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Article

Assessment of Ecosystem Vulnerability in the Tropic of Cancer (Yunnan Section)

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Abstract: The stability and diversity of the natural landscape is critical to maintaining the ecological functions of a region. However, ecosystems in the Yunnan section of the Tropic of Cancer face increasing pressure from climate change, human activities, and natural disasters, which significantly influence their vulnerability. Ecosystem vulnerability is determined by structural and functional sensitivity, coupled with insufficient adaptability to external stressors. While previous research has emphasized the effects of climate change, the multidimensional impacts of land use and human activities have often been overlooked. This study aims to comprehensively assess the ecological vulnerability of the Yunnan section of the Tropic of Cancer, addressing this research gap by utilizing geographic information system (GIS) technology and the Vulnerability Scoping Diagram (VSD) model. The study constructs a multidimensional evaluation index system based on exposure, sensitivity, and adaptive capacity, with a specific focus on the effects of land use, human activities, and natural disasters. Key indicators include road and population density, soil erosion, and geological hazards, along with innovative considerations of economic adaptive capacity to address gaps in previous assessments. The findings highlight that ecological vulnerability is predominantly concentrated in areas with low vegetation cover and severe soil erosion. Human activities, particularly road and population density, are identified as significant drivers of ecological vulnerability. Sensitivity is heavily influenced by soil erosion and geological disasters, while economic adaptability emerges as a critical factor in mitigating ecological risks. By proposing targeted policy recommendations—such as enhancing ecological protection and restoration, optimizing land use planning, and increasing public environmental awareness—this study provides actionable strategies to reduce ecological vulnerability. The findings offer crucial scientific support for improving the ecological environment in the Tropic of Cancer region and contribute to achieving sustainable development goals.

Keywords: ecosystem vulnerability; VSD model; GIS; land use; policy recommendations; Yunnan section of the Tropic of Cancer

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1. Introduction

Ecosystem vulnerability is an important indicator of the degree of sensitive response of ecosystems and their resilience in the face of external environmental and anthropogenic pressures, as well as a key component in the evaluation of ecological environment quality [1,2]. Economic activities such as human production and living are highly dependent on the ecological environment and land resources, and at the same time, these activities affect the changes in the ecological environment and land resources [3,4]. Therefore, it is of great significance to scientifically and reasonably assess the vulnerability of the ecological environment and carry out effective land resource management and regulation to realize the rational development and utilization of land resources, and to promote the harmonious coexistence of human beings and nature, as well as the balanced development of the ecological environment and economic activities.

The study of ecosystem vulnerability originated in the mid-20th century, when the destructive effects of natural disasters on ecosystems impacted their carrying capacity and resilience [5–7]. Since the 1970s, significant progress has been made in terms of theory, methodology, and application. Theoretically, researchers have deeply explored how ecosystems respond to multiple stressors and their capacity for recovery, with the concept of ecosystem resilience becoming a central focus [8–10]. Key theoretical advancements include the development of the Pressure–State–Response (PSR) framework [11], which has been widely used to assess environmental changes and their impacts on ecosystems. Additionally, the concept of adaptive capacity has been refined to better understand how ecosystems can adjust to changing conditions [12]. Methodologically, the development of remote sensing technology and geographic information systems (GISs) has enabled a shift from qualitative to quantitative research. Model simulations and multi-indicator comprehensive evaluation methods have been widely adopted, resulting in more accurate assessments of ecosystem vulnerability [13–15]. Notable methodologies include the use of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) model for assessing ecosystem services and vulnerability and the application of machine learning techniques to predict vulnerability patterns [16]. These advancements have been applied extensively in environmental protection, resource management, and policy formulation, particularly in ecosystem management, restoration, and sustainable development planning [17]. As global environmental changes intensify, international attention on ecosystem vulnerability has grown, with cross-border cooperation and experience exchange enhancing global ecosystem management science [18–23].

In recent years, ecosystem vulnerability research has become a focal point in the context of global change. Climate change, land use changes, and biodiversity loss have all exacerbated ecosystem vulnerability, especially when facing extreme climate events such as droughts and floods, which severely challenge ecosystems' adaptive capacities [24,25]. Studies have found that climate change not only increases the spatial heterogeneity of ecosystem vulnerability but also affects its resilience. Against this backdrop, multi-scale vulnerability research has gained importance, as vulnerability exhibits complex scale dependencies, ranging from species diversity at the micro level to ecosystem services at the macro level, such as global or regional scales. Recent studies have highlighted the importance of incorporating socio-economic factors into vulnerability assessments to capture a more holistic view of ecosystem health [26–30]. Yunnan, as a biodiversity hotspot with a unique ecological environment and complex natural conditions, offers significant theoretical and practical value for ecosystem vulnerability research in this region.

Moreover, the impact of human activities on ecosystem vulnerability is substantial. Overuse of land, urban expansion, and infrastructure development have heightened ecosystem vulnerability [31,32]. In regions traversed by the Tropic of Cancer in Yunnan, land use changes and vegetation destruction are particularly prominent, with human activities directly affecting ecosystem sensitivity and adaptive capacity. In recent years, vulnerability assessments have gradually expanded from solely evaluating natural factors to integrating human factors in a comprehensive analysis, emphasizing the complex interactions between land use, human activities, and the natural environment. Studies have shown that sustainable land management practices and urban planning can mitigate some of the negative impacts of human activities on ecosystem vulnerability. Additionally, the incorporation of stakeholder perspectives in vulnerability assessments has been advocated to ensure that management strategies are both effective and socially acceptable [27].

At the methodological level, vulnerability models, such as the Vulnerability Scoping Diagram (VSD), have become important tools in ecosystem vulnerability research. The VSD model allows for a comprehensive assessment of ecosystems across three dimensions—exposure, sensitivity, and adaptive capacity—making it especially adaptable at regional scales [3,33]. Combined with remote sensing technology and GIS tools, spatio-temporal analysis methods have significantly improved assessment accuracy. The integration of multi-source data, such as remote sensing images, ground monitoring, and socio-economic data, provides a more comprehensive understanding of the spatio-temporal dynamics of ecosystem vulnerability. Recent methodological advancements include the use of participatory GISs (PGISs) to incorporate local knowledge into vulnerability assessments and the application of Bayesian networks to model uncertainty in vulnerability predictions [29]. These methodological improvements have enhanced the ability to predict and manage ecosystem vulnerability more effectively.

Addressing the balance between regional development and ecological protection, particularly in resource-rich yet development-pressured regions like Yunnan, is crucial. Developing adaptive ecological protection strategies that integrate vulnerability assessment with regional development policies remains a significant challenge for current researchers [8,34].

Despite the substantial progress in ecosystem vulnerability research, many challenges persist. Future research should further integrate multidisciplinary theories and methods, coupled with advanced technologies, to enhance the spatio-temporal precision and predictive capabilities of vulnerability assessments [35,36]. Additionally, establishing region-specific evaluation frameworks tailored to the unique ecological environments of different areas is essential for achieving sustainable ecosystem management.

This study aims to apply the Vulnerability Scoping Diagram (VSD) model to conduct a comprehensive assessment of ecological vulnerability in the Yunnan section of the Tropic of Cancer. Specifically, it seeks to (1) identify and select indicators that comprehensively reflect the ecosystem vulnerability in the Yunnan Tropic of Cancer region; (2) utilize multi-source data and advanced technologies to enhance the spatio-temporal precision of vulnerability assessments; (3) provide scientific foundations for regional ecological protection and sustainable development policies based on the assessment results.

