Spatiotemporal Variation and Driving Forces of Ecological Vulnerability in the Kashgar Region: Postprint

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Abstract

Ecological vulnerability assessment is of great significance for understanding, protecting, and transforming the ecological environment, and promoting harmony between humans and nature. To rationally utilize ecological resources and protect the environment during development and construction, this study investigates the spatiotemporal dynamics of ecological vulnerability in the Kashgar region, providing a scientific basis for the harmonious development of socio-economics and ecological protection. Based on the "exposure-sensitivity-resilience" evaluation framework, 13 indicators were selected from natural conditions and human activities to construct an ecological vulnerability assessment index system for the Kashgar region from 2000 to 2016. The spatial principal component analysis method was employed to analyze the spatiotemporal changes in ecological vulnerability levels in the Kashgar region, and the geographical detector model was used to analyze its driving factors. The results indicate that the ecological vulnerability in the northern part of the Kashgar region is higher than that in the southern part. The area of highly vulnerable zones has increased and is concentrated in the middle and lower reaches of the Yarkant River and the lower reaches of the Kashgar River. The vulnerability shows an overall increase and a shift toward the northeast. From 2000 to 2016, the lowest ecological vulnerability values among counties and cities in the Kashgar region were found in Tashkurgan Tajik Autonomous County, followed by Kashgar City and Zepu County, all belonging to the slightly vulnerable category. The highest values were in Shache County, Jiashi County, and Bachu County, which are highly vulnerable areas. Temperature, terrain, and vegetation coverage factors cause spatial differentiation of ecological vulnerability between the northern and southern zones of the Kashgar region. The increase in cultivated land area and livestock numbers has led to greater landscape fragmentation, which, coupled with the harsh natural environment of the region, has exacerbated the ecological vulnerability of the

Kashgar region, resulting in an overall expansion of ecological environmental vulnerability toward the northeast direction.

Full Text

Spatial-Temporal Variation and Driving Forces of Ecological Vulnerability in Kashi Prefecture

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Abstract

Ecological vulnerability assessment is of great significance for understanding, protecting, and transforming ecological environments, as well as for promoting harmony between humanity and nature. To rationally utilize ecological resources and protect the environment during development and construction, this study examines the spatiotemporal dynamic changes of ecological vulnerability in Kashi Prefecture, providing a scientific basis for the harmonious development of socioeconomic progress and ecological protection. Based on an "exposure-sensitivity-resilience" evaluation framework, we selected 13 indicators from natural conditions and human activities to construct an ecological vulnerability assessment index system for Kashi Prefecture from 2000 to 2016. Spatial principal component analysis was employed to analyze the spatiotemporal changes in ecological vulnerability levels, while the geographic detector model was used to analyze the driving factors. The results indicate that ecological vulnerability in northern Kashi Prefecture is higher than in the southern region. The area of highly vulnerable zones has increased and is concentrated in the middle and lower reaches of the Yarkant River and the lower reaches of the Kashgar River, with vulnerability showing an overall increase and a northeastward shift.

During the study period, the lowest ecological vulnerability values among counties and cities in Kashi Prefecture were found in Taxkorgan Tajik Autonomous County, followed by Kashi City and Zepu County, all classified as potentially vulnerable. The highest values were observed in Shache County, Jiashi County, and Bachu County, which belong to highly vulnerable areas. Temperature, topography, and vegetation coverage factors caused the spatial differentiation of ecological vulnerability between the northern and southern zones of Kashi Prefecture. The growth of cultivated land area and livestock numbers increased landscape fragmentation, which, coupled with the harsh natural environment, exacerbated ecological vulnerability in Kashi Prefecture and led to the overall expansion of ecological vulnerability toward the northeast.

Keywords: ecological vulnerability; driving force analysis; spatial differentiation; Kashi Prefecture

1 Introduction

A healthy ecosystem can maintain and satisfy diverse human needs. However, with sustained socioeconomic development, excessive and disordered exploitation and utilization of natural resources have led to ecosystem degradation, triggering a series of problems including energy shortages, forest reduction, environmental pollution, biodiversity loss, soil erosion, and land desertification. These issues directly or indirectly affect the internal balance of ecosystems, intensifying regional ecosystem vulnerability and further impacting sustainable development of both the natural environment and socioeconomic systems. Ecological vulnerability is an inherent attribute of regional ecosystems, representing the phenomenon of deviation from original states under external disturbances. It results from the coupling of human activities and natural environments and can reflect regional development sustainability to a certain extent.

