Li and Miao Autonomous County showed relatively stable trends with minor fluctuations. Wuzhishan City, Wanning City, Changjiang Li and Miao Autonomous County, and Ledong Li and Miao Autonomous County exhibited more pronounced fluctuations. Specifically, the composite sensitivity of Sanya City was 3.7685 in 2002, dropped slightly to 3.7220 in 2007 (-1.23%), rebounded to 3.7670 in 2012 (+1.24%), declined to 3.6995 in 2017 (-1.81%), and increased to 3.7515 in 2022 (+1.41%). Despite fluctuations, Sanya City's sensitivity showed significant variability, indicating instability. Wuzhishan City's composite sensitivity was relatively stable, starting at 4.1672 in 2002, slightly increasing to 4.1969 in 2007 (+0.71%), remaining stable at 4.1963 in 2012 (-0.01%), decreasing to 4.1031 in 2017 (-2.22%), and rebounding to 4.1485 in 2022 (+1.10%). Despite minor fluctuations, overall sensitivity in Wuzhishan City remained largely unchanged. Dongfang City's composite sensitivity remained stable with minimal changes, starting at 3.2743 in 2002, nearly unchanged at 3.2739 in 2007 (-0.01%), slightly increasing to 3.2832 in 2012 (+0.28%), decreasing to 3.2180 in 2017 (-1.99%), and increasing slightly to 3.2250 in 2022 (+0.22%). This stability indicates relatively smooth ecological changes in Dongfang City. Conversely, Changjiang Li and Miao Autonomous County experienced significant fluctuations, starting at 3.2853 in 2002, increasing slightly to 3.2873 in 2007 (+0.06%), significantly rising to 3.3674 in 2012 (+2.44%), declining to 3.3081 in 2017 (-1.76%), and slightly decreasing to 3.2967 in 2022 (-0.35%). These fluctuations highlight the volatile ecological environment in Changjiang Li and Miao Autonomous County during the study period. Baoting Li and Miao Autonomous County exhibited a steady upward trend, beginning at 4.0243 in 2002, increasing to 4.0462 in 2007 (+0.54%), further increasing to 4.0633 in 2012 (+0.42%), slightly decreasing to 3.9810 in 2017 (-2.03%), and rebounding to 4.0128 in 2022 (+0.80%). Overall, the sensitivity changes in Baoting Li and Miao

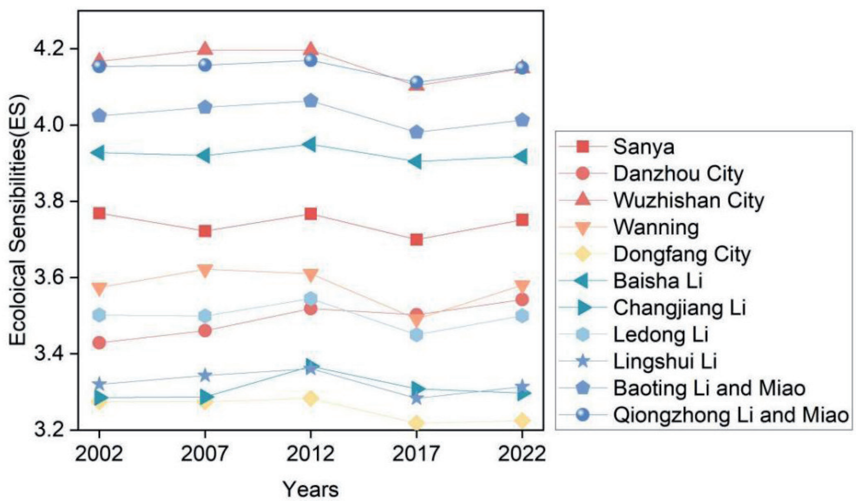

Fig. 5. Trends in comprehensive sensitivity of tropical rainforest national parks in Hainan Province, 2002-2022.

