Analysis of Spatiotemporal Variation Characteristics and Influencing Factors of Resilience in the Loess Plateau Social-Ecological System: A Postprint

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Abstract

Social-ecological system resilience theory provides a new perspective for sustainable development research. Establishing an evaluation index system for social-ecological system resilience from the three major subsystems of society, economy, and ecology, along with the two key elements of vulnerability and adaptive capacity, this study employs set pair analysis to measure the resilience of each subsystem and the overall social-ecological system in the Loess Plateau from 2000 to 2018, utilizes exploratory spatial data analysis to examine spatiotemporal evolution patterns, and identifies the main influencing factors of social-ecological system resilience. The results show that: (1) From 2000 to 2018, social-ecological system resilience increased from 0.522 to 0.721. Social resilience increased from 0.548 to 0.629 and then decreased to 0.525; economic resilience continuously increased from 0.401 to 0.850; ecological resilience decreased from 0.725 to 0.607 and then increased to 0.734. The evolution trends of subsystem resilience were not coordinated, whereas the evolution trend of the economic system was coordinated with that of the social-ecological system. The enhancement of economic system resilience has a significant promoting effect on the enhancement of social-ecological system resilience. (2) Social-ecological system resilience exhibited a significant spatial agglomeration trend. In addition to provincial capital cities and energy-rich areas such as Baotou, the Guanzhong Plain region consistently showed a high-high (H-H) agglomeration pattern, while resilience in other regions was generally relatively low. (3) Since 2000, the obstacle degree of the ecological dimension of social-ecological system resilience in the Loess Plateau region has consistently been higher than that of the social and economic dimensions, and the primary influencing factor at the indicator level in different regions was per capita GDP.

Full Text

Spatio-temporal Characteristics and Influencing Factors of Social-Ecological System Resilience in the Loess Plateau

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Abstract: The resilience of social-ecological systems provides a new perspective for sustainable development research. To address the problem of highly unbalanced development in ecologically vulnerable areas and achieve sustainable development goals, this study constructed an evaluation index system for social-ecological system resilience. The set pair analysis method was employed to measure the resilience of each subsystem and the overall social-ecological system in the Loess Plateau from 2000 to 2018. Exploratory spatial data analysis was then used to examine spatio-temporal evolutionary patterns, while barrier degree models identified the main influencing factors. The results indicate: (1) Social-ecological system resilience gradually increased from 0.522 to 0.721, with the Guanzhong Plain region consistently showing higher values than other areas. Social resilience increased from 0.548 to 0.629 then decreased to 0.525, with high-value regions primarily located in provincial capitals such as Lanzhou and resource-based cities like Tongchuan, and its enhancement closely related to policy support for western regions. Economic resilience increased from 0.401 to 0.850, with its distribution pattern basically coinciding with urban agglomerations. Ecological resilience decreased from 0.725 to 0.607 then increased to 0.734, showing a gradual eastward-increasing ladder-like distribution pattern, with its enhancement closely related to ecological policies and climate warming-humidification trends. This demonstrates that the evolutionary trends of subsystem resilience were uncoordinated, except for economic system resilience which remained coordinated with the social-ecological system. Improving economic system resilience significantly promotes social-ecological system resilience. (2) The resilience of social-ecological systems exhibited pronounced spatial agglomeration trends. Except for provincial capitals and energy-rich regions such as Baotou City, the Guanzhong Plain region consistently showed high-high clusters, while other regions had relatively low resilience. Low-resilience areas were mainly concentrated in western regions such as Yinchuan City, whereas high-resilience areas were primarily concentrated in the Guanzhong Plain region centered around Baoji and Xi' an. (3) Since 2000, per capita GDP has been a major influential factor across all aspects. Ecological barriers to maintaining social-ecological resilience in the Loess Plateau were higher than socio-economic barriers. Except for slight increases in ecological barriers in individual areas, most regions showed a gradually decreasing trend, indicating that ecological policies are effective and that ecological construction represents one important strategy for improving social-ecological system resilience.

Keywords: social-ecological system; resilience; set pair analysis (SPA); exploratory spatial data analysis (ESDA); Loess Plateau

1 Introduction

Global climate change and human activities are causing ecosystem transformations, making sustainable development a key focus for scholars. The concept of resilience first emerged in ecosystem studies, and with its introduction to social-ecological systems, the concept has gradually been refined. The Resilience Alliance defines resilience as a system' s capacity to recover from external disturbances or unexpected events, which exhibits threshold effects—if a threshold is crossed, the system cannot return to its previous state. In the face of continuously changing and unpredictable environments, effective management of social-ecological system resilience can increase the likelihood of sustainable development.

