Spatiotemporal Variation and Driving Factors of Ecological Vulnerability in the Loess Plateau of Northern Shaanxi (Postprint)

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Abstract

Based on multi-source data, an evaluation index system was constructed using the sensitivity-resilience-pressure model to analyze the spatiotemporal differentiation patterns and driving mechanisms of ecological vulnerability across different administrative districts, ecological function zones, and slope gradients on the Loess Plateau of northern Shaanxi before and after the implementation of ecological restoration projects (1997 and 2021). The results indicate: (1) The ecological vulnerability on the Loess Plateau of northern Shaanxi has improved significantly, with the mean ecological vulnerability index decreasing from 41.74 to 32.96, a reduction of 21.0%; the overall ecological vulnerability level has also declined, shifting from a pattern dominated by moderate and low vulnerability to one dominated by low vulnerability. Ecological vulnerability exhibits distinct zonal distribution characteristics, with vulnerability levels gradually increasing from south to north. (2) From 1997 to 2021, ecological vulnerability improved in 51.2% of the region, primarily through transitions from moderate to low vulnerability; vulnerability increased in 4.6% of the region, mainly through transitions from slight vulnerability to low vulnerability and from low vulnerability to moderate vulnerability. In the jurisdictions of Tongchuan City, Yan'an City, and Yulin City, both the ecological vulnerability index and levels are decreasing, with Tongchuan City having the lowest ecological vulnerability and Yulin City the highest. In the three ecological function zones, both the ecological vulnerability index and levels are decreasing significantly, with the magnitude of reduction following the order: Grain-for-Green area > sandy area > Huangqiao forest area. (3) In areas meeting the criteria for returning farmland to forest/grassland, high-level vulnerability has been substantially converted to low-level vulnerability, resulting in significant improvement in ecological vulnerability and demonstrating considerable effectiveness of the project. (4) Analysis of the driving mechanisms reveals that anthropogenic factors and natural factors account for 83.1% and 16.9% of the driving force, respectively, indicating that ecological restoration projects are the primary driver of significant improvement in regional ecological vulnerability. The research results can provide scientific reference data for evaluating the effectiveness of ecological restoration projects and for sustainable ecological restoration in this region.

Full Text

Spatiotemporal Variation and Driving Factors of Ecological Vulnerability in the Loess Plateau of Northern Shaanxi

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Abstract: Based on multi-source data and an evaluation index system constructed using the Sensitivity-Resilience-Pressure (SRP) model, this study analyzes the spatiotemporal variation patterns and driving mechanisms of ecological vulnerability across different administrative regions, ecological functional zones, and slope gradients in the Loess Plateau of northern Shaanxi before and after the implementation of ecological restoration projects (1997–2021). The results reveal four key findings. First, ecological vulnerability in the region has improved significantly, with the ecological vulnerability index decreasing by 21.0% and the overall vulnerability grade shifting from a pattern dominated by medium and low vulnerability to one dominated by low vulnerability. The region exhibits distinct zonal distribution characteristics, with vulnerability grades gradually increasing from south to north. Second, 51.2% of the region showed improved ecological vulnerability, primarily through transitions from medium to low vulnerability, which accounted for 75.3% of the total improved area and was concentrated mainly in farmland-to-forest conversion zones and wind-sand areas. The ecological vulnerability indices and grades of all three ecological functional zones declined significantly, with the magnitude of reduction following the order: farmland-to-forest conversion zone > wind-sand area > Huangqiao forest area. Conversely, 4.6% of the region experienced increased ecological vulnerability, mainly through transitions from general to low vulnerability and from low to medium vulnerability, which accounted for 52.9% and 45.6% of the increased area, respectively, and were scattered across wind-sand areas and the Huangqiao forest area. Among the three administrative units, Tongchuan City exhibited the lowest ecological vulnerability while Yulin City showed the highest, though all three municipalities demonstrated declining vulnerability indices and grades. Third, in areas meeting the criteria for farmland-to-forest conversion, high-grade vulnerability was largely transformed into low-grade vulnerability, yielding significant ecological improvements and demonstrating the project's effectiveness. Fourth, analysis of the driving mechanisms reveals that human factors and natural factors accounted for 83.1% and 16.9% of the driving forces, respectively, indicating that ecological restoration projects constitute the primary driver of regional ecological vulnerability improvement. These findings provide scientific reference data for evaluating the effectiveness of ecological restoration projects and guiding sustainable ecological rehabilitation in the region.