The Tropic of Cancer crosses through the Yunnan region, and the area's unique geographical and climatic characteristics make its ecosystems highly sensitive and diverse, making them susceptible to both natural disasters and human activities. A scientific assessment is urgently needed to address the escalating environmental pressures [37]. Moreover, in recent years, population growth, economic development, and climate change have posed severe threats to the region's ecological environment. A scientific vulnerability assessment can provide critical guidance for environmental protection and resource management [38–40]. In addition, as a result of the frequent and intense external pressures, the region's rich biodiversity is at risk of loss. Through vulnerability assessment, effective protection measures can be devised to safeguard biodiversity [41–43]. This research not only provides scientific support for local governments and relevant departments in making informed decisions, facilitating the development and implementation of environmental protection policies, but also promotes the harmonious integration of economic development and ecological conservation. It enhances the resilience and recovery capacity of ecosystems, ensuring regional ecological security.

The influencing factors of regional ecosystem vulnerability mainly stem from three aspects: (1) Natural geographic environment factors: Factors such as regional elevation, vegetation coverage, climate temperature, rainfall, geological environment, and geological disasters directly determine the degree of ecosystem vulnerability based on inherent conditions [44–46]. (2) Ecosystem's self-recovery ability: During the continuous succession and replacement of ecosystem communities, the ecosystem develops a potential resistance and regeneration capacity against external environmental disturbances. However, once the level of external disturbance exceeds the ecosystem's original ecological threshold, its ability to self-repair and recover becomes extremely limited, with recovery occurring at a much slower rate compared to the pressure from external damage [47–50]. (3) Human activity interference: When population density increases and social development needs surpass the carrying capacity of current resources and the environment, issues such as deforestation for cultivation, excessive tree cutting, water supply shortages leading to drought, white pollution, and acid rain caused by air pollution leading to land degradation occur [6,7,46,51]. Therefore, based on the actual conditions of the study area, the Vulnerability Scoping Diagram (VSD) model was selected to decompose ecosystem vulnerability into three aspects for evaluation: the exposure index (EI), the sensitivity index (SI), and the adaptive capacity index (ACI).

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

Yunnan Province is located between 21°N and 29°N, with the Tropic of Cancer running through its southern part, crossing from west to east through 17 counties and cities: Cangyuan, Gengma, Shuangjiang, Jinggu, Ning'er, Mojiang, Yuanjiang, Honghe, Shiping, Jianshui, Gejiu, Mengzi, Yanshan, Wenshan, Xichou, Malipo, and Funing (Figure 1). The region is characterized by complex and varied topography, with densely distributed mountains and deep valleys, abundant water resources, and a unique vertical climate system [52,53]. However, these counties and cities share several common climatic characteristics: small annual temperature variation, of typically only 10–12 °C; large diurnal temperature variation, ranging from 12 to 20 °C; the mean temperature of the coldest month is above 6–8 °C; and the mean temperature of the hottest days is between 19 and 22 °C. Rainfall is abundant, with most counties receiving more than 1000 mm annually; however, the region experiences distinct wet and dry seasons, with 85% of the rainfall occurring between May and October, while the dry season from November to April is also the annual forest fire prevention period. There is a marked uneven distribution of rainfall across the counties [54,55]. Due to Yunnan's north–south elevation gradient, combined with increasing latitude and altitude, vertical climate variation is highly pronounced. In particular, the mountain and valley areas exhibit prominent vertical climatic features, often described by the saying "one mountain has four seasons, and the weather changes every ten miles". The complex terrain and diverse vertical climate types create a unique regional ecological environment along the Yunnan section of the Tropic of Cancer [56,57]. Thus, the Yunnan section of the Tropic of Cancer, with its unique geographical location, complex climate conditions, and significant ecological vulnerability, serves as an ideal research area for ecosystem vulnerability assessments. This study not only aids in scientifically understanding regional ecological changes but also provides essential guidance for ecological protection and resource management.

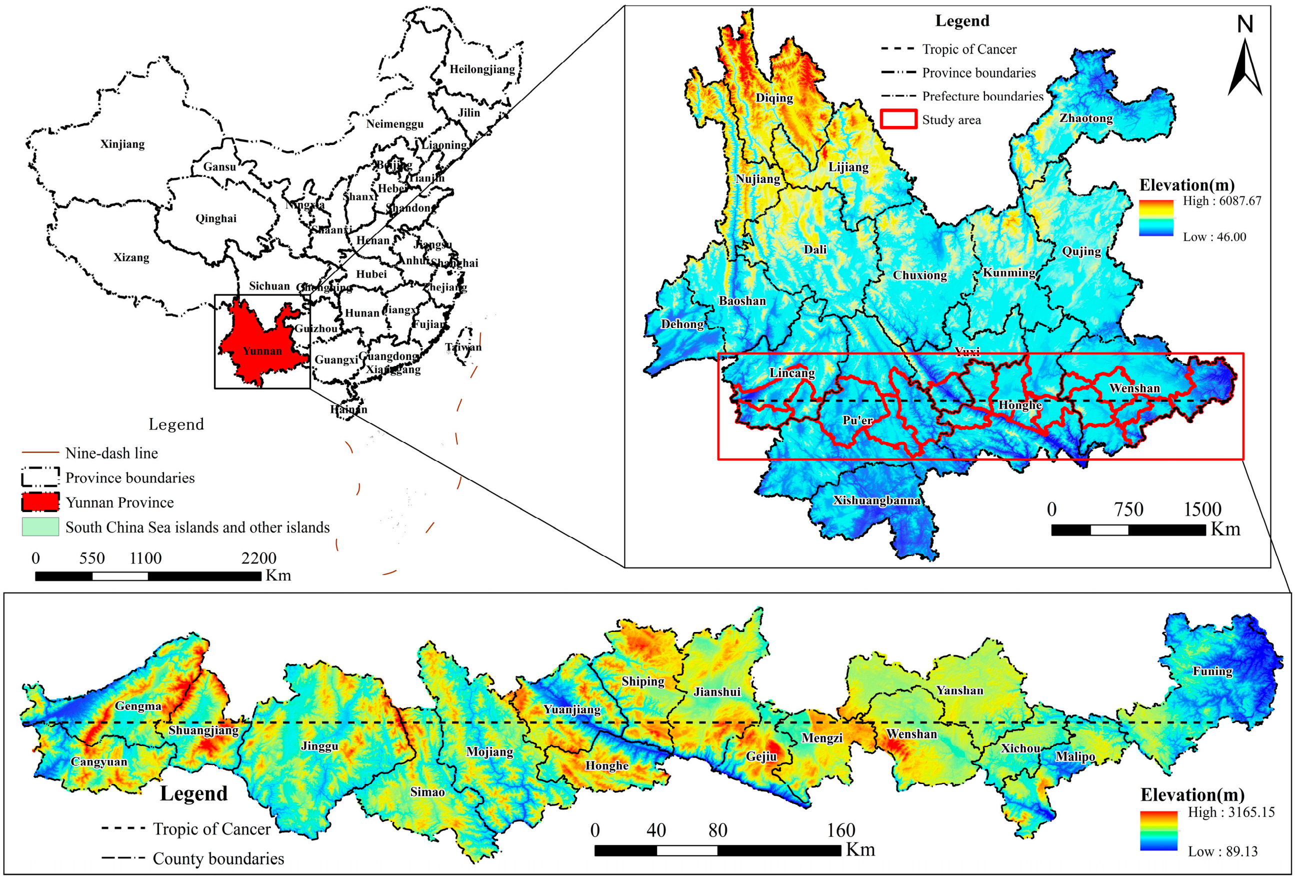

Figure 1. Location map of the study area.