The transition from theoretical research to practical application requires resilience assessment to identify main influencing factors and reveal driving mechanisms, thereby providing a basis for social-ecological system management. International research on resilience assessment has produced abundant theoretical and qualitative results. Cumming et al. proposed an exploratory framework for empirically measuring resilience. Michael et al. developed an analytical framework for coastal land optimization management based on specific research contexts and objectives. Bennett et al. proposed three basic models for quantifying resilience surrogates, while Gulay and Chaiteera presented methods for assessing ecosystem resilience using sensitivity and uncertainty evaluation. These frameworks and models are mostly based on specific research backgrounds and purposes, and no universally applicable framework has yet been developed.

Domestic research on resilience is still in its early stages, with limited achievements beyond literature reviews. Wang et al. measured drought resilience at the household scale in Yuzhong County, Gansu Province. Zhang et al. quantified resilience from a landscape perspective in ecologically fragile areas. Wang et al. and Chen et al. conducted quantitative studies on social-ecological system resilience in Qiandao Lake and Shennongjia Forest District respectively. Hou et al. evaluated grassland social-ecological system resilience using system dynamics methods. Recent scholarship emphasizes studying the adaptability of complex social-ecological systems when facing disturbances and the interaction processes between system vulnerability and adaptability. Vulnerability and resilience are closely related, with uncertain directional relationships. While some scholars treat resilience as the opposite of vulnerability, this approach remains scientifically controversial because quantifying resilience requires simultaneous consideration of system vulnerability and adaptive capacity.

The Loess Plateau holds an important position in national development strategy and serves as a crucial guarantee for sustainable energy security. Against the backdrop of the national strategy for ecological protection and high-quality development in the Yellow River Basin, the Loess Plateau, as a core ecologically fragile area in the middle and upper reaches of the Yellow River, is significant for advancing national strategy implementation. However, long-term unreasonable economic activities and resource development patterns have caused severe ecosystem degradation, becoming a major constraint on socio-economic sustainable development. Although phased progress has been achieved in ecological construction and environmental governance, residents' demands for continuously improving living standards will further intensify human-land relationships. Therefore, this study attempts to construct a research framework from the resilience perspective, selecting surrogate factors from the two major elements of system vulnerability and adaptive capacity to build a measurement index system for social-ecological system resilience. By measuring the resilience change patterns in the Loess Plateau from 2000 to 2018 and identifying influencing factors, this research aims to provide scientific decision-making support for ecological construction and socio-economic development in the region.

2 Data and Methods

2.1 Study Area and Data Sources

The Loess Plateau is located in northwestern China, spanning the middle and upper reaches of the Yellow River across Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, and Henan provinces. This study adopts the Loess Plateau boundary defined by the Resources and Environmental Science Data Center of the Chinese Academy of Sciences (Fig. [Figure 1: see original paper]), comprising 341 county-level administrative units (counties, banners, prefectures, and cities) with a total area of approximately 6.4\$×10^{5}\$ km^2, accounting for 6.4% of national territory. The region receives 300-650 mm annual precipitation, with elevation ranging from 1500-2000 m. Loess layer thickness increases from south to north, and the loose structure makes it highly susceptible to wind and water erosion, causing severe soil and water loss.

From 2000 to 2018, the Loess Plateau' s permanent population increased from 1.07\$×10^{8}\$ to 1.18\$×10$^{\{8\},whilepercapitaGDPgrewfrom5.1\times10}$\{3\}\$ to 4.6\$×10^{4}\$ yuan. Research data were obtained from: (1) Statistical yearbooks including the China County Statistical Yearbook, China City Statistical Yearbook, China Forestry Statistical Yearbook, and provincial statistical yearbooks from 2000-2018, with missing data replaced by adjacent years; (2) Land use data, NDVI, and DEM from the Resources and Environmental Science Data Center of the Chinese Academy of Sciences, derived from Landsat TM/ETM remote sensing images with 30m resolution, classified into 6 primary types; (3) Administrative boundary data for extraction using ArcGIS. To eliminate dimensional inconsistencies, range standardization was applied.

2.2 Research Framework

Social-ecological system research examines resilience from a complex dynamics perspective, providing new insights for human-environment relationships and sustainable development. Resilience has three key attributes: (1) the magnitude of disturbance a system can absorb while maintaining its structure and function; (2) system self-organization capacity; and (3) learning and adaptation capability. A resilient system can transform crises into opportunities to enter more desirable states.

