Spatiotemporal Evolution of Coupled Ecosystem Resilience and Obstacle Factor Identification in the Qilian Mountains Region: Postprint

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Date: 2024-03-15T00:00:00+00:00

Abstract

The Qilian Mountains region is an important ecological functional area in China and also one of the country' s ecologically vulnerable zones. This study investigates the resilience of the natural-economic-social composite ecosystem in the Qilian Mountains region with the aim of effectively addressing its ecological and environmental issues. A three-dimensional spatial vector model, coupling coordination model, and obstacle degree model were constructed to measure the composite ecosystem resilience and subsystem coupling coordination in the Qilian Mountains region from 2007 to 2021, reveal the obstacle factors influencing the enhancement of composite ecosystem resilience, and analyze the spatial evolution process of composite ecosystem resilience utilizing geographic information system technology. The results indicate: (1) The composite ecosystem resilience in the Qilian Mountains region demonstrates an upward trend, spatially characterized by a gradual decrease from east to west; the natural subsystem resilience exhibits a downward trend, spatially characterized by a gradual decrease from the central-eastern part to the northwest; the economic subsystem resilience shows an upward trend with rapid growth, with high economic resilience concentrated in the eastern and northern areas; the social subsystem resilience exhibits a modest increase, with high social resilience concentrated in the eastern region. (2) The coupling degree of composite ecosystem resilience in the Qilian Mountains region has improved significantly, achieving a high-level coupling stage; the coupling coordination degree displays a fluctuating upward trend, reaching an intermediate coordination level. (3) The natural subsystem exerts a substantial influence on the enhancement of composite ecosystem resilience, while the obstacle degree of indicators from the economic subsystem has increased notably.

Full Text

Spatiotemporal Evolution and Obstacle Identification of Complex Ecosystem Resilience in the Qilian Mountain Area

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Abstract

The Qilian Mountain area serves as a crucial ecological function zone and represents one of China' s most environmentally fragile regions. This study investigates the natural-economic-social complex ecosystem resilience in the Qilian Mountain area to provide effective solutions for its ecological and environmental challenges. We constructed a three-dimensional spatial vector model, coupling coordination model, and obstacle degree model to measure complex ecosystem resilience and subsystem coupling coordination from 2007 to 2021. The research reveals obstacles impeding resilience enhancement and analyzes spatial evolution patterns using geographic information system technology. The results demonstrate that: (1) Complex ecosystem resilience in the Qilian Mountain area shows an upward trend, spatially decreasing from east to west. Natural subsystem resilience exhibits a declining trend, decreasing from the central-east to the northwest. Economic subsystem resilience increases rapidly, with high economic resilience concentrated in the eastern and northern regions. Social subsystem resilience rises modestly, with high social resilience primarily distributed in the east. (2) The coupling degree of complex ecosystem resilience has improved significantly, reaching a high-level coupling state, while the coupling coordination degree shows a fluctuating upward trend, achieving an intermediate coordination level. (3) The natural subsystem substantially influences complex ecosystem resilience improvement, with the obstacle degree of indicators from the economic subsystem showing a notable increase.

Keywords: complex ecosystem resilience; three-dimensional space model; coupling coordination degree; obstacle factor; Qilian Mountain area

1. Introduction

The Qilian Mountain area constitutes an important ecological function zone, a critical water source conservation area, and an ecological security barrier in northwest China, yet it remains environmentally fragile. Its ecological protection is vital for regional stability in western China. Rich in mineral deposits and water resources, the region has experienced severe anthropogenic ecological damage in recent years. Since the 18th National Congress of the Communist Party of China, General Secretary Xi Jinping has repeatedly emphasized ecological restoration in the Qilian Mountain area, demanding urgent resolution of prominent environmental protection and restoration issues. Therefore, quantifying complex ecosystem resilience, analyzing its spatiotemporal evolution, and identifying underlying obstacles provide an objective basis for ecological protection and restoration governance, holding significant implications for scientific conservation efforts.

