Remote Sensing Assessment of Ecosystem Vulnerability in Southwest China Karst Mountainous Areas under Extreme Climate Stress: Postprint

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Abstract

Global warming has led to the frequent occurrence of extreme weather events. In response to the special geographical conditions of the karst mountainous areas in Southwest China (severe soil erosion and rocky desertification), large-scale landscape pattern indices (Shannon' s evenness index and contagion index) and extreme climate indices (extreme high temperature days, extreme low temperature days, and extreme precipitation days) were introduced to construct a remote sensing evaluation system for ecosystem vulnerability. Subsequently, the spatiotemporal variation patterns and driving mechanisms of ecosystem vulnerability in this region over the past 13 years were analyzed and discussed. The research results indicate that the ecosystems in the karst mountainous areas of Southwest China exhibit light-to-moderate vulnerability, with a distribution pattern showing a decreasing trend from the Sichuan-Yunnan-Guizhou core area to the surrounding regions. From 2000 to 2013, ecosystem vulnerability in the karst mountainous areas of Southwest China showed a trend of first increasing and then decreasing. The spatiotemporal variation patterns of ecosystem vulnerability in the karst mountainous areas of Southwest China over the past 13 years were significantly influenced by human activities (GDP of different industries and population density), precipitation, topography and landforms, soil erosion, rocky desertification, and other factors. This study can provide a decision-making basis and technical support for ecosystem conservation and ecological environment restoration and management in the karst mountainous areas of Southwest China.

Full Text

Preamble

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Remote Sensing Assessment of Ecosystem Vulnerability in Southwestern Karst Mountain Areas Under Extreme Climate Stress

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Abstract

Global warming has led to increasingly frequent extreme weather events in recent decades. This study introduces large-scale landscape pattern indices (Shannon uniformity index and contagion index) and extreme climate indices (extreme high/low temperature days and extreme precipitation days) to establish a remote sensing-based evaluation system for ecosystem vulnerability, considering the unique geographical conditions of southwestern karst mountain areas—particularly severe soil erosion and rocky desertification. The spatial and temporal patterns of ecosystem vulnerability over the past 13 years (2000–2013) were subsequently analyzed and discussed. Results indicate that ecosystem vulnerability in the karst mountain region belongs to the mild-moderate level, decreasing from the Sichuan–Yunnan–Guizhou core zone toward surrounding areas. Severe and extremely vulnerable zones are mainly distributed in central and northern regions due to severe rocky desertification, low vegetation coverage, and intensive human disturbance. Conversely, slight and mild vulnerable zones are predominantly found in southeastern and southwestern areas, benefiting from high vegetation coverage, abundant precipitation, and lower levels of human disturbance. From 2000 to 2013, ecosystem vulnerability in the southwestern karst mountain areas initially increased then decreased. The spatial and temporal patterns of vulnerability changes were significantly influenced by human activities (industrial GDP and population density), precipitation, topography, soil erosion, and rocky desertification. This research provides a decision-making foundation and technical support for ecosystem protection and ecological environment restoration and management in the karst mountain regions of southwestern China.

Keywords: ecosystem vulnerability; dynamic monitoring; remote sensing; southwestern karst mountain area; extreme climate

Introduction

Global climate warming has intensified in recent years, causing significant changes in the global ecological environment, frequent extreme weather events, biodiversity loss, and sea-level rise, which pose severe threats to human survival and sustainable socioeconomic development. Ecosystem vulnerability research serves as an important analytical tool in global environmental change and sustainability science, attracting attention from international scientific programs and organizations such as the International Human Dimensions Programme (IHDP), Intergovernmental Panel on Climate Change (IPCC), and International Geosphere-Biosphere Programme (IGBP). The spatial and temporal heterogeneity of ecosystem vulnerability is a major cause of unbalanced economic development and wealth disparity, significantly affecting social harmony in China. Conducting ecosystem vulnerability assessments to analyze formation mechanisms and driving factors is essential for maintaining ecosystem integrity and achieving harmonious development between humans and nature, representing an inevitable requirement for implementing scientific development concepts, establishing ecological civilization, and promoting sustainable socioeconomic development.