2.2. Data Sources

The data used in this study were from a wide range of sources, encompassing climate data, geological data, topographic data, vegetation coverage data, land use data, soil data, and socio-economic data (Table 1), ensuring the comprehensiveness and accuracy of the ecosystem vulnerability assessment. The climate data mainly included indicators such as precipitation, temperature, and humidity, sourced from the China Meteorological Administration and the China Meteorological Information Center; these were data for the year 2022. Geological data, including stratigraphy, geological structures, and mining conditions, were sourced from the China Geological Data Center (http://dc.ngac.org.cn/Home (accessed on 1 January 2025)). Topographic data, such as elevation, slope, and aspect data, were sourced from the National Geomatics Center of China (https://www.ngcc.cn/dlxxzy/gjjcdlxxsjk/ (accessed on 1 January 2025)), and the data were also from 2022. Vegetation coverage data, used to assess the distribution and changing trends of vegetation in the region, came from the Chinese Ecosystem Research Network (CERN), MODIS satellite data, and global land cover datasets such as GLC2000 and GlobCover, with a time frame of 2022. Soil data, including soil types, texture, and fertility, were sourced from the China Soil Database, soil survey data, and the FAO World Soil Database, with all data also from 2022. Socio-economic data, which were used to analyze the impact of human activities on ecosystems, included population density, land use, and economic development levels, and were sourced from the National Bureau of Statistics of China, the Yunnan Provincial Statistical Yearbook, and statistical bulletins and annual reports published by local governments, with the latest available data.

Table 1. Summary of data sources.

Type	Relevant Indicator	Source of Data	Time Frame
Climate Data	Precipitation, temperature, humidity	China Meteorological Administration, China Meteorological Information Center	2022
Geological Data	Stratigraphic lithology, geological structure, mine development status	China Geological Information Data Center (http://dc.ngac.org.cn/Home (accessed on 1 January 2025))	2000–2022
Geomorphologic Data	Elevation, slope, slope direction	China Basic Geographic Information Center (https://www.ngcc.cn/dlxxzy/gjjcdlxxsjk/ (accessed on 1 January 2025))	2022
Vegetation Cover Data	Vegetation index (NDVI), vegetation cover type	China Ecosystem Research Network (CERN), MODIS satellite data, GLC2000, GlobCover, etc.	2022
Soil Data	Soil type, texture, fertility	China Soil Database, Soil Census Data, FAO World Soil Database	2022
Socio-economic data	Population density, land use, level of economic development	China Bureau of Statistics, Yunnan Provincial Statistical Yearbook, local government statistical bulletins and annual reports	2022

To address the spatial scale differences among various data sources, this study employed the following spatial harmonization techniques. First, climate data were processed into raster format using the Kriging interpolation method to ensure the continuity and spatial consistency of point data. Second, geological and soil data in vector format were directly converted into raster format to facilitate integration with other raster datasets. Topography and vegetation coverage data were originally in raster format and required no further processing. Socio-economic data were transformed into continuous raster layers using the Inverse Distance Weighting (IDW) interpolation method, enhancing spatial continuity. Finally, all data were resampled to a uniform raster resolution of 1000 m, and the coordinate system was standardized using the China Geodetic Coordinate System 2000 (CGCS2000) to ensure the spatial alignment and compatibility of all indicators. This unified methodology ensures comprehensive and accurate integration of multi-source data, enhancing the robustness of the ecological vulnerability assessment.

3. Evaluation Methods

3.1. Exposure Indicators

Exposure primarily refers to the key parameters by which an ecosystem is subjected to external pressures, disturbances, and stresses [34,47]. In the study area, the main factors contributing to exposure include human activities, climatic conditions, and land use patterns [58,59]. During our field investigations in the region (Figure 2), we selected 50 survey points and 80 soil sampling points. The field survey was meticulously planned and executed to ensure comprehensive data collection across various environmental and anthropogenic variables. Soil samples were collected at designated locations to analyze soil quality and composition, providing insights into the region's ecological health. Detailed observations and measurements were taken at each survey point to capture critical environmental data. Furthermore, the field survey route map provides a detailed layout of our investigation, ensuring that all selected points were systematically examined to gather accurate and relevant data.

Based on these field investigations conducted in the region, 13 indicator factors were selected to assess the exposure of ecosystem vulnerability: proportion of construction land, road network density, per capita GDP, population density, area of sloping farmland greater than 25°, distance to mining sites, scale of mining activities, power generation, annual precipitation, mean annual temperature, land use types, residential density, and area of forest and grassland degradation caused by mining activities [60,61]. The orientation (positive or negative) of each indicator depends on the relationship between the respective factor and ecosystem vulnerability [62,63]. The rapid pace of urbanization, coupled with high-intensity human engineering activities, has notably impacted the surface environment of the ecosystem, disrupting the internal balance and exacerbating its vulnerability. Thus, the assessment of exposure offers valuable insights into the extent of external pressures affecting ecosystem stability. Positive indicators represent factors that are beneficial to ecosystem vulnerability. Conversely, negative indicators refer to environmental conditions that are detrimental and severely damaging to ecosystem vulnerability. For instance, indicators such as the proportion of construction land and population density are negative because higher values of these indicators correlate with greater ecosystem vulnerability. In contrast, indicators such as per capita GDP and the biodiversity abundance index may exhibit positive orientations, where increases in GDP investment could potentially reduce certain aspects of vulnerability, depending on the specific ecological context and characteristics.

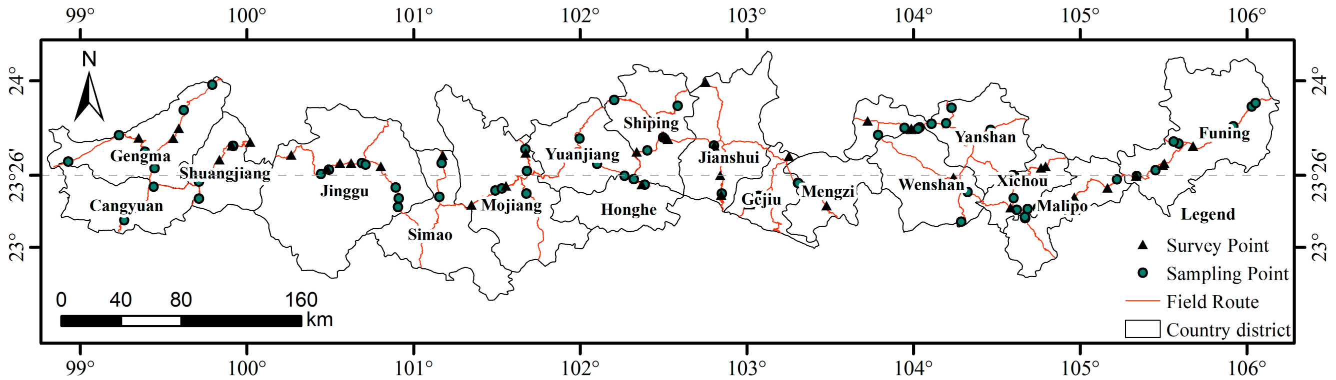

Figure 2. Field survey route map.

3.2. Sensitivity Indicators

Across different temporal and spatial scales, all natural phenomena, economic development, cultural characteristics, and levels of social development exhibit significant variation. This concept, known as spatial heterogeneity, is a key aspect of geographical studies. Extensive research has demonstrated that ecological vulnerability also displays distinct spatial and temporal variability across different scales of analysis. Ecological sensitivity refers to the inherent responsiveness and recovery capacity of an ecosystem when it is subjected to external disturbances and pressures within a given temporal and spatial context, and it too exhibits notable regional variability [64–67]. The study area, located in the mountainous regions of southwestern China, is characterized by significant elevation differences and severe issues with soil desertification, rock desertification, and sandification [68,69]. Considering these regional features, 10 indicators closely related to ecological vulnerability were selected to comprehensively evaluate and quantify the ecological sensitivity of the region. These indicators include soil erosion type, soil type, vegetation coverage index (NDVI), biological abundance index, density of geological hazards, proximity to geological structures, stratigraphy and lithology, elevation, slope, and aspect. Together, these factors provide a detailed assessment of the area's ecological sensitivity.

3.3. Adaptive Capacity Indicators

Ecosystem adaptive capacity refers to the degree to which an ecosystem can adjust, govern itself, and recover after being subjected to external disturbances and pressures. This capacity is influenced by two primary factors: changes in natural ecological resources and shifts in local government economic investments and socio-economic development. While an ecosystem's inherent recovery capacity is limited, human intervention through economic investment can enhance its adaptive capacity, leading to faster recovery and a greater degree of adaptation [17,34,35]. To assess the adaptive capacity of the ecosystem, 11 evaluation indicators were selected. These include public budget expenditure, mine service life, per capita disposable income, forest and grassland area, per capita arable land, green coverage rate, residents' year-end savings, growth rate of fixed asset investment, available water resources, environmental capacity, and land resources. These indicators reflect the strength of protection efforts, the degree of recovery, and the intensity of the ecosystem's adaptive capacity.