Keywords: ecological restoration project; Loess Plateau of northern Shaanxi; ecological vulnerability; driving factors

1 Introduction

The ecological environment encompasses the quantity and quality of water, biological, natural, and climatic resources that affect human survival and development, representing a complex ecosystem within the context of social and economic sustainability. Protecting the ecological environment is fundamental to ensuring long-term human survival and steady development. Ecological vulnerability refers to the evolution of an ecosystem from its current state to another state when subjected to specific internal and external environmental disturbances, without the capacity to return to its initial condition—an inherent characteristic of ecosystems. This vulnerability is closely related to numerous factors including land surface cover, climate change, topography, and soil texture. As global climate and land surface conditions continue to change, research on regional ecological vulnerability has become a core issue in global environmental change and sustainable development studies.

Currently, various evaluation index systems exist for regional ecological vulnerability assessment. However, because different regions face distinct ecological and environmental problems, applying generic models to evaluate different areas lacks scientific rigor and accuracy. Consequently, evaluation indicators vary according to local ecological issues. Commonly used models include the Sensitivity-Resilience-Pressure (SRP) model, Exposure-Response model, and Sensitivity-Pressure model, among others. Scholars have employed these models to conduct ecological vulnerability assessments across different spatial units, including watersheds, administrative regions, and forested mountainous areas. A comprehensive analysis of existing research reveals that detailed studies examining the spatiotemporal variation patterns of ecological vulnerability across the entire Loess Plateau of northern Shaanxi, along with quantitative assessment of driving forces, have not yet been undertaken.

Since 1999, the Loess Plateau of northern Shaanxi has implemented comprehensive ecological restoration projects. Related research indicates that the implementation of these projects, combined with climate change, has induced significant changes in land use, vegetation cover, and soil erosion, all of which differentially affect the spatiotemporal distribution characteristics of regional ecological vulnerability. Therefore, this study utilizes multi-source data from remote sensing and observational sources to construct an evaluation index system based on the SRP model. It investigates the spatiotemporal variation of ecological vulnerability across different administrative units, ecological functional zones, and slope gradients in 1997 and 2021, while quantitatively analyzing the driving forces of both human and natural factors. The objective is to obtain timely, objective, and accurate data on changes before and after ecological restoration project implementation, thereby providing scientific reference for project effectiveness evaluation and sustainable ecological rehabilitation.

2 Study Area and Methods

2.1 Study Area Overview

The Loess Plateau of northern Shaanxi is located in the arid and semi-arid region of northern Shaanxi Province, representing the core area of China's Loess Plateau. From north to south, it comprises the wind-sand control area along the Great Wall, the farmland-to-forest conversion area, and the Huangqiao forest area, primarily including the cities of Yulin, Yan'an, and Tongchuan [Figure 2: see original paper]. Driven by external forces such as wind and water erosion, the region experiences intense slope erosion, well-developed gullies, highly fragmented land surfaces, complex topographic variations, severe soil erosion, and extremely fragile ecological conditions.

2.2 Data Sources and Preprocessing

Data sources include: (1) Land use data derived from Landsat satellite imagery for 1997 and 2021, obtained from the United States Geological Survey (USGS). Following radiometric correction, geometric precision correction, and mosaicking, the data were used to classify land use in the study area, achieving overall classification accuracies of 86.0% and 84.5% for the two periods, respectively, both meeting classification accuracy requirements. (2) Vegetation cover data were obtained from the MOD13Q1 vegetation index product (250 m resolution) provided by NASA's LP DAAC (Land Processes Distributed Active Archive Center). (3) Digital Elevation Model (DEM) data, used primarily for extracting slope data as a topographic factor, were obtained from surveying and mapping data provided by the Shaanxi Provincial Bureau of Surveying and Mapping. (4) Data on annual precipitation and heavy rainfall days were obtained from meteorological observation stations of the Shaanxi Provincial Meteorological Bureau.