Autonomous County were relatively smooth, showing a consistent upward trajectory.

Landscape Pattern Index

From 2002 to 2022, land use data were analyzed using Fragstats 4.2 software. A grid analysis method was employed to compute five class-level indices and five landscape pattern indices in the surrounding areas of HTNP. Spatial mapping of these indicators was conducted using ordinary kriging interpolation in ArcGIS 10.8 to acquire spatial assessments of different landscape pattern metrics, with the outcomes depicted in Fig. 6.

At the grid scale, areas with higher Patch Density (PD) are primarily concentrated in regions with significant coastal urbanization, whereas PD is notably lower around the national park, especially in the northeastern and southern areas. This suggests that the surrounding areas of the national park, particularly in the northeast and south, have experienced less damage. Effective conservation measures have led to a notable decrease in PD values across the central region of the study area from 2007 to 2022, contrasting with higher values observed in 2002.

The spatial distribution characteristics of LSI and SHEI are similar, with both indices indicating low values around the national park and in the study area. Notably, in 2002, there were more pronounced variations, with higher values in some areas, but overall, the areas around the national park and the study area in Hainan are relatively less impacted by human activities.

Higher values of the Largest Patch Index (LPI) correspond to increased landscape fragmentation. Thus, as one moves gradually from the coast towards the interior of the region surrounding Tohana National Park, there is a noticeable trend of decreasing landscape fragmentation. Thus, there is a trend of decreasing landscape fragmentation from the coast to the inland areas around Hainan National Park. CONTAG describes the degree of patch aggregation or dispersion within the landscape. Typically, higher values of spread indicate greater connectivity of dominant patch types in the landscape. Conversely, they suggest increased structural complexity, the presence of multiple elements, and a higher degree of fragmentation.

As shown in Fig. 6, CONTAG value generally increases from the coast to the interior, reflecting improved landscape connectivity around Hainan National Park. Over time, from 2017 to 2022, PD, LSI, CONTAG, and SHEI in the peripheral region exhibit a decreasing trend, with PD and LSI showing a more pronounced decline. This indicates a significant improvement in landscape fragmentation around Hainan National Park during this period. Conversely, in the study area, CONTAG and SHEI show a significant downward trend from 2002 to 2022, demonstrating substantial improvements in landscape fragmentation. Notably, CONTAG values in the peripheral region increased more significantly in areas with concentrated coastal urban construction.

Spatial Autocorrelation Analysis

Global spatial autocorrelation analyses were conducted on the Ecological Sensitivity Index and LPI in the vicinity of HTNP. These analyses provided insights into the level and spatial characteristics of habitat quality within the park. As shown in Table 3, Moran's I values for LPI and CONTAG were greater than 0, indicating a positive correlation with habitat quality. Conversely, Moran's I values for PD, LSI, and SHEI were less than 0, indicating a negative correlation with habitat quality. Comparing the mean absolute values of Moran's I for each landscape pattern index and habitat quality, the order (LPI > CONTAG > LSI > SHEI > PD) underscores that LPI exhibits the strongest correlation, while PD shows the weakest correlation with habitat quality. Except for LPI, the relationship between each landscape pattern metric and habitat quality in the study region remained consistent from 2002 to 2022. During this period, Moran's Index for PD decreased overall by 0.057. LPI initially increased and then decreased, resulting in a net change of 0.007. LSI consistently increased by 0.093. CONTAG decreased by 0.012, while SHEI increased by 0.072.

The LISA (Local Indicators of Spatial Association) diagram for ecological sensitivity and landscape pattern around HTNP, as shown in Fig. 7, presents an analysis based on five landscape pattern indices. The study reveals significant spatial aggregation characteristics in both ecological sensitivity and landscape patterns. The primary aggregation types identified are as follows: low Patch Density (PD) with low Ecological Sensitivity (ES), high LPI with high ES, low LSI with high ES, high CONTAG (Contagion Index) with high ES, and low Shannon's Entropy Index (SHEI) with high ES.