3.4. Standardization of Evaluation Indicators

The indicators used for assessing ecological environmental vulnerability encompass various aspects and originate from diverse data sources. However, the dimensions of these evaluation indicators are not uniform, leading to a lack of comparability. Even for the same parameter, although it is possible to assess the degree of impact on ecological environmental vulnerability based on their actual values, the absence of a comparable environmental standard makes it challenging to accurately reflect their influence on the ecological environment. Therefore, before conducting a comprehensive evaluation, it is essential to standardize the evaluation indicators to eliminate the impact of differing dimensions.

Due to the varying sources and statistical departments of the selected indicators, a single standardization method cannot be applied; instead, each evaluation indicator requires separate standardization procedures. The indicators chosen for this study can be categorized into three types: positive indicators, negative indicators, and moderate indicators. Moderate indicators refer to those that do not have a positive or negative impact on ecological environmental vulnerability but instead represent the optimal level of vulnerability within a specific range. This category of evaluation indicators primarily undergoes interval statistics using interval statistical methods, followed by standardization based on previous research findings [14,20,36]. The specific standardization methods for the other two categories of indicators are as follows:

1. Standardization of Positive Indicators

Positive indicators refer to evaluation metrics where larger values indicate lower ecological environmental vulnerability and higher adaptive capacity. For such indicators, the following formula is used for standardization:

$$X_i' = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \times 100 \quad (1)$$

2. Standardization of Negative Indicators

Negative indicators refer to evaluation metrics where larger values indicate greater ecological pressure and, consequently, higher ecological vulnerability. For such indicators, the following formula is used for standardization:

$$X_i' = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \times 100 \quad (2)$$

where X_i' is the converted dimensionless value of indicator i; X_i is the original value of indicator i before normalization; $X_{\max}$ is the maximum value of indicator i in the region; and $X_{\min}$ is the minimum value of indicator i in the region.

3.5. Calculation of Indicator Weights

When conducting an ecological vulnerability assessment, the calculation of weights for various indicator factors is crucial to the evaluation process and its results. Accurately determining these weights ensures that each indicator appropriately reflects its significance in assessing ecosystem vulnerability. Currently, methods for calculating and assigning weights can be broadly categorized into two types: subjective weighting and objective weighting methods. Among the subjective methods, the Analytic Hierarchy Process (AHP) is widely used due to its effectiveness in handling evaluations involving numerous indicator factors through relatively straightforward computational procedures. The AHP method involves structuring a hierarchy that includes the overall goal, criteria, and sub-criteria, followed by pairwise comparisons of indicators within each criterion to establish their relative importance. Experts assign numerical values based on a predefined scale to indicate the degree of preference between each pair of indicators. These comparisons are organized into a judgment matrix, from which the principal eigenvalue and corresponding eigenvector are calculated to derive the weights for each indicator. A consistency ratio (CR) is then computed to ensure the reliability of the pairwise comparisons; if the CR is below a certain threshold (commonly 0.1), the judgments are considered consistent. Despite its effectiveness, the AHP approach is susceptible to subjective influences, as the weights are heavily reliant on expert judgments and perceptions [11,36].

To mitigate the subjectivity inherent in the AHP method, the entropy value method is employed as an objective weighting technique. This method primarily reflects the degree of variability or dispersion among the indicator factors, providing an unbiased determination of weights based on the inherent information within the data. First, the raw data for each indicator are standardized using Equations (1) and (2) to ensure comparability among different indicators. Second, for each standardized indicator, the proportion of each data point relative to the total is calculated, forming a proportion matrix $P = [P_{ij}]$, where P_{ij} represents the proportion of the j-th data point of the i-th indicator. Then, Equation (3) is used to calculate the entropy value for each indicator. Next, the degree of divergence for each indicator is obtained by subtracting the entropy value from 1 (Equation (4)). Finally, the degree of divergence for each indicator is normalized using Equation (5) to determine the weight of each indicator. The entropy value method objectively determines weights based on the variability of the data, free from subjective biases, and thus effectively captures the intrinsic information and the relationship among indicator factors.

$$E_j = -k\sum_{i=1}^{n} P_{ij}\ln(p_{ij}) \tag{3}$$

where $k = \frac{1}{\ln(n)}$ is a constant to ensure that E_j ranges between 0 and 1.

$$d_j = 1 - E_j \tag{4}$$

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \tag{5}$$

where m is the total number of indicators.

To leverage the strengths of both subjective and objective weighting methods, this study employs a combined approach, integrating the weights derived from the AHP and entropy value methods. This hybrid method capitalizes on the complementary advantages of subjectivity (expert knowledge) and objectivity (data-driven insights), resulting in a more balanced and robust weighting scheme.

The combined weight W_j for each indicator is calculated using the following formula:

$$Wj = \mu \cdot W_j^{AHP} + (1-\mu) \cdot W_j^{Entropy} \tag{6}$$

where

W_j^{AHP} is the weight obtained from the AHP method.

$W_j^{Entropy}$ is the weight obtained from the entropy value method.

μ is the preference coefficient, set to 0.5 in this study to equally emphasize both methods.

This approach ensures that the final weights encapsulate both expert judgments and objective data characteristics, enhancing the reliability and validity of the ecological vulnerability assessment [70]. The resulting weights for the ecological vulnerability factors of the Yunnan section of the Tropic of Cancer are presented in (Table 2).

Table 2. Weights of ecological vulnerability evaluation index system of Yunnan section of Tropic of Cancer. * Represents disaggregated indicators.

Goal Level	Criterion Level	Indicator Level	Indicator Orientation	Hierarchical Analysis Weights	Entropy Weighting	Combined Weights
Assessment of Ecosystem Vulnerability in the Yunnan Section of the Tropic of Cancer	Exposure Index (EI) 0.3157	Percentage of built-up land area (E01)	–	0.1101	0.1313	0.1207
		Road network density (E02)	–	0.0952	0.0635	0.0794
		GDP per capita (E03)	+	0.0951	0.1109	0.1030
		Population density (E04)	–	0.0853	0.1128	0.0991
		Area of cultivated land on >25° slope (E05)	–	0.1201	0.0649	0.0925
		Distance to mining surface (E06)	–	0.1325	0.0421	0.0873
		Power generation (E07)	–	0.0857	0.0319	0.0588
		Mining scale (E08)	–	0.1025	0.1473	0.1249
		Annual rainfall (E09)	+	0.0312	0.0137	0.0225
		Annual average temperature (E10)	+	0.0127	0.0109	0.0118
		Land use type (E11)	+	0.0102	0.0571	0.0337
		Density of settlements (E12)	–	0.0902	0.1209	0.1056
		Area of forest and grassland damaged by the mine (E13)	–	0.0292	0.0927	0.0610
	Sensitivity Index (SI) 0.3319	Geologic hazard density (S01)	–	0.1322	0.1039	0.1181
		Distance to geologic formations (S02)	–	0.1103	0.0912	0.1008
		Stratigraphic lithology type (S03)	*	0.1508	0.0881	0.1195
		Elevation (S04)	*	0.0152	0.1566	0.0859
		Slope direction (S05)	*	0.0206	0.0397	0.0302
		Slope gradient (S06)	–	0.0315	0.1058	0.0687
		Biological abundance index (S07)	+	0.1121	0.1132	0.1127
		Soil type (S08)	*	0.1008	0.0996	0.1002
		Soil erosion type (S09)	–	0.1433	0.1026	0.1230
		Vegetation cover index (S10)	–	0.1832	0.0993	0.1413
	Adaptive Capacity Index (ACI) 0.3524	Public budget expenditures (A01)	+	0.0792	0.0813	0.0803
		Years of mine service (A02)	–	0.0846	0.0998	0.0922
		Per capita disposable income (A03)	+	0.0656	0.0729	0.0693
		Area of forest and grassland (A04)	+	0.0921	0.0756	0.0839
		Cultivated land area per capita (A05)	+	0.0638	0.0711	0.0675
		Green coverage rate (A06)	+	0.1205	0.1133	0.1169
		Residents' year-end deposits (A07)	+	0.0618	0.0804	0.0711
		Growth rate of fixed asset investment (A08)	–	0.0794	0.0811	0.0803
		Utilizable water resources (A09)	+	0.1218	0.1107	0.1163
		Environmental capacity (A10)	+	0.1165	0.1037	0.1101
		Amount of land resources (A11)	+	0.1147	0.1101	0.1124