Ecological destruction generates unpredictable impacts on social development and regional economies, necessitating the concept of "ecological resilience." Ecological resilience emphasizes inherent capacities for self-organization, learning, and adaptation, alongside the ability to absorb disturbances and undergo change while maintaining system functions, structures, and characteristics. International research on ecological resilience focuses on conceptualization, evaluation systems, and measurement methods. Domestic theoretical and empirical research remains in its early stages, concentrating primarily on three aspects: (1) theoretical studies addressing conceptual definitions and theoretical analysis; (2) empirical research establishing indicator systems and evaluation models to measure ecological resilience; and (3) analyses of driving factors and obstacle factors behind resilience patterns. Current research predominantly examines provincial and municipal scales, with limited studies on ecological function zones and fragile areas like the Qilian Mountain region.

Existing ecological resilience evaluation frameworks contain relatively few indicators reflecting social and economic conditions, making it difficult to accurately characterize complex ecosystem resilience. Therefore, constructing a natural-economic-social complex ecosystem resilience evaluation system using a three-dimensional spatial vector model, coupling coordination model, and obstacle degree model can expand theoretical perspectives and provide support for enhancing ecological resilience in the Qilian Mountain area.

2.1 Study Area Overview

The Qilian Mountains, located in western Gansu and northeastern Qinghai, constitute a vital ecological barrier in China' s arid and semi-arid western regions and represent an environmentally fragile zone. The area features extensive grasslands and abundant water resources, with animal husbandry as the primary industry. Rich in coal, iron, and petroleum deposits, industrial development has made mining a major industry, causing various ecological problems. While national attention and scholarly research on the Qilian Mountain environment have increased, boundary definitions vary due to different research perspectives.

This study examines complex ecosystem resilience at the macro level across the entire Qilian Mountain region, dividing it into natural, economic, and social subsystems. The research area includes 25 counties (districts) in Gansu Province and 8 counties (districts) in Qinghai Province within the Qilian Mountain radiation zone [Figure 1: see original paper].

2.1.1 Complex Ecosystem Resilience: Concept and Evaluation Indicators

A complex ecosystem integrates natural, economic, and social subsystems. Its resilience refers to the capacity to resist disturbances, recover original states, and adapt to changes under internal and external pressures. Natural subsystem resilience represents resistance to environmental disturbances; economic subsystem resilience denotes the economic conditions necessary for ecological recovery; and social subsystem resilience reflects human adaptation through resource utilization and environmental transformation.

When selecting natural subsystem indicators, we considered the region' s complex topography and major ecological challenges including vegetation loss, forest degradation, soil erosion, and desertification. We selected desertification index (C1), soil erosion index (C2), land salinization index (C3), water conservation index (C4), biological abundance index (C5), and forest-grass coverage rate (C6) as natural subsystem indicators. For the economic subsystem, we emphasized rural economic evaluation indicators given the predominance of agricultural and pastoral areas, selecting growth rate of total agricultural, forestry, and animal husbandry output value (C7), per capita net income of rural residents (C8), gross domestic product (GDP) growth rate (C9), proportion of secondary industry (C10), and proportion of public fiscal expenditure (C11). For the social subsystem, we focused on population dynamics, livelihood improvement, and regional competitiveness in science and technology and education, selecting population density (C12), population growth rate (C13), per capita cultivated land area (C14), urbanization rate (C15), science and technology investment intensity (C16), and education investment intensity (C17). Based on existing research, we established the evaluation index system shown in [Figure 3: see original paper], where "+" indicates positive indicators and "-" indicates negative indicators.

2.1.2 Entropy Weight Method

This study combines time series data with indicator entropy to determine weights more accurately. Larger weights indicate greater importance in the evaluation system. The calculation formulas are:

$$f_{\alpha ij} = \frac{R_{ij}}{\sum_{\alpha=1}^{t}\sum_{i=1}^{n} R_{ij}}$$

$$H_j = -\frac{1}{\ln(t \times n)} \sum_{\alpha=1}^{t}\sum_{i=1}^{n} f_{\alpha ij} \ln(f_{\alpha ij})$$

$$\omega_j = \frac{1 - H_j}{\sum_{j=1}^{m}(1 - H_j)}$$

where ω_j is the weight of indicator j, n is the total number of indicators, H_j is the information entropy of indicator j, t is the study period, $f_{\alpha ij}$ is the proportion of indicator j for county (district) i in year α, and R_{ij} is the standardized indicator value.