Southwest China' s karst mountain region is a typical ecologically fragile area, characterized by widespread karst landforms, frequent geological disasters, complex terrain, and concentrated populations of ethnic minorities. Sharp human-land contradictions and long-term unordered resource exploitation have led to increasingly severe soil erosion and vegetation destruction, creating serious rocky desertification that continues to expand. This region hosts over 30 ethnic minorities, whose populations account for more than 50% of the total regional population. With relatively backward overall socioeconomic development, the area concentrates nearly 1/3 of China' s impoverished population, making the demonstration of ecosystem vulnerability particularly significant for ecological protection and scientific development in mountainous regions.

Current domestic scholars have conducted extensive research using various evaluation methods tailored to different regional ecological characteristics. For instance, Liu Zhenqian et al. established a wetland ecosystem vulnerability evaluation index system for the Sanjiang Plain and applied a comprehensive index method for assessment. Yao Jian et al. analyzed spatial distribution patterns of the ecological environment in the upper Minjiang River basin using fuzzy mathematics clustering analysis. Li Pingxing and Fan Jie decomposed vulnerability into sensitivity and adaptability for the Xijiang River Economic Belt in Guangxi, establishing a 20-indicator system covering natural and anthropogenic factors. Li Yangbing et al. evaluated ecological vulnerability in southwestern karst mountainous areas from the perspectives of causal factors, fluctuation vulnerability, interface vulnerability, and substrate vulnerability. Zhang Xiaonan et al. assessed ecological vulnerability in northwestern Guangxi' s karst region using landscape structure information. He Dongxiao analyzed ecological vulnerability in Chongqing' s karst areas, discussing ecological reconstruction technologies. Zhang Dianfa et al. revealed manifestations of fragile ecological environments in Guizhou Province and analyzed causes from atmospheric circulation and socioeconomic pressure perspectives.

However, existing vulnerability evaluation systems vary considerably across different study areas and scales in southwestern mountainous regions, lacking a systematic and standardized framework. With global warming intensifying and extreme climate events becoming more frequent, profound impacts on the ecological environment of southwestern mountainous areas have emerged. This study addresses the special geographical conditions of southwestern karst mountain areas—severe soil erosion and rocky desertification—by introducing large-scale landscape pattern indices and extreme climate indices to construct a comprehensive ecosystem vulnerability evaluation system. The system analyzes spatial-temporal patterns and driving mechanisms of vulnerability over the past 13 years, providing technical references for continued small- and medium-scale vulnerability research in southwestern mountainous regions.

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1. Study Area Overview

The southwestern karst mountain area encompasses Guizhou, Yunnan, Chongqing, and Guangxi. This region exhibits strong landscape heterogeneity, with mountains and plateaus covering over 95% of the total area. The special geological background and intense karst processes result in small ecological capacity and inherently fragile ecological environments. Sharp human-land contradictions, large populations, and long-term unordered resource development have severely constrained ecological protection and sustainable development, causing increasingly serious soil erosion, vegetation destruction, and expanding rocky desertification. The region is home to 30+ ethnic minorities, with minority populations exceeding 50% of the total. Overall socioeconomic development remains relatively backward, with impoverished populations concentrating in this area, which accounts for nearly one-third of China' s total poor population.

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2. Methodology

2.1 Comprehensive Index Method

Current ecological vulnerability research predominantly employs hierarchical weighting evaluation models. This method assigns grades and weights to selected vulnerability factors, with results aggregated for assessment. While suitable for large-scale macro studies and capable of producing reliable results when indicators are scientifically selected, the approach is heavily influenced by subjective classification schemes.

To minimize human interference in indicator classification, this study employs two complementary evaluation models: (1) Level 1 indicators with hierarchical weighting and Level 2 indicators with normalized weighting, and (2) normalized weighting for all indicators. Both models use the identical formula:

$$ESVI = \sum_{i=1}^{n} I_i \times \omega_i$$

where $ESVI$ is the Ecosystem Vulnerability Index, I_i is the ith normalized or graded indicator, ω_i is the weight of the ith indicator, and n is the total number of indicators.