3.6. Ecosystem Vulnerability Assessment

Ecosystem vulnerability is the result of the integrated effect of multiple factors throughout the whole ecosystem. According to the characteristics of its own influencing factors, and through the comprehensive analysis of the existing research results on the evaluation of ecosystem vulnerability, this paper selected the integrated weighted summation model and the integrated index method based on the ArcGIS 10.8.1 software platform's raster calculator and the superposition analysis function to evaluate the ecosystem exposure degree of the Yunnan section of the Tropic of Cancer, sensitivity and adaptive capacity, and then cited the ecosystem vulnerability model constructed by previous scholars to evaluate the vulnerability of ecosystems in the study area, in order to better show the functional relationship between ecosystem exposure, sensitivity and adaptive capacity [7,36]. The calculation formula is as follows:

1. Comprehensive Weighted Sum Model

Ecosystem vulnerability is a comprehensive decision-making system affected by multi-objective factors. Combining regional characteristics and the degree of data availability, ecosystem vulnerability was decomposed into three dimensions: ecosystem exposure, ecosystem sensitivity, and ecosystem adaptive capacity, and then the corresponding evaluation index factors were selected, and the comprehensive weighted summation model was used to calculate exposure (*EI*), sensitivity (*SI*), and adaptive capacity (*ACI*) indices, respectively. (*EI*), sensitivity (*SI*) and adaptive capacity (*ACI*) indices were calculated using a comprehensive weighted summing model, and are presented as follows:

$$EI = \sum_{i=1}^{n} W_{ij} X_{ij} \tag{7}$$

$$SI = \sum_{i=1}^{n} W_{ij} X_{ij} \tag{8}$$

$$ACI = \sum_{i=1}^{n} W_{ij} X_{ij} \tag{9}$$

where EI is the ecosystem exposure index, SI is the ecosystem sensitivity index, ACI is the ecosystem resilience index, W_{ij} denotes the weight of the jth indicator factor, X_{ij} denotes the value of the jth indicator factor after normalization, and n denotes the number of indicators.

2. Vulnerability Model

To comprehensively explore and analyze the internal functional relationships among ecosystem exposure, sensitivity, and adaptive capacity, we employed an ecosystem vulnerability model based on existing research findings. This model integrates the three key dimensions—exposure, sensitivity, and adaptive capacity—to evaluate the overall vulnerability of ecosystems. Specifically, higher values of ecosystem exposure (*EI*) and sensitivity (*SI*) are associated with lower ecosystem vulnerability, whereas higher values of ecosystem adaptive capacity index (*ACI*) indicate greater ecosystem resilience and thus lower vulnerability. Conversely, lower adaptive capacity increases ecosystem vulnerability [1,6,20]. The ecosystem vulnerability index (*VI*) is calculated using the following formula:

$$VI = EI \times \frac{SI}{ACI^2} \tag{10}$$

where VI is the ecosystem vulnerability index, EI is the ecosystem exposure index, SI is the ecosystem sensitivity index, ACI is the ecosystem adaptive capacity index, and higher ecosystem exposure (*EI*) and sensitivity (*SI*) values are associated with higher ecosystem vulnerability.

The squaring of the *ACI* in the denominator emphasizes the diminishing returns of adaptive capacity in reducing vulnerability. This adjustment ensures that variations in adaptive capacity have a more pronounced effect on the vulnerability index, thereby enhancing the model's sensitivity to changes in adaptive capacity.

3.7. Results Grading and Spatial Autocorrelation

According to the ecological vulnerability evaluation index system and ecological vulnerability calculation formula of the Yunnan section of the Tropic of Cancer, the data layers after the rasterization of all the evaluation indexes were calculated in ArcGIS software platform, and the spatial distribution characteristics of the ecosystem exposure index, the ecosystem sensitivity index, the ecosystem adaptive capacity index, and the ecosystem vulnerability index of the Yunnan section of the Tropic of Cancer were obtained, respectively. The ecosystem exposure index of the Yunnan section of the Tropic of Cancer ranged from 0.30 to 0.66, the ecosystem sensitivity index ranged from 0.28 to 0.77, the ecosystem resilience index ranged from 0.24 to 0.86, and the ecosystem vulnerability index ranged from 0.36 to 0.66. Then, the Natural Breaks (Jenks) method in ArcGIS software was applied to classify the exposure and sensitivity index values. Areas with index values between 0.24 and 0.41 were classified as the lowest-vulnerability zones, values between 0.42 and 0.46 were classified as moderately low-vulnerability zones, values between 0.47 and 0.51 were classified as moderate-vulnerability zones, values between 0.52 and 0.56 were classified moderately high-vulnerability zones, and values between 0.57 and 0.86 were classified as the highest-vulnerability zones. In contrast, for ecosystem adaptive capacity, the higher the adaptive capacity, the lower the vulnerability. This process resulted in the distribution map of ecosystem vulnerability in the Yunnan section of the Tropic of Cancer.

In order to explore the spatial distribution characteristics of ecological vulnerability and its heterogeneity in the Yunnan section of the Tropic of Cancer, this study was based on the global spatial autocorrelation analysis tool of the ArcGIS software, which was used to carry out spatial autocorrelation analysis on the ecological vulnerability evaluation results of the Yunnan section of the Tropic of Cancer, to calculate the global Moran's I index, the Z-value and the p-value of the regional ecological vulnerability, and to organize the global spatial autocorrelation distribution pattern of the regional ecological vulnerability.

4. Results and Analysis

4.1. Results of Ecosystem Vulnerability Assessment

Based on the spatial distribution map of ecological vulnerability of the Yunnan section of the Tropic of Cancer (Figure 3), combined with the spatial statistical analysis function of ArcGIS software, the administrative boundaries of the 17 counties in the study area were superimposed and analyzed through the area tabulation tool. The area status and spatial distribution characteristics of ecological vulnerability in each county were counted, and the main spatial distribution characteristics of ecological vulnerability in the Yunnan section of the Tropic of Cancer were obtained.

Lowest-vulnerability zone: The ecological lowest-vulnerability area of the Yunnan section of the Tropic of Cancer accounted for 13.99% of the total area of the study area, amounting to 7839.07 km^2, and it was mainly distributed in the whole of Yanshan County, the area outside of the central part of Wenshan City, the southern and eastern parts of Jinggu County, and the southern part of Mengzi City. These areas are mostly distributed in areas with high vegetation cover, abundant water and gas resources, and low construction indexes, and have not suffered too much external environmental damage and human interference, so the original ecological environment is well protected and maintained, and there are few geologic disasters occurring at the same time.