2.1.3 Three-Dimensional Spatial Vector Model

During complex ecosystem development, the three subsystems exhibit distinct structures and functions with intricate nonlinear relationships. This study constructs a three-dimensional spatial vector model for the Qilian Mountain area' s natural-economic-social complex ecosystem [Figure 4: see original paper]. The vector OS represents the optimal development trajectory, while subsystem trajectories OP cannot completely coincide with it. We define development degree, coordination degree, and development index as follows:

1) **Resilience Development Index of Subsystems**

$$X_t = \sum_{j=1}^{m} \omega_j R_{\alpha ij}$$

$$Y_t = \sum_{j=1}^{m} \omega_j R_{\alpha ij}$$

$$Z_t = \sum_{j=1}^{m} \omega_j R_{\alpha ij}$$

where X_t, Y_t, and Z_t represent the resilience development indices of natural, economic, and social subsystems, respectively.

2) **Resilience Development Degree**

$$OP = \sqrt{(X_t - 0)^2 + (Y_t - 0)^2 + (Z_t - 0)^2}$$

where OP is the development degree of complex ecosystem resilience.

3) **Resilience Coordination Degree**

Coordination degree measures the fitness between actual and optimal development trajectories. The deviation angle θ is defined as the coordination degree, with larger θ values indicating poorer coordination:

$$\theta = \arccos\left(\frac{X_t + Y_t + Z_t}{\sqrt{3} \times OP}\right)$$

4) **Resilience Development Index**

The development index reflects the actual resilience level, defined as the length along the optimal trajectory (OP'):

$$OP' = OP \times \cos\theta$$

where OP' is positively correlated with resilience level. Values closer to 1 indicate development nearer to the optimal state.

2.1.4 Coupling Coordination Degree Model

This model measures interaction intensity among subsystems and their benign coordination degree:

1) **Coupling Degree (C)**

$$C = \frac{3 \times \sqrt[3]{U_1 \times U_2 \times U_3}}{U_1 + U_2 + U_3}$$

where $C \in [0, 1]$, with higher values indicating stronger subsystem relationships. U_1, U_2, and U_3 represent the comprehensive evaluation values of natural, economic, and social subsystems.

2) **Coupling Coordination Degree (D)**

$$D = \sqrt{C \times T}, \quad T = \gamma_1 U_1 + \gamma_2 U_2 + \gamma_3 U_3$$

where $D \in [0, 1]$ reflects the benign coupling degree. Higher D values indicate better synergy. γ_1, γ_2, and γ_3 are coefficients (set as $\gamma_1 = \gamma_2 = \gamma_3 = 1/3$ given equal importance).

2.1.5 Obstacle Diagnosis Model

This model identifies factors constraining resilience improvement, where higher obstacle degrees indicate stronger constraints:

$$O_j = \frac{\omega_j (1 - R_{\alpha ij})}{\sum_{j=1}^{m} \omega_j (1 - R_{\alpha ij})}$$

where O_j is the obstacle degree of indicator j, ω_j is its weight, and $R_{\alpha ij}$ is the standardized value.

2.2 Data Sources

Data were obtained from the *Gansu Statistical Yearbook* (2007-2021), *Qinghai Statistical Yearbook* (2007-2021), and statistical bulletins of relevant counties (cities, districts). Vector data were downloaded from the National Geographic Information Resources Directory Service System (http://www.webmap.cn), with boundary data sourced from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn).

3.1 Spatiotemporal Characteristics of Complex Ecosystem Resilience

Using the natural breaks method, we classified resilience levels into five categories: low, relatively low, moderate, relatively high, and high. Based on calculations for 33 counties (districts) from 2007 to 2021, we mapped resilience classes using ArcGIS 10.2 [Figure 5: see original paper].

Complex ecosystem resilience shows an upward trend, spatially decreasing from east to west. Natural subsystem resilience declined, with high-resilience areas decreasing significantly and showing a spatial pattern of reduction from central-east to northwest. Economic subsystem resilience increased rapidly, particularly in the east and north, with low-resilience areas substantially decreasing. Moderate and higher resilience concentrated in the east and north, while lower levels dominated the central and western regions. Social subsystem resilience rose modestly, with higher levels concentrated in the east.