Research on ecological vulnerability in China has evolved from focusing on typical ecologically fragile zones at large scales to specific administrative regions such as Hexi Region in Gansu Province, Beijing, Karamay City, and Urumqi City, with increasingly refined evaluation units. Supported by "3S" technology (Remote Sensing, Geographic Information Systems, and Global Positioning Systems), research content has deepened to incorporate natural and human factors related to ecological vulnerability, including land cover change and spatial landscape pattern evolution. Traditional vulnerability assessments dominated by socioeconomic data have developed into comprehensive quantitative evaluations and analyses with multiple factors. For instance, Huang et al. conducted quantitative analysis and evaluation of Xinjiang' s ecological environment using RS and GIS technology, while Lin et al. comprehensively analyzed ecological environmental vulnerability changes and driving forces in the Fujian Delta urban agglomeration based on a "cause-effect" model using indicators from natural, social, and economic dimensions.

In driving force analysis, research has primarily focused on regional land use change, with limited quantitative analysis of driving forces related to ecological vulnerability. The geographic detector model, proposed by Wang Jinfeng et al., excels at analyzing categorical variables and can effectively identify relationships among multiple factors. It has been widely used and achieved good results in urbanization spatial driving force analysis, environmental pollution evolution, poverty regional analysis, and soil erosion factor analysis, but its application in regional ecological vulnerability driving force analysis remains limited. Regional ecological vulnerability assessment and driving force analysis target factors that threaten or potentially threaten ecosystems, providing effective methods to understand regional ecosystem weaknesses. Evaluation results can help achieve harmonious development of regional socioeconomic and ecological environments and optimize resource allocation for green development.

Kashi serves as China' s western gateway with obvious location advantages. The Kashi Economic Development Zone was designated as China' s sixth special economic zone and the first special economic zone in inland China. Under the "Belt and Road"initiative, the rapid and high-quality development of Kashi Prefecture is crucial for achieving leapfrog development in Xinjiang' s economy. However, unique geological, geomorphological, and climatic factors have created a harsh ecological environment. Combined with long-term overexploitation of resources, Kashi Prefecture faces a series of ecological and environmental problems both inside and outside its oasis areas, including river dry-up, land salinization, and desertification, demonstrating obvious ecological vulnerability. Therefore, clarifying the spatiotemporal changes of ecological vulnerability in Kashi Prefecture is significant for regional sustainable development and its role as an ecological corridor.

Current research on long-term dynamic quantitative changes in ecological vulnerability in Kashi Prefecture remains relatively weak. This study, based on the "exposure-sensitivity-resilience" framework, combines land cover landscape pattern indices with adaptive indices. Using 2000-2016 remote sensing image data as the foundation, we dynamically evaluate the ecological vulnerability of counties and cities in Kashi Prefecture and analyze the driving forces, aiming to provide theoretical support for regional ecological environmental protection and construction and to offer scientific guidance for rational ecological resource development policies and sustainable development in Kashi Prefecture.

2 Data Sources and Research Methods

2.1 Data Sources and Preprocessing

The primary data used in this study include Landsat satellite imagery, meteorological data, Digital Elevation Model (DEM) data, socioeconomic statistics, and other supplementary data. Landsat imagery and DEM data were obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn), including TM/ETM+ and OLI images for Kashi Prefecture from 2000 to 2016. Image acquisition dates were selected between May and October with cloud cover less than 10%. After atmospheric correction, geometric correction, and image mosaic processing using ENVI software, land cover types were classified into six categories (forestland, cropland, grassland, construction land, water bodies, and unused land) according to the national land use classification standard, with classification accuracy meeting requirements (Kappa coefficient > 0.75).

Meteorological data include annual average temperature, annual average precipitation, and $ 10°Caccumulatedtemperaturerasterdataforcountiesin KashiPrefecture.Otherdataincludenorm
//www.resdc.cn).Socioeconomicstatisticsincludelivestocknumbers(cattle, horses, donkeys, pigs, goats, andsh
10^{4}$ heads) and population data from the Xinjiang Statistical Yearbook (2001-2017) and Xinjiang Production and Construction Corps Statistical Yearbook (2001-2017).

2.2 Research Methods

2.2.1 Construction of Ecological Vulnerability Evaluation Index System Regional ecosystems are complex systems coupling society and nature. Regional natural environmental conditions form the foundation for ecosystem development. Based on relevant ecological vulnerability research and the "exposure-sensitivity-resilience" evaluation framework, combined with major ecological issues in Kashi Prefecture such as land desertification and soil erosion, and considering data timeliness and availability, we ultimately selected 13 evaluation indicators to construct a graphical and attribute database in ArcGIS 10.5, forming the ecological vulnerability evaluation index system for Kashi Prefecture (Table 1).