In the southwestern coastal region, low PD and low LPI with low ecological sensitivity (ES) are primarily concentrated. Conversely, the western region exhibits high LSI and high ES, alongside low CONTAG and low ES, and high SHEI with high ES. In the eastern sector of the peripheral study area, areas with elevated LPI and high ecological sensitivity (ES), as well as those with pronounced CONTAG and high ES, are primarily located. From 2007 to 2022, regions characterized by elevated LPI and ES, reduced LSI but high ES, and diminished SHEI but high ES are primarily concentrated in the western segment of the study region. Furthermore, areas with high CONTAG and high LPI, along with high ecological sensitivity (ES), are widely dispersed from the central region outward.

Discussion

Policy Implications

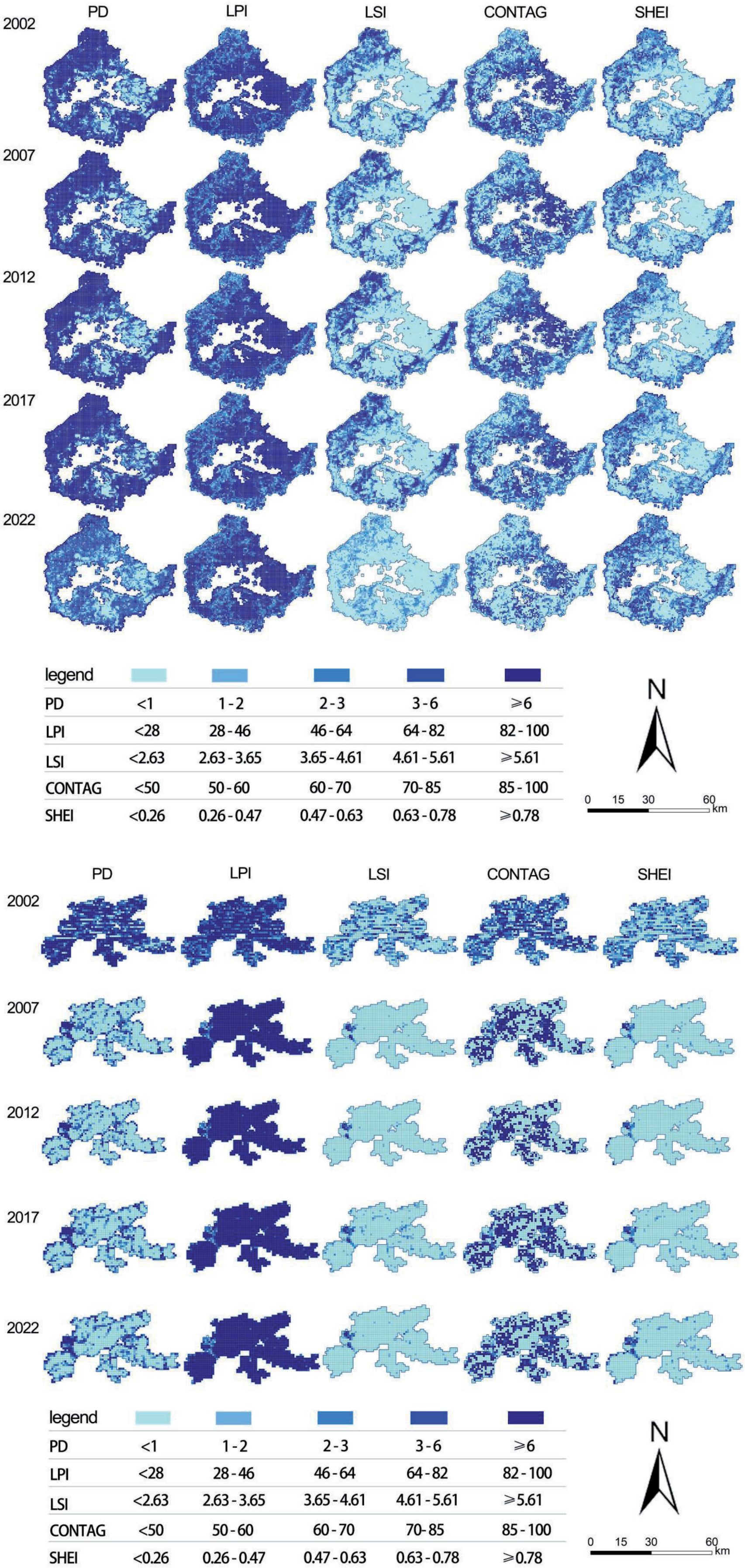

Fig. 6. Analysis of temporal and spatial changes in landscape pattern indices in tropical rainforest national parks and surrounding areas in Hainan Province, 2002-2022.

Table 3. Global Moran'I Index.

Years	PD	LPI	LSI	CONTAG	SHEI
2002	-0.141	0.188	-0.153	0.092	-0.147
2007	-0.139	0.171	-0.118	0.097	-0.124
2012	-0.142	0.213	-0.157	0.116	-0.169
2017	-0.151	0.216	-0.149	0.131	-0.156
2022	-0.198	0.181	-0.060	0.104	-0.075

HTNP was established to safeguard the originality and integrity of its tropical rainforest ecosystem. The establishment of a protection and development zone around the national park is crucial for preserving its core area [32-33]. This zone aims to create a comprehensive tourism service platform that integrates management, services, and operations. Therefore, the planning phase of this protective belt should prioritize ecological conservation and regulate human activities around the national park. This study focuses on the area surrounding HTNP, using ArcGIS 10.8, Fragstats 4.2, and GeoDa 1.20 to analyze changes in landscape patterns and ecological sensitivity from 2002 to 2022. The goal is to offer scientifically informed recommendations for the development of the national park's protection and development zone.

In the study of ecological sensitivity at HTNP, each factor was analyzed and categorized into five sensitivity zones: not sensitive, mildly sensitive, moderately sensitive, highly sensitive, and extremely sensitive. From 2002 to 2022, NDVI responsiveness in the research zone demonstrated a rising pattern from the north toward the west. This trend is attributed to regional ecological protection policies and the establishment of national parks, which aim to safeguard high-sensitivity areas through designated vegetation ecosystem protection zones, thereby preserving the authenticity and integrity of