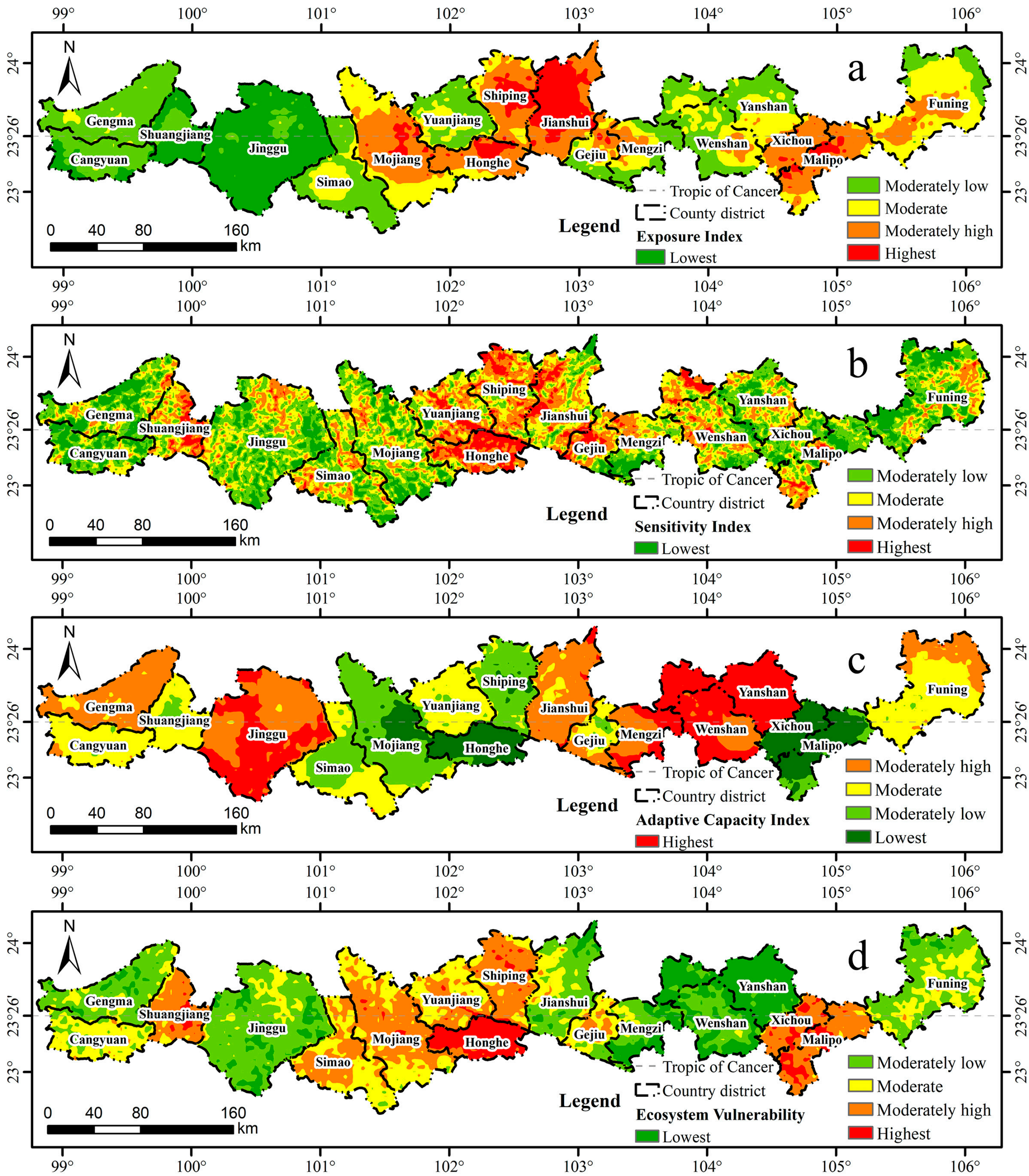

Figure 3. Spatial distribution map of ecological vulnerability assessment in Yunnan section of the Tropic of Cancer (**a**) Exposure index, (**b**) sensitivity index, (**c**) adaptive capacity index, (**d**) ecosystem vulnerability).

Moderately low-vulnerability zone: The moderately low-vulnerability area was the one with the largest area share of the five ecological fragile types, occupying 30.99% of the total area of the study area, with an area of 17,366.53 km^2, and was mainly distributed in the whole of Jinggu County, outside the central part of Funing County, and in the southern and eastern parts of Gengma County and Jianshui County. Compared with the lowest-vulnerability area, there were a small amount of man-made mining phenomena such as farming and mineral resources mining areas in the moderately low ecological vulnerability area. Due to the farming and mineral resources mining for the vegetation cover and forest resources have caused some damage, which led to a certain amount of soil erosion phenomenon under the effect of rainfall.

Moderate vulnerability zone: The moderate-vulnerability area covered an area of 13,887.24 km^2, accounting for 24.79% of the total area of the study area, and was mainly distributed in the northern and southern parts of Mojiang County, the central part of Funing County, the northern and southern parts of Ning'er County, and Cangyuan and Yuanjiang Counties. In the study area, 80% of the exposed bedrock was dominated by limestone, and the karst phenomenon, desertification and desertification were more serious in the areas where limestone was developed, and the moderately vulnerable areas were mainly distributed in the mountainous areas where the phenomenon of rocky desertification was serious, and the terrain in these areas was steeper and the vegetation coverage was lower, and the soil erosion was extremely serious under the erosion and weathering of the rainfall in the long term.

Moderately high-vulnerability zone: The moderately high-vulnerability areas were mainly located in the central part of Mojiang County, Shiping County, central part of Ning'er County, Malipo County and Shuangjiang County, accounting for 23.85% of the total area of the study area, comprising an area of 13,363.40 km^2. The moderately high-vulnerability areas were mainly located in the periphery of the cities of the counties, the township centers with a high density of buildings and the areas with frequent human engineering activities, where soil erosion, soil sanding, and rock desertification are common. Soil erosion, soil sanding, and rock desertification are common in these areas, and frequent human engineering activities have caused a certain number of geologic disasters, destroying the stability and shape of the original land surface.

Highest-vulnerability zone: The overall ecological vulnerability of the study area was low, so the highest-vulnerability area was the smallest, only accounting for 6.38% of the total area of the study area, 3574.06 km^2; Honghe County occupies 51.82%, with the majority of the rest being distributed across the central and southern areas of of Ma Lipo County, the middle of Xichou County, the east of Shuangjiang County, and the middle of Shiping County. The main influencing factors for high-vulnerability areas in the ecological environment include mineral resource extraction, engineering geological activities, human cultivation of land, and soil erosion. The highest-vulnerability areas were primarily located on both sides of newly constructed roads within the past three years and within the range of mineral resource extraction zones. Extensive and high-intensity extraction and construction activities led to the loss of the original mechanical stability of the surface bedrock, which in turn triggered a series of disasters that increased the vulnerability of the ecological environment.

4.2. Spatial Autocorrelation Analysis

The results showed that the global Moran's I index of regional ecological vulnerability of the Yunnan section of the Tropic of Cancer (Figure 4) was positive and greater than 0.9, indicating that the regional ecological vulnerability of the study area had a high degree of positive correlation in the spatial distribution characteristics. The highest-vulnerability areas had a significant impact on the stability of the surrounding ecological environment, and also led to an increase in the ecological vulnerability of the surrounding areas, while areas with lower ecological vulnerability had a positive impact on the surrounding areas. The Z-score was greater than 303, which was much higher than the reference value of 2.58, which further verified that the regional ecological vulnerability was highly aggregated in the spatial distribution pattern. Without the intervention of external management factors, the spatial distribution of the highly vulnerable areas will continue to expand over time, and it is difficult to rely on the ecosystem's own restoration capacity to achieve a high degree of restoration and have a sustained impact on the neighboring areas. In addition, the *p*-value of ecological vulnerability of the Yunnan section of the Tropic of Cancer was 0, which was smaller than the reference value of 0.01, reflecting that the confidence level of the ecological vulnerability evaluation results was higher than 99%, indicating that the probability of random generation was less than 1%. These results not only reflect the precision and credibility of the evaluation results, but also confirm that the regional ecological vulnerability has obvious spatial clustering characteristics, which is consistent with the reality.