The eastern region features flat terrain, lower elevation, high vegetation coverage, favorable climate, and strong water conservation capacity, with fewer ecological problems. The western region suffers from severe soil erosion, large desert areas, and salinization due to improper irrigation. Consequently, the eastern natural subsystem demonstrates stronger recovery capacity. The eastern region' s proximity to major cities, greater investment in science and education, and higher population and development levels contribute to faster recovery from economic and social disturbances compared to the western region. Overall, complex ecosystem resilience is higher in the east, with greater improvement 幅度, enabling better maintenance of subsystem stability under interference.

Comparing resilience class distributions reveals that rising complex ecosystem resilience classes result from improved economic and social subsystem resilience, while declining classes stem from natural subsystem deterioration, underscoring the critical role of the natural subsystem.

3.2 Coupling Coordination Analysis

Based on coupling and coordination calculations, we analyzed interaction intensity and coordination levels among subsystems from 2007 to 2021 [FIGURE:7, TABLE:1, TABLE:2].

The coupling degree improved significantly after 2015, reaching high-level coupling, while coupling coordination showed a fluctuating upward trend, achieving intermediate coordination. In 2007, coordination was at the brink of imbalance ($D = 0.39$), indicating uncoordinated development where economic growth came at the expense of ecological health. By 2012, coordination improved to primary coordination ($D = 0.51$), correlating with the 18th National Congress' s incorporation of ecological civilization into national policy. Coordination reached intermediate level by 2017 ($D = 0.62$), though fluctuations occurred due to illegal mining and overgrazing. Enhanced governmental measures subsequently restored intermediate coordination by 2021.

3.3 Obstacle Factor Analysis

The obstacle diagnosis model calculated obstacle degrees for 17 indicators across 33 counties (districts) from 2007 to 2021. Primary obstacles originated from the natural subsystem, with high-frequency factors including water conservation index (C4), biological abundance index (C5), and forest-grass coverage rate (C6). The top-ranking obstacles are shown in .

Natural subsystem obstacles consistently ranked first with the highest frequency, requiring strengthened ecological protection and restoration efforts. From 2007 to 2021, natural and economic subsystems remained the primary constraints, with economic subsystem obstacle degrees increasing notably. Social subsystem obstacles decreased over time.

Spatial differences in obstacle factors are significant. In 2021, counties with top-three obstacles concentrated in the east and center, predominantly from the natural subsystem, indicating that eastern resilience improvement faces natural constraints despite better economic and social development. Western counties showed obstacles from both natural and economic subsystems, reflecting harsh natural conditions and lagging economic development [FIGURE:8, FIGURE:9].

4. Discussion

Complex ecosystem resilience shows substantial spatial variation in the Qilian Mountain area, requiring targeted strategies. The western region needs prioritized environmental protection, ecological restoration, and industrial restructuring to enhance resilience, while the eastern region' s advantages must be preserved. The natural subsystem forms the foundation for economic and social development, playing a decisive role in high-quality sustainable development. Economic subsystems support social development and enable ecological protection measures, while social subsystems, through livelihood conditions, urbanization, and education investment, shape environmental awareness.

The three subsystems exhibit strong interactions and improving conditions, with negative environmental impacts from economic and social development gradually diminishing. However, coordination development remains slow, requiring policy innovation and new growth drivers to achieve optimal states.

Natural and economic subsystems constitute primary constraints. Eastern regions, with better socioeconomic conditions, should prioritize ecological protection while pursuing development. Western regions, facing harsh environments and economic lag, should enhance economic development through multiple channels while protecting ecology, improving infrastructure, increasing science and education investment, and raising living standards.

5. Conclusions

From 2007 to 2021, complex ecosystem resilience in the Qilian Mountain area increased, with low and moderate resilience classes decreasing and high resilience classes increasing, particularly in the east. Spatial patterns show a gradual decrease from east to west. Natural subsystem resilience declined, decreasing from central-east to northwest. Economic subsystem resilience increased rapidly, concentrated in the east and north. Social subsystem resilience rose modestly, with higher levels in the east.

Coupling degree improved significantly, reaching high-level coupling, while coupling coordination fluctuated upward to achieve intermediate coordination. Primary obstacle factors include water conservation index, biological abundance index, forest-grass coverage rate, agricultural output growth rate, rural per capita net income, secondary industry proportion, and population density. The natural subsystem substantially influences resilience improvement, with economic subsystem indicator obstacle degrees increasing notably.

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