Social-ecological systems are open, adaptive systems with close human-nature coupling, vulnerable to external disturbances with unpredictable, nonlinear, and multi-stable characteristics. When subjected to external shocks or crises, systems move within one or multiple "state spaces" defined by state variables. Stable systems are controlled by variables including: difficulty of system change (resistance), distance from thresholds (vulnerability), and magnitude of external disturbance. System stability under disturbance results from interactions between vulnerability and resistance, which jointly determine resilience. If resilience is high and disturbance remains below thresholds, the system maintains its original state or transitions to higher quality; if resilience is low and disturbance exceeds thresholds, the system stagnates, collapses, or enters a new state.

Direct resilience measurement is difficult as it requires determining thresholds between different stable states. However, measurable surrogate factors can be selected to quantify resilience through its main components: system vulnerability and adaptive capacity. Social-ecological systems can be deconstructed into social, economic, and ecological dimensions. In the Loess Plateau, vulnerability primarily stems from meteorological drought and fragmented topography, while resistance is mainly characterized by adaptive capacity. These surrogate factors act on the system in linear or nonlinear, rapid or slow, deterministic or uncertain ways, collectively determining system state and function.

2.3 Indicator System Construction

Following principles of scientific rigor, systematicity, and data availability, key controlling variables were selected through field investigation, researcher knowledge, and correlation analysis. The final system comprises 16 indicators across three subsystems and two elements (Table).

Social Subsystem: Population density measures social pressure; per capita fixed asset investment and fiscal expenditure measure social investment support; consumption capacity, education level, and medical care level measure learning and adaptation capacity.

Economic Subsystem: Industrial structure is the core, directly affecting regional economic level and ecological environment. Given lagging industrial development in the Loess Plateau, the industrial structure diversification index reflects comprehensive development level. The diversification index (r) is calculated as: r = - (xi × ln xi), where xi is the proportion of each industry' s output value to total output, and n is the total number of industries (here n=3). Financial institution loans characterize economic vulnerability, while fiscal revenue, per capita GDP, and deposit balances measure economic strength and adaptive capacity.

Ecological Subsystem: Precipitation, fertilizer application intensity, and terrain fragmentation characterize ecological vulnerability, with terrain fragmentation measured by elevation standard deviation. Land use intensity, afforestation area, and NDVI characterize adaptive capacity. Land use intensity (L) is calculated as: L = (Ai × si), where Ai is the land use intensity grading index (construction land=4, cultivated land=3, woodland/grassland/water=2, unused land=1), si is the area of land type i, and s is total land area.

2.4 Methods

2.4.1 Weight Determination To avoid subjectivity and bias from data itself, a combined weighting method was adopted using both Analytic Hierarchy Process (AHP) and mean-square deviation decision layering. The mean-square deviation method reflects random variable dispersion degree. For each dimension layer, evaluation indicators are treated as random variables, with mean-square deviations normalized:

$sij = \sqrt{[\ (rij - uij)^2/n]}$
$wij = sij\ /\ \ sij$

where sij, wij, rij, uij represent variance, weight, standardized value, and mean value of indicator j in dimension i, respectively, and n is sample size.

2.4.2 Set Pair Analysis (SPA) SPA treats uncertainty and certainty as an integrated system, describing their interdependence, connection, and transformation under specific conditions. It has been widely applied in comprehensive evaluation, risk assessment, and vulnerability evaluation. For multi-attribute evaluation, let $M = \{E, Q, W, U, V\}$, where $E = \{e_1, e_2, \cdots, e\ \}$ is the evaluation object set, $Q = \{q_1, q_2, \cdots, q\ \}$ is the evaluation scheme set, $W = \{w_1, w_2, \cdots, w\ \}$ is the indicator weight set, $U = \{u_1, u_2, \cdots, u\ \}$ is the optimal evaluation set, and $V = \{v_1, v_2, \cdots, v\ \}$ is the worst evaluation set. The connection degree between scheme q and optimal set U is:

$= a\ \ + b\ i + c\ j$

where a is identity degree, b is difference degree, c is opposition degree, i and j are coefficients. The relative closeness degree r is:

$r\ \ = a\ /(a\ \ + c\ )$

where a = w a and c = w c . For positive indicators: a = t /(u + v), c = t /(u + v); for negative indicators: a = t /(u + v), c = t /(u + v). Larger r values indicate closer proximity to the optimal scheme.