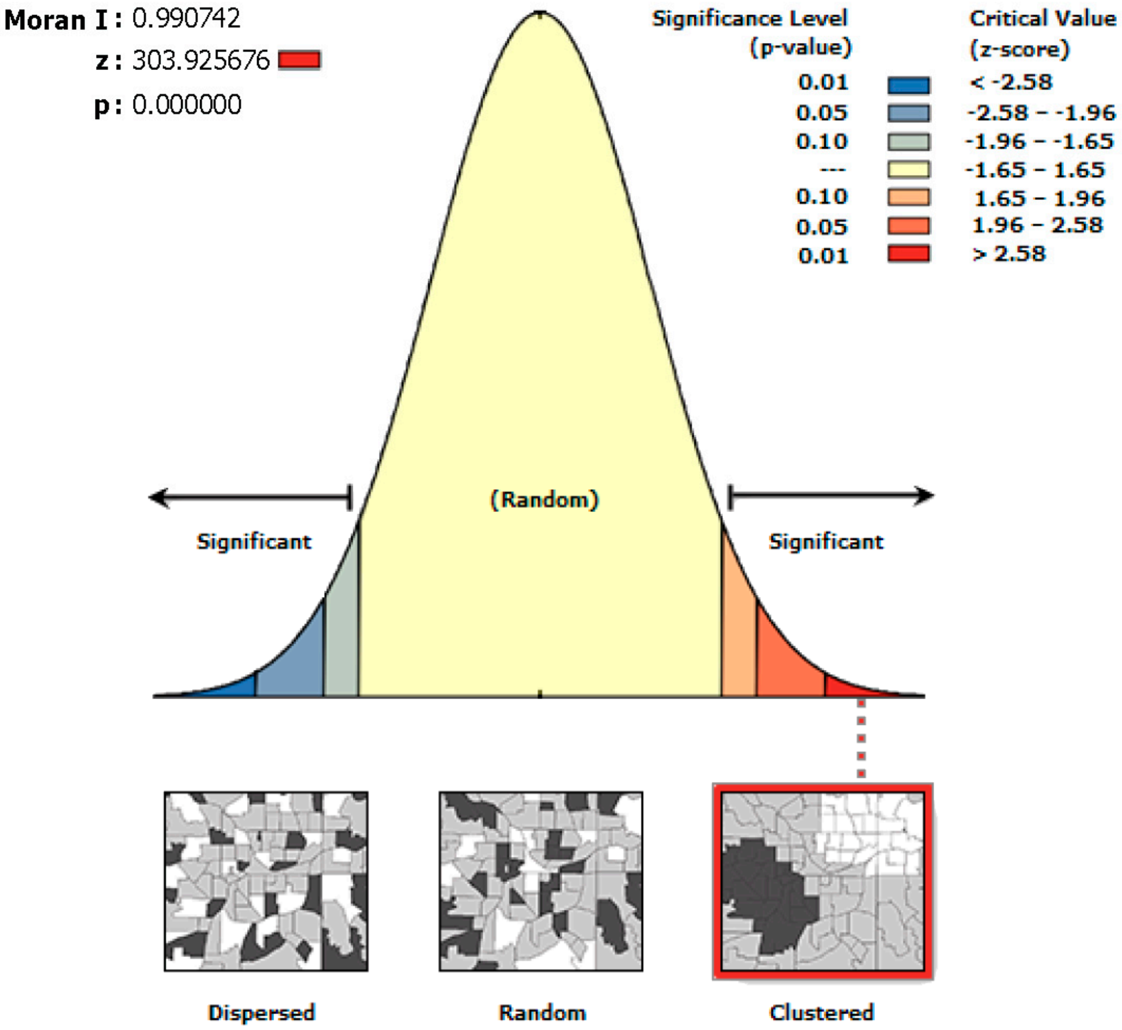

Figure 4. Spatial autocorrelation characteristics of regional ecological vulnerability of the Yunnan section of the Tropic of Cancer.

By analyzing the results of the ecosystem vulnerability assessment along the Yunnan section of the Tropic of Cancer, it is found that there are obvious differences in the spatial distribution of vulnerability in the region. Overall, the areas with higher exposure are mainly concentrated in areas with intensive economic activities, high population density, and high land use intensity, such as the periphery of major cities and along the main transportation routes. This indicates that human activities are exerting significant pressure on the ecosystem, especially in areas where infrastructure is being built and agriculture and livestock are expanding. In addition, climate change also significantly affects exposure, especially in areas with uneven precipitation distribution.

In terms of sensitivity, areas with low vegetation cover and serious soil erosion show higher vulnerability. Geohazard-prone areas, especially counties and districts located in mountains and river valleys, are significantly more sensitive due to both geological and climatic conditions. Reduction in vegetation cover and soil erosion are the main factors leading to increased vulnerability of ecosystems in these areas.

The regions with relatively low adaptive capacity are mainly concentrated in counties and districts with insufficient economic inputs, limited land resources and low environmental carrying capacity. The lack of adequate financial support and infrastructure development in these areas makes them less able to adapt in the face of environmental change and ecosystem degradation. Therefore, increasing economic investment and improving resource management in these areas is the key to enhancing their adaptive capacity.

Overall, the results show that regions with high exposure and sensitivity tend to have weaker adaptive capacity, which exacerbates the vulnerability of ecosystems. Therefore, these highly vulnerable areas should be prioritized for regional ecological conservation and targeted conservation and restoration measures should be implemented.

5. Discussion

5.1. Analysis of Technical Methods

In this study, a comprehensive ecosystem vulnerability assessment framework was constructed by using the VSD model combined with GIS technology, and the practice proved the efficiency and applicability of this method in regional ecological assessment. The introduction of GIS technology, and exploration of its advantages in spatial analysis and data integration, enables us to realize multidimensional and multi-scale vulnerability assessment, which not only improves the accuracy of the assessment, but also intuitively demonstrates the spatial distribution characteristics. Recent studies have highlighted the superiority of integrated models like VSD-GIS over traditional methods, noting their enhanced ability to capture complex spatial patterns and interactions within ecosystems [71,72]. Compared with the traditional single-factor assessment, this study provides a comprehensive understanding of the vulnerability of regional ecosystems by integrating the three dimensions of exposure, sensitivity, and adaptive capacity.

In the exposure assessment, the study specifically considered mining activities and the area of damaged forests and grasslands, an innovation that is consistent with the ecological context of the region and provides a more targeted assessment basis for this type of human-intensive area. Mining not only has a direct impact on land use, but also may increase the vulnerability of ecosystems, and this integrated consideration of the scale of mining activities and their impact on vulnerability has strong practical and theoretical value in the field of ecological assessment [49]. Furthermore, incorporating specific human activities like mining aligns with recent advancements in vulnerability assessments, which advocate for context-specific indicators to improve the relevance and accuracy of evaluations [73].

In terms of sensitivity, this study added factors such as geological disasters and soil erosion to the indicator system, which made up for the lack of attention to environmental sensitivity in previous studies by refining the impact of these natural disasters on ecosystem stability. This approach is supported by the findings of Martinez and Gonzalez [74], who emphasized the importance of including geophysical factors to enhance the sensitivity analysis in vulnerability assessments. In the assessment of adaptive capacity, we comprehensively considered indicators such as mine service life, greening coverage, and environmental capacity, which not only improved the model's ability to assess the adaptive capacity of regional economic activities, but also provided an important basis for future ecological restoration and management decisions [1]. Integrating socio-economic indicators, as shown in this study, has been shown to provide a more holistic view of adaptive capacity, aligning with recommendations from recent literature [75].

Overall, the technical approach of this study demonstrates promising feasibility and versatility, suggesting potential applicability to other ecological vulnerability assessment projects. Comparative analyses in the literature indicate that frameworks combining VSD with GIS can offer greater flexibility and precision in diverse ecological contexts compared to isolated methodologies [76,77]. In this study, our data processing flow and model selection process illustrate a method for constructing an assessment framework tailored to regional characteristics through the integrated analysis of multi-source data. This integrated approach aligns with contemporary best practices, which advocate for the use of multi-source data to enhance the robustness and applicability of vulnerability assessments [78,79]. However, it is important to note that while these findings are encouraging, further validation is necessary to establish the generalizability and effectiveness of this framework across different ecological settings.