2.3 Evaluation Methodology

2.3.1 Index System Construction The Loess Plateau of northern Shaanxi represents an ecologically fragile and sensitive region. The implementation of ecological restoration projects since 1999 has effectively restored ecological factors such as land surface vegetation and land use patterns. Concurrently, the frequency of heavy rainfall events in the region has increased significantly, creating new pressures on the ecological environment. Therefore, this study employs the Sensitivity-Resilience-Pressure (SRP) model to construct an evaluation index system for assessing ecological vulnerability in the region [Figure 2: see original paper].

Ecological sensitivity refers to potential environmental problems that ecosystems may experience under external influences. From the perspectives of topography and land surface conditions, slope was selected to reflect topographic vulnerability, while land use and vegetation coverage were chosen to reflect the degree of human disturbance on nature. Ecological resilience represents the adaptive capacity of ecosystems under external interference. From climatic and land surface perspectives, effective increases in annual precipitation can promote ecological recovery, while land use and vegetation coverage can reflect both sensitivity and ecosystem recovery status. Ecological pressure refers to factors affecting ecosystem stability. Heavy rainfall can alter soil erosion patterns, exerting pressure on regional ecological restoration. Therefore, heavy rainfall days were selected as an indicator of ecological pressure.

2.3.2 Index Standardization and Grading Following quantification, factor data represent a set of values reflecting attribute characteristics, ranging between 0 and 100. Based on the degree of influence on ecological vulnerability, indices were classified and assigned values .

2.3.3 Weight Determination Index weights can be determined using either subjective comprehensive integration methods or objective weighting methods. This study employed the expert scoring method to determine index weights .

2.3.4 Comprehensive Evaluation Model The ecological vulnerability index was calculated using the comprehensive index method according to the following formula:

$$EVI = \sum_i W_i \times P_i \times 100$$

where EVI represents the ecological vulnerability index, W_i denotes the weight of evaluation index i, and P_i represents the standardized score of evaluation index i.

2.3.5 Vulnerability Classification To comprehensively understand ecological vulnerability characteristics, the ecological vulnerability index was classified and graded using the natural breaks method for cluster classification, dividing ecological vulnerability into four grades: general, low, medium, and high .

3 Results and Analysis

3.1 Temporal Variation Characteristics of Ecological Vulnerability

From 1997 to 2021, ecological vulnerability in the Loess Plateau of northern Shaanxi improved significantly, with the ecological vulnerability index decreasing from 41.74 to 32.96, representing a 21.0% reduction. As shown in , the overall vulnerability grades also declined, with the areas of general and low vulnerability zones increasing substantially by 6,383.11 km^2 and 27,177.62 km^2, respectively, representing increases of 91.0% and 16.0% in proportional share from 44.7% to 85.3% and from 12.2% to 29.3%, respectively. Conversely, medium and high vulnerability zones decreased significantly by 31,403.28 km^2 and 2,157.45 km^2, respectively, with their proportional shares declining from 44.3% to 10.8% and from 1.6% to 0.1%, representing reductions of 84.7% and 95.1%, respectively.

3.2 Spatial Variation Characteristics of Ecological Vulnerability

Ecological vulnerability in the Loess Plateau of northern Shaanxi exhibits distinct zonal distribution characteristics, with vulnerability grades gradually increasing from south to north and southern ecological conditions being significantly better than northern areas [Figure 3: see original paper]. High vulnerability zones are primarily distributed in the wind-sand areas along the Great Wall and their junctions with farmland-to-forest conversion zones. Medium vulnerability zones are located north of Yan'an City and south of Yulin City within the farmland-to-forest conversion area. General vulnerability zones are distributed in the farmland-to-forest conversion area south of Yan'an City, while low vulnerability zones are concentrated in the Huangqiao forest area.

