Ecological Vulnerability Assessment in the Qilian Mountains Region Based on the SRP Conceptual Model (Postprint)

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Abstract

Based on the ecological sensitivity-ecological resilience-ecological pressure (SRP) conceptual model, eight evaluation indicators were selected from topographic, climatic, vegetation, and socio-economic factors. Utilizing remote sensing and GIS technologies, and employing principal component analysis to determine weights, a systematic and quantitative assessment of the ecological vulnerability degree in the Qilian Mountains region was conducted for nearly 10 years before and after the initiation of the Water Source Conservation Area Ecological Environment Protection and Comprehensive Management Planning Study, aiming to reveal the distribution characteristics, spatiotemporal evolution, and driving factors of ecological vulnerability, and to provide references for regional ecological protection, resource utilization, and sustainable development. The results indicate: (1) From the perspective of ecological vulnerability distribution in the study area, the Qilian Mountains region is primarily characterized by mild and severe vulnerability, with the degree of vulnerability gradually decreasing from northwest to southeast. The low vegetation coverage, high altitude, and harsh ecological environment in the northwestern region are the reasons for the higher degree of vulnerability; (2) The ecological vulnerability degree in the Qilian Mountains region showed a gradual decreasing trend across the three periods, with composite indices of 3.307, 3.118, and 3.103, respectively. In 2005, ecological vulnerability was relatively high, with an area of extreme vulnerability of 28,610 km^2, which decreased to 11,723 km^2 in 2010 and further reduced to 6,174 km^2 in 2015, showing a continuous reduction in the area of extreme vulnerability; (3) From the perspective of driving factors of ecological vulnerability evolution in the Qilian Mountains region, all eight indicators had significant impacts on ecological vulnerability, but the degree of impact varied at different times. In the three periods of data from 2005 to 2015, the vegetation index had the greatest impact on ecological vulnerability, followed by precipitation, while topographic factors had the smallest impact. Overall, the degree of ecological vulnerability in the Qilian Mountains region has decreased in recent years, but it is still necessary to strengthen protection efforts to promote sustainable development of the ecological environment.

Full Text

Ecological Vulnerability Assessment of Qilian Mountains Region Based on SRP Conceptual Model

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Abstract

Based on the Sensitivity-Resilience-Pressure (SRP) conceptual model, this study systematically and quantitatively evaluates the ecological vulnerability of the Qilian Mountains region during the decade surrounding the implementation of the Water Source Conservation Area Ecological Environment Protection and Comprehensive Management Plan. Using eight evaluation indicators selected from topographic, climatic, vegetation, and socio-economic dimensions, remote sensing and GIS technologies, and Principal Component Analysis (PCA) for weight determination, we analyze the spatial distribution characteristics, temporal evolution, and driving factors of ecological vulnerability to provide references for regional ecological protection, resource utilization, and sustainable development.

The results indicate: (1) The Qilian Mountains region is predominantly characterized by light and severe vulnerability, with vulnerability gradually decreasing from northwest to southeast. The northwestern area exhibits high altitude, sparse vegetation cover, and harsh ecological conditions, resulting in higher vulnerability. (2) The comprehensive vulnerability index decreased from 3.307 in 2005 to 3.118 in 2010 and 3.103 in 2015, showing a gradual decline over the study period. (3) The extremely fragile area measured 28,610 km^2 in 2005, decreasing to 11,723 km^2 in 2010 and further to 6,174 km^2 in 2015. (4) All eight indicators significantly influence ecological vulnerability, though their impacts vary across time periods. The vegetation index consistently shows the greatest influence, followed by precipitation, while topographic factors have the smallest impact.

Overall, ecological vulnerability in the Qilian Mountains region has decreased in recent years, yet strengthened protection efforts remain essential to promote sustainable ecological development.

Keywords: ecological vulnerability; SRP conceptual model; ecological remote sensing; principal component analysis; Qilian Mountains

1. Study Area Overview

The Qilian Mountains region is located at the intersection of the Tibetan Plateau, the Mongolian-Xinjiang Plateau, and the Loess Plateau, spanning western Gansu Province and northeastern Qinghai Province (35.5°-40°N, 95°-104°E). The region consists of multiple northwest-southeast trending parallel mountain ranges and broad valleys, extending approximately 800 km east-west and 300 km north-south. It stretches from Wushaoling in the east, adjacent to the Chaka Basin and Qaidam Basin in the south, to Dangjin Pass in the west, and borders the Hexi Corridor in the north [Figure 1: see original paper].

Characterized by a typical plateau continental desert climate, the region receives annual precipitation of 400–700 mm, decreasing from east to west. Precipitation concentrates in summer, creating humid conditions, while winter remains dry with minimal precipitation. The region serves as a crucial water source for multiple inland rivers in northwestern China, primarily through mountain precipitation and glacier meltwater. Vegetation types are diverse and follow vertical zonation patterns. Under the combined influence of mid-high latitude westerly circulation, the Tibetan Plateau, and the East Asian monsoon, the Qilian Mountains ecosystem is inherently fragile with low natural recovery capacity. In recent years, rapid socio-economic development has intensified human-environment conflicts, further exacerbating ecological pressures.