2.4.3 Exploratory Spatial Data Analysis (ESDA) ESDA was used to reveal spatial distribution and correlation characteristics of resilience. Global spatial autocorrelation measures overall spatial association through Moran’ s I:

$$I = [n\ \ w\ \ (x\ - \bar{x})(x\ - \bar{x})]\ /\ [S^2\ \ w\ \ ]$$

where n is the number of spatial units, w is the spatial weight matrix element, x and x are resilience indices at locations i and j, and $\bar{x}$ is the mean resilience.

Local spatial autocorrelation measures local association between each region and its neighbors:

$$I\ = Z\ \ w\ \ Z$$

where Z and Z are standardized resilience values. If I is significantly positive and $Z > 0$, it indicates high-high (HH) clustering; if $I > 0$ and $Z < 0$, low-low (LL) clustering; if $I < 0$ and $Z < 0$, low-high (LH) clustering; if $I < 0$ and $Z > 0$, high-low (HL) clustering. Significance is tested using Z-statistics.

2.4.4 Obstacle Degree Model The obstacle degree model identifies key obstacle factors from factor contribution degree (G), indicator deviation degree (P), and obstacle degree (Z):

$$P\ \ = 1 - Y$$
$$Z\ \ = (P\ \ \times G\ \ )\ /\ \ (P\ \ \times G\ \ ) \times 100\%$$

where Y is the standardized value of indicator j in dimension i, and G represents factor contribution degree (generally expressed as weight).

3 Results

3.1 Temporal Evolution Characteristics of Subsystem Resilience

3.1.1 Social System Resilience Using the natural breaks method in ArcGIS, results were classified into five levels and visualized. Social resilience averaged 0.548, 0.629, and 0.525 for 2000, 2009, and 2018 respectively, showing an initial increase followed by decrease (Fig. [Figure 3: see original paper]a_1-a_3). In 2000, high social resilience areas were mainly provincial capitals and resource-based cities such as Lanzhou, Xi’ an, Baotou, Hohhot, Yinchuan, and Tongchuan. By 2009, social resilience generally improved, particularly in energy-rich regions centered on Ordos. By 2018, except for provincial capitals, energy-rich regions, and some counties, most areas showed declining trends, especially in Qinghai, northern Shaanxi, and Shanxi counties dependent on external investment. The initial increase resulted from western development policies that boosted fixed asset investment, fiscal expenditure, and medical facilities. The subsequent decline reflects slowing fiscal expenditure growth.

3.1.2 Economic System Resilience Economic resilience averaged 0.401, 0.647, and 0.850 for the three periods, showing continuously accelerating enhancement (Fig. [Figure 3: see original paper]b_1-b_3). In 2000, except for provincial capitals and cities like Xi’ an and Taiyuan, most counties had low values, particularly in eastern Gansu. By 2009, significant improvements occurred in Longdong, Guanzhong Plain, and most of Inner Mongolia. By 2018, areas around growth poles showed widespread enhancement. The improvement primarily resulted from increased economic development and per capita GDP. The distribution pattern aligns with urban agglomerations, with high values in resource-rich regions (Ordos, Baotou) in the northwest and in Taiyuan, Xi' an, and Luoyang in the southeast. Economic resilience heavily depends on per capita GDP and capital investment, with "double non" regions (non-resource-rich, non-urban agglomeration) consistently showing low levels.

3.1.3 Ecological System Resilience Ecological resilience averaged 0.725, 0.607, and 0.734, showing initial decline followed by increase, with significant spatial differentiation and a ladder-like distribution from low (west) to high (east) (Fig. [Figure 3: see original paper]c_1-c_3). The Guanzhong Plain maintained high levels, while northwestern regions (Qinghai, Inner Mongolia, Ningxia) remained low. The initial decline resulted from severe soil erosion and land degradation. After 2009, national ecological projects, especially the "Grain for Green" program, and warming-humidification climate trends improved vegetation growth and primary productivity, reducing soil erosion and desertification. Post-2013, as the program entered its consolidation phase, afforestation area decreased.

3.1.4 Social-Ecological System Resilience Overall system resilience averaged 0.522, 0.639, and 0.721, showing continuous enhancement with significant spatial differentiation (Fig. [Figure 3: see original paper]d_1-d_3). The Guanzhong Plain consistently showed high levels. Except for economic and social-ecological systems maintaining coordinated trends, other subsystems and subsystem-system relationships were uncoordinated. While high economic resilience doesn' t guarantee high social-ecological resilience, high social-ecological resilience regions always have relatively high economic resilience.

3.2 Spatial Exploratory Analysis

Global spatial autocorrelation analysis revealed significant positive spatial correlation (Table). Moran's I values were 0.421, 0.408, and 0.384 for 2000, 2009, and 2018 respectively, all significant at the 0.01 level, indicating significant spatial clustering.