The normalization method is calculated as:

$$I_i = \frac{I - I_{\min}}{I_{\max} - I_{\min}}$$

where I_i is the normalized vulnerability indicator value, I is the original indicator value, $I_{\min}$ is the minimum value, and $I_{\max}$ is the maximum value. Larger normalized values indicate more significant impacts on vulnerability.

2.2 Climate Tendency Rate

The climate trend coefficient primarily reflects the direction and magnitude of long-term trends in climate factors, calculated as the correlation coefficient between a climate factor and the time series 1, 2, 3, ···, n:

$$r_{xt} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(t_i - \bar{t})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(t_i - \bar{t})^2}}$$

where x_i is the climate factor value in year i, $\bar{x}$ is the multi-year average, t_i is the time series value, and $\bar{t} = (n+1)/2$. Larger absolute values of r_{xt} indicate more intense interannual variation.

The linear trend equation for meteorological elements is:

$$\hat{x} = a + bt$$

where b is the climate tendency rate (units per 10 years). According to linear regression theory:

$$b = r_{xt} \frac{\sigma_x}{\sigma_t}$$

where σ_x is the standard deviation of element x and σ_t is the standard deviation of the series 1, 2, ···, n. Thus, the climate tendency rate can be calculated from the trend coefficient.

3. Evaluation Indicators and Data Sources

Based on the ecological characteristics of southwestern karst mountain areas, national main functional area planning implementation schemes, ecological environment status evaluation technical specifications, and ecosystem service function assessment protocols, this study selected indicators from five dimensions: water, climate, vegetation, soil, and human factors, while considering data operability and relevance.

Water factors include water resources quantity and water network density, which provide crucial ecological support functions. Water resources quantity is an inverse indicator in vulnerability assessment. The 1 km grid water resources data were provided by the Ministry of Water Resources, calculated through weighted aggregation of provincial water resources statistics. Water network density, also an inverse indicator, was determined using the percentage area of rivers, glaciers, and snow cover in 1 km grids derived from land use data. Land use remote sensing monitoring datasets (2000, 2005, 2010, 2013) at 1 km resolution were obtained from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, and the National Natural Resources and Geospatial Basic Information Database Project Office.

Vegetation factors comprise Net Primary Productivity (NPP), biological abundance index, and large-scale landscape pattern indices. NPP, obtained from the MOD17A3 product (1 km resolution) via the LAADS website (https://lpdaac.usgs.gov/products), serves as the material basis for human survival and development and is an inverse indicator. The biological abundance index was calculated following the Ministry of Environmental Protection' s biodiversity formula. Large-scale landscape pattern indices (Shannon' s Evenness Index and Contagion Index) were computed using ArcGIS 10.2 and Fragstats 3.4 based on land cover data to reflect landscape morphology and spatial structure impacts on humans and organisms, serving as inverse indicators.

Climate factors were selected against the backdrop of intensifying global warming and increasing extreme climate events. Indicators include average annual precipitation, extreme low temperature days, extreme high temperature days, and extreme precipitation days.

Soil factors address the region’ s severe soil erosion and rocky desertification. Rocky desertification is a unique land degradation phenomenon in humid karst areas, where intensive human activities on fragile geological backgrounds cause large-scale rock exposure, creating desert-like landscapes. Hydraulic erosion refers to soil erosion primarily driven by surface water, causing surface cutting, natural vegetation degradation, biodiversity destruction, and land quality decline. Both are positive indicators in vulnerability assessment.

Human factors constrain regional ecosystem health and include population density, GDP, agricultural population proportion, Engel coefficient, and per capita net income of farmers/herdsmen. Population and GDP grid data (2000, 2005, 2010, 2013) were obtained from the Institute of Remote Sensing and Digital Earth and the National Natural Resources and Geospatial Basic Information Database Project Office, derived from land use remote sensing monitoring and nighttime light data.

[Figure 2: see original paper] shows the ecosystem vulnerability evaluation system framework.

4. Results and Analysis

4.1 Ecosystem Vulnerability Assessment Results Comparison

Referencing the ecological characteristics of southwestern karst mountain areas, ecosystem vulnerability was classified into five levels based on ESVI values: slight (ESVI 3.30), mild (3.30 < ESVI 4.4), moderate (4.4 < ESVI 4.5), severe (4.5 < ESVI 4.7), and extreme (ESVI 4.7). The vulnerability classifications for 2000, 2005, 2010, and 2013 were determined through histogram distribution and standard deviation analysis.