2.1 Evaluation Indicator Selection and Data Sources

The SRP (Sensitivity-Resilience-Pressure) conceptual model is a comprehensive evaluation framework based on ecosystem stability. The system exhibits an unstable internal structure that demonstrates sensitivity to external disturbances while lacking adaptive capacity to prevent unfavorable evolution. This model has been widely applied in ecological vulnerability assessment research. Referencing indicator systems from studies on arid region ecological vulnerability and spatiotemporal differentiation, and considering the primary causes and manifestations of ecological vulnerability in the Qilian Mountains, we constructed a criterion layer comprising ecological sensitivity, ecological resilience, and ecological pressure.

Ecological sensitivity factors include topographic and meteorological factors. Topographic factors encompass terrain relief degree, surface fragmentation, and surface roughness. Meteorological factors include precipitation and temperature. Ecological resilience refers to the self-recovery capacity of ecosystems when subjected to internal disturbances, represented by the Normalized Difference Vegetation Index (NDVI) obtained through maximum value compositing. Ecological pressure refers to physiological effects on ecosystems when subjected to external interference, represented by population density and per capita GDP. The ecological vulnerability evaluation indicator system and data sources are detailed in .

2.2 Methods

2.2.1 Data Standardization To facilitate measurement and ensure comparability across different years, all evaluation indicators underwent data standardization. The indicators exhibit either positive or negative relationships with ecological vulnerability, requiring different standardization formulas. For positive indicators, the standardization formula is:

$$Z_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}$$

For negative indicators:

$$Z_i = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}}$$

where Z_i is the standardized value of indicator i, X_i is the original value, $X_{\max}$ is the maximum value, and $X_{\min}$ is the minimum value.

2.2.2 Ecological Vulnerability Index Calculation Principal Component Analysis (PCA) was employed to determine indicator weights and calculate the Ecological Vulnerability Index (EVI). Based on a cumulative contribution rate threshold of 85%, the first five principal components were extracted from eight indicators. The EVI was calculated as:

$$\mathrm{EVI} = \sum_{i=1}^{n} Y_i \times w_i$$

where Y_i is the ith principal component and w_i is its corresponding contribution rate, calculated as:

$$w_i = \frac{\lambda_i}{\sum_{i=1}^{n} \lambda_i}$$

with λ_i representing the eigenvalue of the ith principal component.

2.2.3 Ecological Vulnerability Classification and Comprehensive Index To enable intuitive representation of ecological vulnerability states, the EVI was standardized using:

$$\mathrm{SI}_i = \frac{\mathrm{EVI}_i - \mathrm{EVI}_{\min}}{\mathrm{EVI}_{\max} - \mathrm{EVI}_{\min}}$$

where SI_i is the standardized EVI value ranging from 0 to 1, EVI_i is the actual value, and $\mathrm{EVI}_{\mathrm{max}}$ and $\mathrm{EVI}_{\mathrm{min}}$ are the maximum and minimum values, respectively.

Based on regional ecological characteristics and existing domestic and international standards, ecological vulnerability was classified into five levels: micro-vulnerability (0–0.2), light vulnerability (0.2–0.4), moderate vulnerability (0.4–0.6), severe vulnerability (0.6–0.8), and extreme vulnerability (0.8–1).

The Ecological Vulnerability Synthetic Index (EVSI) was calculated using a multiplicative model:

$$\mathrm{EVSI} = \sum_{i=1}^{n} P_i \times A_i$$

where P_i is the vulnerability level value for class i and A_i is the proportion of area for that class.

2.2.4 Spatiotemporal Evolution Analysis To analyze spatiotemporal evolution patterns, we used ArcGIS 10.2 raster calculator to overlay the three-period vulnerability classification maps. A dynamic change map was generated using the formula:

$$\mathrm{Code} = 2005 \times 100 + 2010 \times 10 + 2015$$

where Code represents the change type code. In the resulting three-digit code, the hundreds place indicates the 2005 classification, the tens place indicates the 2010 classification, and the units place indicates the 2015 classification.

2.3 Spatial Differentiation Analysis Geodetector methodology was employed to analyze spatiotemporal patterns and driving mechanisms. The factor detector quantifies the explanatory power of each indicator on ecological vulnerability:

$$P_{D,H} = 1 - \frac{\sum_{h=1}^{L} n_h \sigma_h^2}{n\sigma^2}$$

where $P_{D,H}$ is the explanatory power of indicator D on ecological vulnerability H, n is the sample size, L is the number of strata, and n_h and σ_h^2 are the sample size and variance of stratum h, respectively. Larger q-values indicate stronger influence, while p-values assess statistical significance.