Local spatial autocorrelation analysis (Fig. [Figure 4: see original paper]) identified four cluster types. HH clusters numbered 25, 31, and 35 units, mainly in Baoji, Xi' an, Sanmenxia, Luoyang in the south and Yangquan, Changzhi in the east. LL clusters numbered 28, 30, and 32 units, mainly in Xining, Ordos, Bayannur, Wuhai, Yinchuan, Shizuishan, Wuzhong, and Qingtongxia. LH clusters numbered 15, 12, and 10 units, mainly in Tianshui, Baoji, Tongchuan, Weinan, and Sanmenxia. HL clusters numbered 12, 11, and 10 units, mainly in Lanzhou, Baiyin, most of Ningxia, and Bayannur. High resilience concentrated in the Guanzhong Plain, while low resilience concentrated in northwestern regions like Bayannur and Zhongwei.

3.3 Influencing Factors Analysis

Barrier degree analysis identified key obstacles at both dimension and indicator levels (Tables and). At the dimension level, ecological barriers consistently exceeded social and economic barriers. Qinghai, Gansu, Ningxia, and Inner Mongolia showed ecological > economic > social dimensions, while Shaanxi, Shanxi, and Henan showed social > economic > ecological dimensions. Ecological barriers gradually decreased in most areas, indicating policy effectiveness.

At the indicator level, top five obstacles varied by period and region. Per capita GDP was the primary obstacle factor across the entire region and time series. Precipitation was the main obstacle in Ningxia and Inner Mongolia. Fiscal expenditure and fixed asset investment were major obstacles in Gansu and Shaanxi. Terrain fragmentation became the primary obstacle in Shanxi after 2009. Industrial structure was a key constraint in Qinghai. Overall, per capita GDP, fiscal expenditure, precipitation, fixed asset investment, and industrial output value of enterprises above designated size were the main factors limiting resilience improvement.

4 Discussion

Resilience theory provides a new perspective for sustainable development research. This study represents an attempt to explore Loess Plateau sustainability and Yellow River Basin high-quality development from the resilience perspective, particularly following the “Grain for Green” program. The analysis of resilience changes since 2000 offers valuable references for establishing future ecological construction and socio-economic development directions.

Several limitations exist. Land use data were classified into 6 primary types without finer subdivision, which should be improved in future research to provide optimization bases for land use planning from a resilience perspective. The obstacle degree model was applied at provincial level for policy convenience, though internal regional similarities exist. Social-ecological systems are complex and dynamic, and this study may not include all influencing factors, focusing only on ranking their importance without analyzing internal interactions. The 2000-2018 period represents a relatively short historical phase; longer-term studies are needed to determine resilience thresholds and stable states, or comparative studies with other regions for more objective evaluation. Micro-scale household data could reveal bottom-up driving mechanisms through scale interaction analysis.

Based on findings, we propose: (1) The Loess Plateau’ s arid climate and terrain constrain resilience. While ecological construction has achieved remarkable results, the contradiction between ecological construction and sustainable development persists. The main task is exploring a sustainable development path under ecological protection. (2) Internal development is extremely unbalanced, with energy-rich regions and the Guanzhong Plain showing clear economic advantages. Sustainable development requires resource-based city transformation and green industry transition, with policy adjustments according to local conditions to narrow internal gaps. (3) While improving economic development and narrowing gaps, promote equalization of basic public services, strengthen infrastructure, and enhance social welfare. (4) Advance the national rural revitalization strategy, develop characteristic agriculture with intensive and scaled cultivation, and improve rural living conditions.

5 Conclusions

This study integrated socio-economic statistics and remote sensing data to establish a multi-level, multi-factor research framework for social-ecological system resilience in the Loess Plateau, revealing spatio-temporal evolution characteristics and influencing factors. Main conclusions are:

(1) From 2000-2018, social resilience showed an initial increase then decrease, with high values in provincial capitals and resource-based cities, closely related to national policy support. Economic resilience continuously increased, with distribution patterns matching urban agglomerations. Ecological resilience initially decreased then increased, showing a ladder-like eastward-increasing distribution, with enhancement closely related to ecological policies and climate trends.

(2) Social-ecological system resilience showed significant spatial positive correlation with pronounced local clustering trends. High-high clusters centered on the Guanzhong Plain, while low-low clusters concentrated in northwestern regions.

(3) Ecological barriers consistently exceeded socio-economic barriers, though most areas showed gradually decreasing ecological barriers, indicating effective ecological policies. Per capita GDP was the primary obstacle factor across all regions and periods.

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