From 1997 to 2021, ecological vulnerability in the Loess Plateau of northern Shaanxi improved overall, with high vulnerability zones decreasing markedly and low and general vulnerability zones increasing significantly, particularly in the farmland-to-forest conversion and wind-sand areas north of Yan'an City. The area of general vulnerability zones also expanded noticeably in the southern Huangqiao forest area. Overall, 51.2% of the region showed improved ecological vulnerability, dominated by transitions from medium to low vulnerability, which accounted for 75.3% of the total improved area and were concentrated primarily in farmland-to-forest conversion and wind-sand areas. The second most significant improvement involved transitions from low to general vulnerability, accounting for 16.9% of the improved area and occurring mainly in the Huangqiao forest area. However, 4.6% of the region experienced increased ecological vulnerability, primarily through transitions from general to low vulnerability and from low to medium vulnerability, which accounted for 52.9% and 45.6% of the increased area, respectively, and were scattered across wind-sand areas and the Huangqiao forest area [Figure 4: see original paper] .

3.3 Characteristics by Administrative Unit

Among the three administrative units of Yulin, Yan'an, and Tongchuan, Yulin City exhibited the highest overall ecological vulnerability, though all three municipalities showed declining vulnerability indices and grades. Specifically, Yulin's vulnerability index decreased from 45.32 to 34.31 (24.3% reduction), Yan'an's from 40.55 to 30.40 (25.0% reduction), and Tongchuan's from 28.91 to 25.79 (10.8% reduction). In terms of vulnerability grade structure, Tongchuan was dominated by low vulnerability zones in both periods (76.7% and 81.0%, respectively), with general vulnerability zones increasing from 20.6% to 42.6% and low vulnerability zones decreasing from 76.7% to 55.4%. Yan'an transitioned from a pattern dominated by medium and low vulnerability zones (63.0% and 35.4%, respectively) to one dominated by low vulnerability zones (48.8%). By 2021, Yan'an contained no high vulnerability zones, with medium vulnerability zones accounting for only 10.8% of the area .

3.4 Characteristics by Ecological Function Zone

The ecological vulnerability indices of all three functional zones decreased significantly, with the farmland-to-forest conversion zone showing the largest reduction (from 42.51 to 30.18, a 29.0% decrease), followed by the wind-sand area (from 46.92 to 38.25, an 18.5% decrease), and the Huangqiao forest area (from 31.69 to 25.85, a 18.5% decrease). All three zones exhibited declining vulnerability grades: the wind-sand area transitioned from a structure dominated by medium vulnerability zones (53.8%) to one dominated by low vulnerability zones (62.7%); the farmland-to-forest conversion zone shifted from medium and low vulnerability dominance (42.9% and 55.4%, respectively) to low vulnerability dominance (69.8%); and the Huangqiao forest area contained no high vulnerability zones, with its structure dominated by low vulnerability zones (83.7% and 85.3% in the two periods, respectively) .

3.5 Characteristics by Slope Gradient

Analysis of ecological vulnerability across different slope gradients reveals that in 1997, high vulnerability zones were concentrated primarily in Yulin City, while Tongchuan City showed no high vulnerability distribution. From 1997 to 2021, all slope ranges exhibited reduced medium and high vulnerability areas. High vulnerability zones decreased by over 90.0% across all slope gradients, with reductions reaching 97.6% in the 15°–25° and 25°–35° ranges. Medium vulnerability zones also decreased across all slope ranges, with reductions exceeding 60.0% and reaching up to 85.3%. Notably, in areas meeting the criteria for farmland-to-forest conversion (slopes >15°), the reductions in medium and high vulnerability were smallest at 60.0% and highest at 97.6%, indicating that ecological restoration projects have significantly improved ecological vulnerability in these designated areas, yielding substantial environmental recovery and project effectiveness .

3.6 Driving Factor Analysis

From 1997 to 2021, the average annual temperature in the Loess Plateau of northern Shaanxi showed a non-significant increasing trend (0.003°C·a^{-1}), while annual precipitation exhibited a significantly increasing trend ($P < 0.01$) at a rate of 7.42 mm·a^{-1}. This overall shift toward warmer and wetter conditions has promoted vegetation growth and recovery, facilitating ecological vulnerability restoration. However, the relative contributions of natural and human factors warrant deeper investigation.