tropical rainforest ecosystems [34-35]. Despite the designation of national pivotal ecological function zones in 2010 to bolster vegetation conservation and prohibit practices such as forest clearing, grassland destruction, and wetland degradation, human activities have intensified, leading to a decline in ecosystem service provision from 2000 to 2010. According to the comprehensive study on ecological sensitivity, areas of extreme and high sensitivity predominantly expand outward from the center of the study area. This pattern reflects both strategic ecological protection planning for the national park and heightened human activity intensity along the coastal zones [36]. Remarkably, the southern and eastern sectors of the national park demonstrate notably greater ecological sensitivity than other regions. Therefore, future efforts in establishing conservation and development zones within the national park should prioritize minimizing construction activities in these sensitive regions to ensure effective ecological protection [37-38].

Landscape patterns result from intricate interactions among physical, biological, and socio-economic processes, profoundly influencing ecological dynamics. Quantitative description and analysis of spatial patterns enable us to uncover the intrinsic links between landscape structure and function, integrating spatial features with ecological processes to reveal underlying landscape regularities. HTNP was established with the goal of preserving the originality and integrity of its tropical rainforest ecosystem [39]. Analysis of landscape pattern index changes from 2002 to 2022 highlights pronounced shifts in PD, LSI, and CONTAG, particularly notable during the period from 2017 to 2022, as evidenced by specific landscape pattern index data. Spatial and temporal variations in landscape pattern indices surrounding the national park exhibit distinct regional disparities and aggregation from 2002 to 2022, influenced by both human activities and natural processes [40-41]. Originally irregular, the distribution of built-up areas evolved into dense clusters, illustrating the influence of human activities on landscape configurations. The small, scattered population within the park is being strategically relocated outside, with ecological restoration efforts focusing on former settlement areas. This approach aims to preserve the park's originality and integrity while enhancing management efficiency. Furthermore, areas with low landscape fragmentation require stable environmental management practices, whereas regions with high fragmentation benefit from a structured approach to logging, land reclamation, and water resource utilization.