Severe and extremely vulnerable zones are concentrated in central and northern areas, primarily due to intense karst development, low vegetation coverage, severe soil erosion, extensive rock exposure, slow soil formation processes, poor ecosystem self-recovery capacity, low productivity levels, large impoverished populations, weak environmental awareness, and intensive human disturbance. Slight and mild vulnerable zones are mainly distributed in southeastern and southwestern regions, benefiting from abundant precipitation, high vegetation coverage, lower erosion and desertification intensity, and ecological protection measures such as returning farmland to forest.

Comparative analysis of area and percentage across the four periods reveals that from 2000–2005, ecosystem vulnerability in southwestern karst mountain areas intensified, with slight and mild vulnerable areas decreasing while moderate and severe areas increased. From 2005-2010, overall vulnerability remained basically stable with minor local fluctuations. From 2010-2013, the ecosystem vulnerability showed overall stability with local improvements: slight vulnerable areas decreased while severe and extreme vulnerable areas increased.

[Figure 3: see original paper] illustrates the spatial distribution of ecosystem vulnerability in southwestern karst mountain areas.

4.2 Ecosystem Vulnerability Change Intensity Analysis

To further analyze vulnerability changes over the 13-year period, ArcGIS 10.2 raster calculator was used to compute change intensity between periods (2000-2005, 2005-2010, 2010-2013). Change intensity (CI) was classified based on histogram distribution and standard deviation into severe increase zone ($\mathrm{CI} > 1$), moderate increase zone ($0.5 < \mathrm{CI}\ \ 1$), stable zone ($-0.5 < \mathrm{CI}\ \ 0.5$), moderate decrease zone ($-1 < \mathrm{CI}\ \ -0.5$), and severe decrease zone ($\mathrm{CI}\ \ -1$).

From 2000-2005, moderate and severe increase zones were mainly distributed in the northeastern and southwestern parts, while moderate and severe decrease zones concentrated in the northwest. The distribution pattern primarily depended on precipitation, land use structure, and human activities. From 2005-2010, stable zones were most widespread, with severe and moderate decrease zones mainly in the northeast and north. From 2010-2013, ecosystem vulnerability initially increased then decreased. Rocky desertification and human activities—particularly rapid population growth—were the main causes of vulnerability intensification, while ecological protection measures contributed to regional improvement.

[Figure 5: see original paper] shows the change intensity of ecosystem vulnerability.

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5. Discussion

This study analyzed the driving mechanisms of ecosystem vulnerability spatiotemporal changes in southwestern karst mountain areas from perspectives of temperature, precipitation, GDP density of different industries, and population density. Data analysis was conducted in SPSS 17.0 with significance level set at $\ = 0.05$, and charts were produced in Excel.

5.1 Temperature Impact on Ecosystem Vulnerability Change

The temperature climate tendency rate reflects the direction and intensity of temperature change. Correlation analysis between temperature tendency rate and 13-year average vulnerability values (2000, 2005, 2010, 2013) and change intensity reveals that ecosystem vulnerability increases with temperature, though change intensity shows little variation with temperature tendency rate. This is attributed to the region' s tropical and subtropical location with high background temperatures, relatively insignificant temperature increases, abundant precipitation, and complex terrain creating significant mountain climate vertical zonation. Consequently, temperature increases have limited impact on the ecosystem.

[Figure 6: see original paper] shows the correlation between annual average temperature tendency rate and 13-year average vulnerability and change intensity.

5.2 Precipitation Impact on Ecosystem Vulnerability Change

The precipitation climate tendency rate reflects regional precipitation change direction and intensity. Analysis indicates that ecosystem vulnerability increases slightly with precipitation tendency rate, while vulnerability change intensity increases more substantially. This pattern primarily stems from the complex hydrological processes in karst areas. Strong karst development leads to continuous rock weathering under rainwater dissolution, forming sinkholes and underground rivers. With infiltration rates reaching 80%, most precipitation infiltrates underground, making it difficult to utilize. The shallow, loose soil layer has poor water retention capacity, and high gravel content combined with karst conduits and fissures creates high spatial heterogeneity in water movement. Consequently, increased precipitation intensifies soil erosion and rocky desertification processes, exacerbating natural disasters such as flash floods, mountain collapses, and landslides.