Topographic relief and slope reflect geomorphological differences in Kashi Prefecture. Annual average precipitation, annual average temperature, and $ $10°C accumulated temperature reflect regional climate and hydrological sensitivity. Human activities directly or indirectly affect the orderly development of ecosystems, and changes in ecosystem vulnerability are closely related to human activity factors. Therefore, we selected population density, cultivated land area, livestock numbers, and per capita GDP as vulnerability factors reflecting human impacts. Land type changes intuitively reflect the process of human transformation of nature and ecosystem resilience strength. Regional ecosystem adaptability is closely related to system structure and function—richer landscape types with continuous and uniform structural distribution indicate higher ecosystem stability and stronger self-adaptability when suffering intense external interference, resulting in lower ecosystem vulnerability.

In Fragstats 4.2 software, we constructed the landscape recovery index using the product of patch richness density index, Shannon diversity index, and Shannon evenness index. Landscape fragmentation index reflects landscape spatial structure changes under human disturbance. We constructed this index using mean patch area and patch number indices, then quantitatively analyzed the ecological environment status and recovery adaptability of Kashi Prefecture through landscape fragmentation index, vegetation coverage, habitat quality index, and landscape recovery index.

The habitat quality index is calculated as follows:

$$\text{生境质量指数} = \frac{\sum_{i=1}^{6} \beta_i \times M_i}{Z} \times \text{bio}$$

where bio is the normalized coefficient for county-level habitat quality (reference value: 0.45); β_i is the weight coefficient for the i-th land structure type (forestland: 0.35, grassland: 0.21, water bodies: 0.28, cropland: 0.11, construction land: 0.04, unused land: 0.01); M_i is the area of the i-th land type; and Z is the area of each county in Kashi Prefecture.

2.2.2 Construction of Ecological Vulnerability Index (EVI) Model Using standardized indicators, we employed spatial principal component analysis in ArcGIS 10.5 to obtain the number of principal components and constructed the EVI function for Kashi Prefecture during 2000-2016 through principal component accumulation. Table 2 shows partial principal component analysis results. To extract maximum information, we selected the first 7 principal components for evaluation. The cumulative contribution rates of the first 7 principal components reached 89.64% in 2000 and 88.41% in 2016, meeting selection requirements.

Using the raster calculator tool, we multiplied each principal component's eigenvector with corresponding standardized indicators, linearly summed them to obtain each principal component score, then summed all principal components to derive the EVI:

$$\mathrm{EVI}_{2000} = PC1_{2000} + PC2_{2000} + PC3_{2000} + \cdots$$

$$\mathrm{EVI}_{2016} = PC1_{2016} + PC2_{2016} + PC3_{2016} + \cdots$$

where $PC1_{2000}$, $PC2_{2000}$, etc. represent scores of different principal components in the spatial principal component model.

To visually display vulnerability levels, we used the natural breaks method to classify ecological vulnerability into five grades: potential vulnerability ($\mathrm{EVI} \leq 1.5$): ecosystem functions are well-maintained with minimal damage; slight vulnerability ($1.5 < \mathrm{EVI} \leq 2.1$): ecosystem structure and function are relatively intact with easy self-recovery; light vulnerability ($2.1 < \mathrm{EVI} \leq 2.7$): ecosystem suffers minor interference with slow recovery; moderate vulnerability ($2.7 < \mathrm{EVI} \leq 3.1$): ecosystem suffers interference approaching ecological thresholds with long recovery times; and high vulnerability ($3.1 < \mathrm{EVI} \leq 3.6$): ecosystem is highly sensitive with low service functions, prone to ecological anomalies requiring focused prevention.

2.2.3 Analysis of Ecological Vulnerability Changes in Kashi Prefecture Using ArcGIS regional statistics tools, we calculated average EVI values and area conversions for counties in Kashi Prefecture during 2000-2016, created vulnerability area transition matrices, and performed difference calculations using raster calculator to analyze vulnerability changes. Negative EVI differences indicate ecological improvement, while positive values indicate deterioration. Positive values were further classified using equal intervals to show vulnerability increase intensity.

2.2.4 Geographic Detector Model Spatial stratified heterogeneity is a fundamental characteristic of geographic phenomena. The geographic detector model, proposed by Wang Jinfeng et al., uses "factor power" and other indicators to detect spatial differentiation and reveal underlying driving forces. The model includes four components: factor detection, interaction detection, risk area detection, and ecological detection (http://www.geodetector.org). In factor detection, the q-value represents the degree to which independent variables explain dependent variable changes. Interaction detection identifies the effects of factor combinations.