5.2. Comparative Analysis of Results

In order to further verify the reliability of the results of this study, we compared it with other similar studies and ecological vulnerability studies on the Yunnan section of the Tropic of Cancer region. Overall, this study was significantly different from previous studies, especially with regard to its fine-grained assessment of exposure, sensitivity, and adaptive capacity.

By comparing with the study of Yajun and Lifang [28], this study included more indicators directly related to human activities in the exposure assessment, such as mining activities and damaged forest and grassland areas. The introduction of these indicators made our assessment results more precise in revealing the impacts of human activities on ecological vulnerability, especially in areas with intensive human activities, where the effects of these factors were particularly significant.

In addition, compared with the study by He, Shen and Zhang [61], we focused more on the impacts of geohazards, soil erosion, and biological abundance in the sensitivity assessment. This adjustment not only improved the applicability of the model, but also strengthened the reflection of the impacts of regional natural hazards, making the assessment results more realistic. For example, the weights of vegetation cover and soil type were increased in this study, highlighting the role of these natural elements in regulating ecological vulnerability.

In terms of adaptive capacity, new socio-economic indicators such as mine service life, greening coverage, and environmental capacity were introduced in this study, which made up for the lack of attention to economic adaptive capacity in previous studies, especially in the assessment of economic investment in rural areas, providing a more comprehensive perspective. This not only enhanced the comprehensiveness of the assessment, but also highlighted the influence of economic factors on ecological resilience.

We also compared our results with those of Hui Ye et al. [53], and this study further refined the impacts of human activities on ecosystem vulnerability, especially in terms of mineral resource extraction and environmental capacity, which made our findings more relevant and valuable for application in the assessment of regional ecological vulnerability.

These comparative analyses suggest that this study offers unique contributions in terms of the assessment framework, indicator selection, and interpretation of results. The initial findings support the accuracy and scientific validity of our approach, indicating potential new perspectives and methodological innovations in the field. However, additional validation is needed to fully confirm these results.

5.3. Limitations and Future Prospects

Although this study has improved the science and applicability of ecological vulnerability assessment by introducing a multidimensional indicator system, there are still some shortcomings. First, due to the complexity of the ecosystems in the study area, the precision and timeliness of the data affected the accuracy of the assessment results to some extent. For example, indicators such as land use and population density in the exposure are not fully represented in the time dynamic changes. In addition, long-term factors such as climate change are not fully integrated into the sensitivity and adaptive capacity assessment; in particular, the impacts of microclimate changes on regional ecosystems are not fully reflected. This limits the model's ability to simulate complex ecological processes, resulting in some local ecological features not being fully captured [38].

Secondly, the model is more reliant on macro data during the assessment of adaptive capacity and lacks sufficient field research and validation, especially in the ecosystem resilience of mining and rural areas, which is not supported by dynamic data at the micro level. Therefore, future research should focus on improving the timeliness and accuracy of data, and increasing the frequency and depth of field research, especially in regions with frequent human activities and significant climate change. Meanwhile, interdisciplinary cooperative research will be an important direction to enhance the capacity of ecological vulnerability assessment in the future. By combining more socio-economic and climate change factors, the vulnerability assessment system can be further improved to provide a more comprehensive and accurate scientific basis for the sustainable development of regional ecological environment.

In conclusion, this study innovatively describes the impacts of mining, human activities, and natural disasters on the vulnerability of ecosystems in the Yunnan section of the Tropic of Cancer by comprehensively considering multidimensional factors, which provides new ideas and methods for ecosystem vulnerability assessment. However, future research still needs to be further strengthened in terms of data accuracy, model optimization, and interdisciplinary collaboration to achieve more timely and accurate assessment results.

5.4. Recommendations

To address the ecosystem vulnerability in the Yunnan section of the Tropic of Cancer, targeted policy measures are proposed based on the specific characteristics of vulnerability zones.

(1) In the lowest-vulnerability zone, covering areas such as Yanshan County, the outskirts of Wenshan City, southern Jinggu County, and southern Mengzi City, efforts should focus on vegetation restoration projects like reforestation and grassland rehabilitation to enhance ecological resilience and safeguard water and gas resources. In the moderately low-vulnerability zone, which includes Jinggu County, the outskirts of Funing County, and southern Gengma and Jianshui Counties, measures such as soil erosion control and sustainable land management should be implemented to mitigate the impacts of agriculture and mining on vegetation and soil stability.

(2) In the moderate-vulnerability zone, spanning northern and southern Mojiang, central Funing, Ning'er, Cangyuan, and Yuanjiang Counties, land use planning should prioritize strict zoning regulations to limit construction and mining activities in erosion-prone karst areas. Similarly, in the moderately high-vulnerability zone, covering central Mojiang, Shiping, Ning'er, Malipo, and Shuangjiang Counties, urban development should adopt sustainable practices to minimize soil erosion and desertification while restricting high-density building projects in vulnerable areas.

(3) To improve adaptive capacity, the moderately high-vulnerability zone should receive increased funding for ecological infrastructure and community education programs

to raise awareness of ecological protection and encourage sustainable practices. In the highest-vulnerability zone, which includes Honghe, Malipo, Xichou, eastern Shuangjiang, and Shiping Counties, advanced ecological protection measures, such as disaster-resistant land management and erosion control systems, should be implemented. Public awareness initiatives should also address the risks associated with resource extraction and unsustainable land practices.

These recommendations, tailored to the unique conditions of each vulnerability zone, aim to strengthen ecological protection, optimize land use, and enhance adaptive capacity. By balancing ecological sustainability with economic development, these measures provide a solid foundation for the long-term resilience of ecosystems in the region. Regular monitoring and evaluation will ensure the effectiveness of these policies and support ongoing improvements.

6. Conclusions

In this study, based on the technical guidelines for dual evaluation of territorial spatial planning, we evaluated the vulnerability of ecosystems in the Yunnan section of the Tropic of Cancer from an ecological point of view and constructed an evaluation index system by selecting the evaluation index factors that have a greater impact on the ecological environment based on the three aspects of exposure, sensitivity, and adaptive capacity in conjunction with the GIS technology, and came to the following main conclusions:

1. The spatial distribution of ecosystem vulnerability exhibited significant regional differences. Through the assessment of ecosystem vulnerability in the Yunnan section of the Tropic of Cancer, the results indicated that the ecological vulnerability in this area showed significant spatial distribution differences. Regions with high exposure concentrated in areas with frequent human activities, such as counties with high population density and dense road networks, while regions with high sensitivity mainly existed in mountainous and valley areas with low vegetation coverage and severe soil erosion.
2. Exposure, sensitivity, and adaptive capacity jointly influenced ecological vulnerability. This study assessed ecological vulnerability through the dimensions of exposure, sensitivity, and adaptive capacity, and found that these factors collectively determined the vulnerability level of the regional ecosystem. Exposure and sensitivity were the primary factors leading to ecosystem vulnerability, while the level of adaptive capacity determined the region's ability to withstand and recover from ecological pressures.
3. Regions with strong adaptive capacity exhibited relatively low ecological vulnerability. Counties with stronger adaptive capacity, such as those with higher economic investment and better environmental carrying capacity, showed lower ecological vulnerability. These areas were capable of effectively reducing the negative impacts of ecological pressures on the system due to their better resource utilization and management capabilities, thereby enhancing the stability and resilience of the ecosystem.
4. Future climate change and human activities were expected to further exacerbate ecological vulnerability. The research results indicated that as climate change intensified and human activities continued to increase, the ecosystem in the Yunnan section of the Tropic of Cancer faced greater challenges, particularly in areas with high exposure. Therefore, it is particularly important to enhance the adaptive capacity of these regions and implement targeted ecological protection measures.

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