Based on the constructed index system, slope, heavy rainfall days, and annual precipitation are less influenced by human activities and thus represent natural factors, whereas vegetation coverage and land use are strongly affected by human activities and represent anthropogenic factors. Assuming natural factors remained constant while only human factors changed, the ecological vulnerability index in 2021 would be 34.52, representing 83.1% of the actual reduction. Conversely, assuming human factors remained constant while only natural factors changed, the 2021 index would be 40.12, representing 16.9% of the actual reduction. These results demonstrate that human factors (primarily ecological restoration projects) have been the dominant driving force (83.1%) in improving ecological vulnerability in the region, while natural factors contributed 16.9%.

4 Discussion

This study provides a detailed analysis of spatiotemporal variation and driving mechanisms of ecological vulnerability across the entire Loess Plateau of northern Shaanxi and its sub-regions before and after ecological restoration project implementation, yielding rich and detailed data for objective project effectiveness evaluation. The finding that regional ecological vulnerability has improved overall aligns with Zhang et al.'s research on landscape ecological vulnerability in Shaanxi Province, which identified improvement trends in the Loess Plateau region. Our results also correspond with Zhong et al.'s conclusion that ecological risk in Yulin City has generally declined. Zhong et al. further suggested that human activities such as farmland-to-forest conversion have positively impacted ecological risk through vegetation recovery, a conclusion consistent with our finding that human factors play a decisive role in ecological vulnerability improvement.

However, previous studies have primarily provided qualitative descriptions of driving factors without quantitative assessment. This study quantitatively demonstrates that human factors account for 83.1% of the driving force behind ecological vulnerability improvement in the region, while natural factors contribute 16.9%. This quantitative approach provides more detailed, objective, and comprehensive results compared to previous research. The analysis across three spatial dimensions—administrative regions, ecological functional zones, and slope gradients—reveals more nuanced patterns and evolution laws, offering more detailed scientific reference data for ecological restoration projects.

5 Conclusions

This study investigated spatiotemporal variation characteristics and driving mechanisms of ecological vulnerability in the Loess Plateau of northern Shaanxi based on the SRP model. The analysis yielded rich and detailed data that can objectively evaluate ecological restoration effectiveness and provide scientific reference information. The main conclusions are as follows:

1) Ecological vulnerability in southern parts of the Loess Plateau of northern Shaanxi is significantly better than in northern areas. From 1997 to 2021, 51.2% of the region showed improved ecological vulnerability, concentrated mainly in farmland-to-forest conversion zones and wind-sand areas, while 4.6% of the region experienced increased vulnerability, scattered across wind-sand areas and the Huangqiao forest area. Overall, the regional vulnerability pattern has shifted from medium and low vulnerability dominance to low vulnerability dominance.

2) Among the three administrative units, Tongchuan City and the Huangqiao forest area exhibit relatively good ecological conditions, while Yulin City and wind-sand areas show the poorest conditions. All three municipalities and all three ecological functional zones demonstrated improved ecological vulnerability with significantly reduced vulnerability grades.

3) Across all slope gradients, medium and high vulnerability zone areas decreased in 2021, with reductions in high vulnerability zones exceeding 90.0% in all slope ranges. In areas meeting farmland-to-forest conversion criteria (slopes >15°), the smallest reduction in medium and high vulnerability zones was 60.0%, while the largest reached 97.6%. These results demonstrate that ecological restoration projects have significantly improved ecological vulnerability in designated areas, yielding notable environmental recovery and project effectiveness.

4) From 1997 to 2021, the regional climate background in the Loess Plateau of northern Shaanxi shifted toward warmer and wetter conditions, promoting vegetation growth and recovery and contributing 16.9% to ecological vulnerability improvement. Human factors, particularly ecological restoration projects, contributed 83.1% and represent the primary driving force behind the significant improvement in regional ecological vulnerability.

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