Ecological vulnerability indicators in Kashi Prefecture show obvious differentiation. To deeply analyze vulnerability change causes, we used the geographic detector model to detect influencing factors. Using EVI differences between 2000 and 2016 as dependent variables and differences in 13 original indicators as independent variables, we divided Kashi Prefecture into 10 km × 10 km grids, extracted corresponding variable values, and imported 1,477 sample points into the geographic detector software for analysis.

3 Results

3.1 Spatiotemporal Distribution Changes of Ecological Vulnerability in Kashi Prefecture

Figure 2 shows the distribution of ecological vulnerability grades and area conversions. The spatiotemporal distribution differences are significant. In 2000, moderate vulnerability areas were largest (42.04% of total area), while high vulnerability areas were smallest (11.30%). High vulnerability areas were mainly distributed in the northeastern parts of Shache and Yecheng counties and eastern Jiashi County. Potential vulnerability areas included Kashi City, Zepu County, and Taxkorgan Tajik Autonomous County.

By 2016, ecological vulnerability changed significantly, with moderate and high vulnerability dominating (25.73% and 37.99% respectively). Only Taxkorgan County remained potentially vulnerable. Recent years have seen decreases in potential, slight, and moderate vulnerability areas, with moderate areas decreasing most (30,392 km^2). Slight and high vulnerability areas increased, with high vulnerability increasing most (18,569 km^2). The area transfer matrix (Table 4) reveals significant conversion differences among vulnerability types. Some potential vulnerability areas deteriorated, mainly converting to slight vulnerability (4,002.67 km^2). Slight vulnerability areas both improved (converting to potential vulnerability, 1,782.90 km^2) and deteriorated (converting to light vulnerability, 2,007.24 km^2). Nearly half of light vulnerability areas converted to moderate vulnerability (12,059.19 km^2). Moderate vulnerability areas further deteriorated to high vulnerability, with the increased high vulnerability area mainly coming from decreased moderate vulnerability. High vulnerability areas showed minimal recovery, with only 554.94 km^2 converting to moderate vulnerability.

Overall, ecological vulnerability in Kashi Prefecture increased during the 17-year period, with environmental pressure concentrated in counties near the Yarkant

River basin in the northeast and the eastern edge of the Taklamakan Desert. Areas near Yecheng, Markit, and Bachu counties border the desert with extremely dry climate, sparse vegetation, and harsh environments—primarily natural factors causing high vulnerability. However, these river basins are also concentrated agricultural areas where rapid cultivated land expansion (notably in Bachu, Tumushuke, Markit, and Shache counties) has intensified vegetation degradation and ecosystem disturbance. Increased farmland water use and inefficient irrigation have dried up tributaries, aggravated land salinization, and increased regional ecological vulnerability.

3.2 Trend Analysis of Ecological Vulnerability Changes in Kashi Prefecture

Figure 3 shows average EVI values for counties and cities in 2000 and 2016. From the overall average perspective, Kashi Prefecture' s ecological conditions deteriorated, with the largest EVI increases in Kashi City, Shule County, Zepu County, and Bachu County. The 17-year average EVI values ranged from 1.20 to 3.06. The lowest was Taxkorgan County (1.20), followed by Kashi City (1.68) and Zepu County (1.71), all slightly vulnerable. The highest was Shache County (3.06), with Jiashi (2.98) and Bachu (2.96) following as highly vulnerable areas. Other counties averaged around 2.50 (lightly vulnerable), except Yecheng County (2.78, moderately vulnerable).

Figure 5 shows the spatial distribution of EVI changes from 2000 to 2016. The maximum difference was 1.53. Ecological recovery areas (negative EVI) were concentrated in Yuepuhu, Yingjisha, Markit, Jiashi, Shache, and southern Yecheng. Areas with significant EVI increases were north of Kashi City and southwest of Zepu County. Overall, areas with increased vulnerability exceeded those with decreased vulnerability, with northern counties showing deteriorating environmental quality.

3.3 Driving Force Analysis of Ecological Vulnerability Changes

Single-factor detection results show varying explanatory power (q-values) of indicators on ecological vulnerability changes, ranked as: $ $10°C accumulated temperature (0.42), slope (0.38), annual precipitation (0.35), topographic relief (0.34), cultivated land area (0.31), habitat quality index (0.29), annual average temperature (0.27), landscape fragmentation index (0.25), landscape recovery index (0.23), population density (0.21), and vegetation coverage (0.19). No single dominant factor explains vulnerability changes; rather, multiple factors are involved. Natural environmental and human activity indicators both contribute significantly.