The interaction detector evaluates whether interactive effects between factors enhance or weaken explanatory power.

3.1 Overall Characteristics of Ecological Vulnerability

Principal component analysis of the eight evaluation indicators for the three periods yielded the results shown in . The cumulative contribution rate of the first five principal components exceeded 85%, meeting analytical requirements. The EVI for 2005, 2010, and 2015 ranged from 0.18 to 1.15, with multi-year averages of 0.68, 0.64, and 0.63, respectively, indicating overall severe vulnerability.

The spatial distribution reveals a clear pattern of high vulnerability in the northwest and low vulnerability in the southeast [Figure 2: see original paper]. Northwestern areas exhibit high altitude, low vegetation cover, and harsh climatic conditions, resulting in elevated vulnerability. Central regions show moderate vulnerability, while southeastern areas demonstrate relatively lower vulnerability.

Statistical analysis of vulnerability class areas shows that light, moderate, and severe vulnerability dominate the region. In 2005, severe vulnerability accounted for the largest proportion at 44.81%, decreasing to 42.43% in 2010 and 39.69% in 2015. Extremely fragile areas decreased significantly from 28,610 km^2 in 2005 to 11,723 km^2 in 2010 and 6,174 km^2 in 2015. Concurrently, light and moderate vulnerability areas increased gradually. The EVSI values of 3.307, 3.118, and 3.103 for 2005, 2010, and 2015, respectively, demonstrate a declining trend, indicating gradual ecological improvement.

3.2 Spatiotemporal Evolution Characteristics

To further investigate spatial evolution patterns, we generated a spatiotemporal change map [Figure 3: see original paper] and transition matrices for 2005–2010 and 2010–2015 . The total transferred areas were 43,938 km^2 and 39,448 km^2, respectively. Overall, the establishment of national protection systems and implementation of measures such as returning farmland to forest and grassland have yielded noticeable ecological improvements. Positive transitions (improvement) exceeded negative transitions (degradation), reflecting successful ecological restoration efforts.

3.3 Driving Factor Analysis

Factor detection results show that all p-values are less than 0.01, indicating that all eight indicators provide sufficient explanatory power. The q-values reveal that vegetation index and precipitation consistently exceed 0.3, exerting the greatest influence on ecological vulnerability, while topographic factors show q-values below 0.2, indicating minimal impact. The influence of per capita GDP and population density gradually decreased over time, suggesting that enhanced government protection efforts have reduced anthropogenic pressures.

Interaction detection results demonstrate that all factor pairs exhibit synergistic effects, with interactive q-values exceeding those of individual factors. The interaction between vegetation index and temperature shows the strongest explanatory power, while precipitation-temperature interactions also yield high *q*-values, confirming that vegetation and precipitation are the primary driving factors. Multi-factor interactions collectively shape the ecological vulnerability patterns in the Qilian Mountains.

4. Discussion

The ecological vulnerability of the Qilian Mountains exhibits a distinct northwest-southeast gradient, with light, moderate, and severe vulnerability occupying substantial areas. As a critical ecological security barrier in northwestern China, the region has experienced severe environmental degradation due to global warming and unsustainable human activities, leading to weakened water conservation capacity and ecosystem imbalance. Northwestern areas suffer from glacier retreat, snowmelt, high altitude, and sparse vegetation, resulting in high vulnerability. Southeastern areas have shown improvement following national policies such as returning farmland to forest and water source conservation.

Our analysis of three-phase spatiotemporal patterns reveals that since the implementation of the 2008 ecological protection and management plan, overall ecological conditions have gradually improved. Factor detection identifies vegetation index and precipitation as the dominant drivers, while topographic factors have minimal influence. To strengthen ecological protection and restoration, region-specific planning and improved management mechanisms are essential. Future research should incorporate more comprehensive indicators and alternative weighting methods to validate and enhance assessment accuracy.

5. Conclusions

This study employed eight evaluation indicators and spatial principal component analysis to assess ecological vulnerability in the Qilian Mountains region for 2005, 2010, and 2015. Geodetector analysis identified primary driving factors and mechanisms. The main conclusions are:

(1) Spatially, ecological vulnerability decreases from northwest to southeast, with central regions showing moderate vulnerability. Temporally, the comprehensive vulnerability index declined from 3.307 in 2005 to 3.103 in 2015, indicating gradual improvement.

(2) Spatiotemporal evolution is dominated by severe and light vulnerability classes. High-vulnerability areas concentrate in alpine regions, while low-vulnerability areas occur at lower altitudes and near urban centers. Since 2008, vulnerability has decreased slowly with overall ecological improvement.

(3) All indicators significantly influence vulnerability, with vegetation index and precipitation having the greatest impact, followed by temperature and socio-economic factors, and topographic factors having the least. In-

teractive effects between any two factors exceed individual factor effects, demonstrating that multi-factor interactions drive ecological vulnerability patterns in the Qilian Mountains.

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Note: Figure translations are in progress. See original paper for figures.