[Figure 7: see original paper] illustrates the correlation between precipitation tendency rate and 13-year average vulnerability and change intensity.

5.3 Impact of Different Industries

Socioeconomic conditions encompass broad and complex factors influencing ecosystem status and change. GDP, as a key indicator, reflects regional economic strength and development intensity.

Overall GDP density shows a two-stage correlation with ecosystem vulnerability. When GDP density is below 1700, vulnerability decreases with increasing GDP, indicating that better ecological environments provide more resources for human survival and development. When GDP density exceeds 1700, vulnerability increases with GDP, demonstrating that development intensity exceeds ecological carrying capacity and self-recovery ability.

Primary industry GDP density also exhibits two-stage correlation. Below 130, vulnerability decreases with primary industry growth, as improved ecological conditions provide water resources and vegetation for agriculture and animal husbandry. Above 130, vulnerability increases because intensified development exacerbates soil erosion and rocky desertification, exceeding the fragile karst ecosystem' s low carrying capacity and weak disturbance resistance.

Secondary industry GDP density shows similar patterns. Below 800, vulnerability decreases with growth, while above 800, vulnerability increases significantly. The region’ s rich mineral resources attract extensive surface mining, causing severe landscape destruction, water pollution, and rocky desertification due to backward production methods and low management levels.

Tertiary industry GDP density demonstrates two-stage correlation as well. Below 500, vulnerability decreases with growth, reflecting well-developed infrastructure and service industries in ecologically sound areas. Above 500, vulnerability increases due to excessive tourism development pressure, infrastructure construction, and human activity exceeding ecological carrying capacity.

[Figure 8: see original paper] shows the correlation between 13-year average GDP density of different industries and average vulnerability.

5.4 Population Density Impact on Ecosystem Vulnerability Change

Population is fundamental to regional economic and social sustainability, and its density closely relates to ecological environmental quality. The southwestern karst mountain region has a total population exceeding 200 million, including 30+ ethnic minorities, making it a major impoverished area in southern China where over 1/3 of the poor population is concentrated. Weak environmental awareness and backward production methods cause enormous ecosystem damage, but more critically, rapid population growth exceeds land carrying capacity, creating a vicious cycle of population increase and environmental degradation.

Analysis at county level reveals a two-stage correlation between population density and ecosystem vulnerability. Below 600 persons/km², vulnerability decreases with increasing density, as better ecological environments support more people. Above 600 persons/km², vulnerability increases sharply with density due to population pressure and unreasonable resource exploitation, causing water and land resource shortages, biodiversity loss, land degradation, and agricultural ecosystem deterioration. Rapid population growth exceeding ecological carrying capacity has become the bottleneck for sustainable development in karst areas.

[Figure 9: see original paper] shows the correlation between 13-year average population density and average vulnerability.

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6. Conclusions

This study constructed an ecosystem vulnerability evaluation system for southwestern karst mountain areas by incorporating large-scale landscape pattern indices and extreme climate indices based on the region’ s special geographical conditions and ecological characteristics. The system analyzed spatiotemporal differentiation patterns of vulnerability and preliminarily explored driving mechanisms. Key findings include:

1. Ecosystem vulnerability in southwestern karst mountain areas belongs to the mild-moderate level, decreasing from the Sichuan-Yunnan-Guizhou core to peripheral regions. Severe and extremely vulnerable zones are concentrated in central and northern areas, while slight and mild zones dominate southeastern and southwestern regions.
2. From 2000-2013, ecosystem vulnerability exhibited an initial increase followed by a decrease. The period 2000-2005 showed intensified vulnerability, 2005-2010 remained relatively stable, and 2010-2013 showed overall stability with local improvements.
3. The spatial and temporal patterns of ecosystem vulnerability changes were significantly affected by human activities, population density, precipitation, topography, soil erosion, and rocky desertification.

This research provides a decision-making foundation and technical support for ecosystem protection and ecological environment restoration and management in southwestern karst mountain areas.

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