Limitation

This paper offers an initial investigation into the spatial distribution features of landform configurations and environmental responsiveness in HTNP. Nevertheless, this research has its constraints. The health of an ecosystem relies on its quality and the ecological services it provides through biophysical processes to humans [42]. Due to variations in spatial resolution, the remote sensing data used in this study exhibited notable inconsistencies. Future research should thus employ higher-resolution data for more detailed analyses. Future studies should consider examining landform configurations and environmental responsiveness across diverse grid scales.

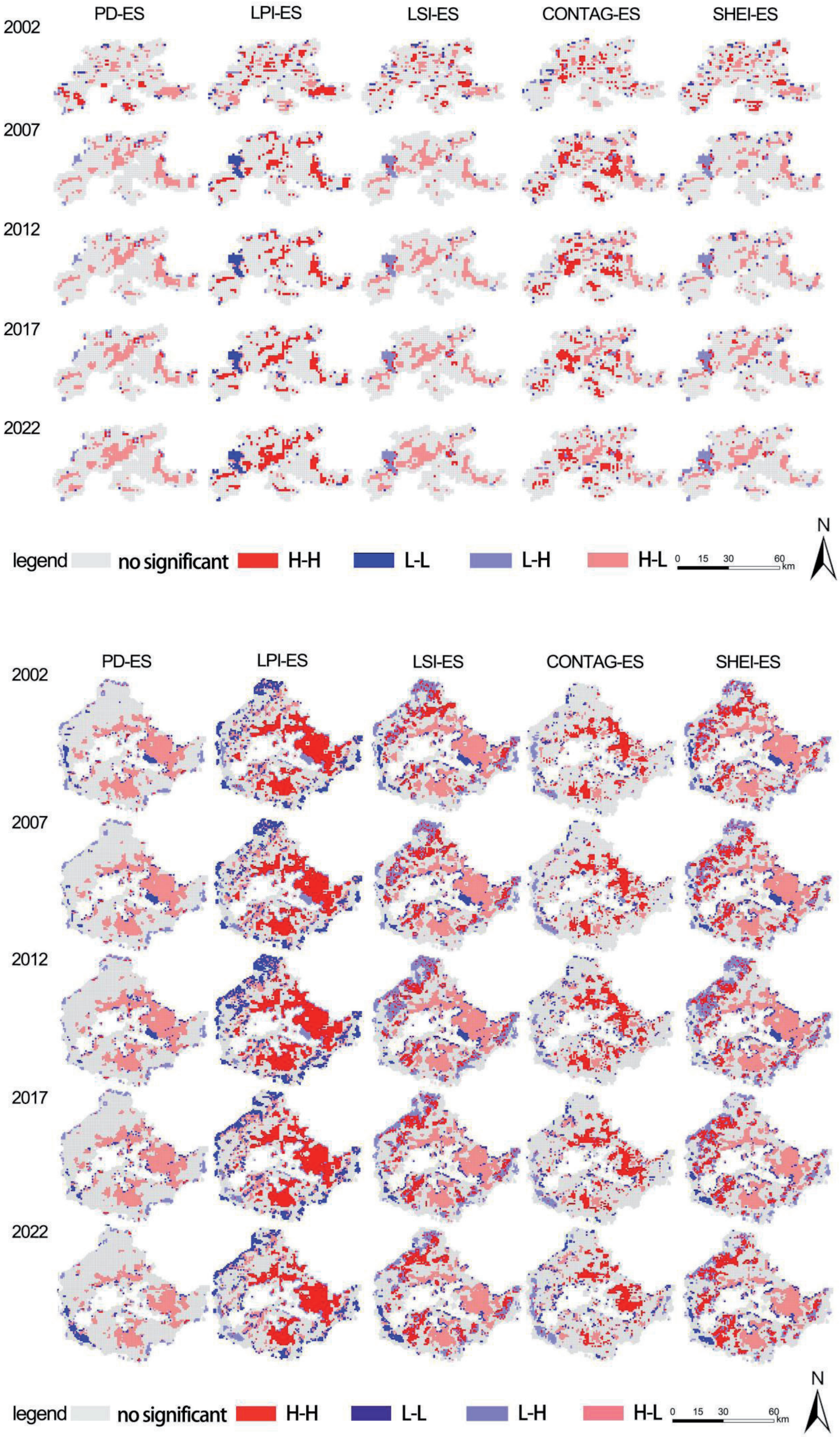

Fig. 7. LISA maps depicting environmental responsiveness and landform configurations of tropical rainforest national parks in Hainan Province, from 2002 to 2022.

Conclusion

This research investigated the spatial and temporal dynamics of landscape fragmentation and ecological sensitivity in HTNP and its surrounding areas using five periods of land use data spanning from 2002 to 2022. Analysis was conducted through ArcGIS, GeoDa, and Fragstats 4.2 software tools, employing hierarchical analysis, landscape pattern analysis, spatial statistical analysis, and other methods. The findings are summarized as follows: (1) The study categorized the area into non-sensitive, mildly sensitive, moderately sensitive, highly sensitive, and extremely sensitive zones. Over time and across geographical changes, the national park and its vicinity exhibited diverse ecological trends. (2) At the grid scale, within the national park, higher Landscape Patch Index (LPI) and Landscape Patch Density (PD) were primarily found in coastal urbanized areas. Conversely, the surrounding northeast, south, and western areas displayed lower PD values, indicating greater environmental degradation compared to the park's immediate surroundings. Notably, PD