Interaction detection reveals that indicator pairs mainly show two interaction types: double-factor enhancement and non-linear enhancement, where combined effects exceed single-factor impacts. Non-linear enhancement relationships include 10 pairs, with annual temperature and landscape fragmentation showing the strongest enhancement. Although annual temperature alone has limited impact, its combination with landscape fragmentation and habitat quality significantly influences vulnerability changes. Overall, the interaction between cultivated land area, livestock numbers, habitat quality index changes, and harsh regional climate exacerbates ecological vulnerability in Kashi Prefecture.

Comprehensive analysis shows that temperature, topography, and vegetation coverage cause spatial differentiation of ecological vulnerability between northern and southern Kashi Prefecture. The southwestern city of Taxkorgan and southern Yecheng County mountains are high-altitude areas (average elevation ~4,126 m) with low effective accumulated temperature for agriculture, large topographic relief, and steep slopes—natural factors that limit human disturbance and result in lower vulnerability than northern and northeastern counties. Conversely, increased cultivated land and livestock in northern counties reduced vegetation coverage, increased landscape fragmentation, decreased habitat quality, and intensified ecological vulnerability, leading to the overall northeastward expansion trend.

From vulnerability change intensity and main indicators (Figure 6), Kashi City and Zepu County show the highest change intensity, shifting from potentially vulnerable to slightly vulnerable areas. Kashi City' s cultivated land didn' t increase significantly, but livestock numbers grew most rapidly (3.73×10^{5} heads), intensifying the contradiction between expanding animal husbandry and insufficient forage land. In Zepu County, habitat quality index declined substantially, causing obvious vulnerability increases in the southwest. Bachu County' s vulnerability increase resulted from rapid expansion of both livestock and cultivated land (48,840 hm^2 increase), with both growth rates ranking among the highest. Large agricultural water demand and severe overgrazing have caused some moderately vulnerable areas to deteriorate to high vulnerability. In contrast, Yingjisha County' s reduced cultivated land and improved habitat quality increased vegetation coverage, reducing ecological pressure and maintaining relatively stable conditions.

4 Conclusions

Based on the "exposure-sensitivity-resilience" framework, this study combined land cover landscape pattern indices with adaptive indices, selecting 13 indicators reflecting natural and social ecosystem development in Kashi Prefecture. Using RS and GIS technology, we obtained spatiotemporal changes in ecological vulnerability grades during 2000-2016 and analyzed driving forces using the geographic detector model. The main conclusions are:

1) **Spatiotemporal distribution changes**: Average EVI values in northern Kashi Prefecture plains were higher than in southern mountainous areas. Slight and moderate vulnerability areas decreased, while high vulnerability areas increased, mainly converted from moderate vulnerability areas. Over 17 years, overall ecological vulnerability deteriorated and shifted

northeastward, concentrating in the middle-lower Yarkant River basin and lower Kashgar River region. Cities with significant EVI increases included Kashi City, Shule County, Zepu County, and Bachu County, while recovery areas were mainly around Yuepuhu, Markit, Yingjisha, and Jiashi.

2) **County-level vulnerability**: The 17-year average EVI was lowest in Taxkorgan Tajik Autonomous County (1.20), followed by Kashi City (1.68) and Zepu County (1.71), all slightly vulnerable. The highest values were in Shache County (3.06), Jiashi County (2.98), and Bachu County (2.96), all highly vulnerable.

3) **Driving forces**: Multiple factors influence ecosystem vulnerability changes without a single dominant indicator. Temperature, topography, and vegetation coverage caused north-south spatial differentiation. Human activities—particularly increases in cultivated land area and livestock numbers—reduced vegetation coverage, increased landscape fragmentation, and decreased habitat quality. The coupling of unreasonable human activities with harsh natural environments exacerbated ecological vulnerability, driving the overall northeastward expansion trend.

Regional ecological vulnerability assessment has become a research hotspot. As a special attribute formed by the interaction between natural environments and human activities, it requires multi-source data integration. Although the geographic detector model identified key indicators related to vulnerability changes in Kashi Prefecture, the specific impacts, restoration methods, and mechanisms for each county require further research. This study dynamically evaluated vulnerability trends and causes over 17 years, providing guidance for future economic development while protecting and restoring local ecological environments.

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