exhibited a decline from 2002, with a significant decrease observed between 2007 and 2022, suggesting effective environmental protection measures. Landscape Shape Index (LSI) and Edge Density Index (SHEI) showed similar spatial distributions, with predominantly low values in the park and its periphery, indicative of lesser human-induced damage. The year 2002 stood out due to significant overall area changes and varying fluctuations, generally reflecting less human activity impact on the park's periphery and surrounding areas. Over the temporal scale, PD, LPI, LSI, Contagion Index (CONTAG), and SHEI indices showed a general decrease between 2002 and 2007. In the peripheral regions, PD, LSI, CONTAG, and SHEI exhibited decreasing trends from 2017 to 2022, with PD and LSI declines being particularly noticeable, indicating marked improvements in landscape fragmentation around Hainan National Park during this period. The CONTAG index showed reduced fragmentation in low-value areas, notably in regions with concentrated coastal urban development, highlighting decreased landscape fragmentation. (3) Global spatial autocorrelation analysis of ecological sensitivity and landscape pattern indices around HTNP revealed positive correlations between LPI and CONTAG with habitat quality, whereas PD, LSI, and SHEI showed negative correlations. In the national park and its surroundings, LPI exhibited the strongest correlation with habitat quality, whereas PD exhibited the weakest. Time-series analysis indicated that between 2007 and 2022, the Moran's Index of CONTAG decreased, while PD, LPI, LSI, and SHEI increased within the study area. From 2002 to 2022, PD and CONTAG's Moran's Index decreased, while LPI, LSI, and SHEI increased in neighboring areas, illustrating dynamic relationships between landscape pattern and habitat quality.

Conflict of Interest

The authors declare no conflict of interest.

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