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Spatiotemporal Differentiation of Composite Ecosystem Resilience in the Ecologically Vulnerable Upper Yellow River Region: A Case Study of Ningxia (Postprint)

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Abstract

Enhancing the disturbance resistance and recovery capacity of ecologically fragile areas constitutes a crucial component of ecological civilization construction. This study develops a composite ecosystem resilience assessment model from multi-dimensional economic, social, and natural perspectives, employing the entropy method and GIS spatial analysis to conduct spatiotemporal heterogeneity analysis of Ningxia's composite ecosystem resilience from 2010 to 2020. The coupling coordination model, correlation analysis, and obstacle degree model are utilized to diagnose key factors influencing ecological resilience enhancement. The results indicate: (1) The composite ecosystem resilience level in Ningxia demonstrates an upward trend, yet the overall level remains relatively low, with economic resilience exhibiting the most rapid growth. High economic resilience is densely distributed in the northern region, high social resilience is distributed in contiguous patches centered on urban districts, and high natural resilience is primarily concentrated in the eastern, southern, western, and northern corners, with northern composite ecosystem resilience surpassing that of the central and southern regions. (2) Ningxia' s composite ecosystem exhibits high coupling but low coordination, with the coupling coordination degree improving slowly during the study period, as most districts and counties remain in states of severe and moderate disharmony. (3) Economic structure shows strong positive correlations with economic potential, infrastructure, livelihood improvement, and natural environment. At the criterion level, population size, environmental pressure, and economic vitality significantly influence composite ecosystem resilience enhancement, while at the indicator level, total energy consumption and the number of personnel in transportation, storage, and postal services substantially impact resilience improvement in most districts and counties. Going forward, actively leveraging the positive synergistic effects of various influencing factors to rapidly enhance Ningxia' s composite ecosystem resilience will effectively support the construction of the Yellow River Basin ecological protection and high-quality development demonstration zone.

Full Text

Spatio-temporal Differentiation of Composite Ecosystem Resilience in Ecologically Fragile Areas of the Upper Yellow River: A Case Study of Ningxia

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Abstract

Enhancing the disturbance resistance and recovery capacity of ecologically fragile areas constitutes a critical component of ecological civilization construction. This study constructs a composite ecosystem resilience assessment model from economic, social, and natural multidimensional perspectives. Using the entropy method and GIS spatial analysis, we analyze the spatio-temporal differentiation of composite ecosystem resilience in Ningxia from 2010 to 2020. The coupling coordination model, correlation analysis, and obstacle degree model are employed to diagnose key factors influencing ecological resilience enhancement. Results indicate: (1) Composite ecosystem resilience demonstrates an upward trend, yet remains at a relatively low overall level, with economic resilience exhibiting the fastest growth rate. High economic resilience is densely concentrated in the north, high social resilience is distributed in contiguous patches centered on urban districts, and high natural resilience is primarily distributed in the eastern, southern, western, and northern peripheries. The composite ecosystem resilience in northern Ningxia exceeds that in the central and southern regions. (2) The coupling degree of Ningxia' s composite ecosystem is relatively high, while the coordination degree is comparatively low. Coupling coordination degree improved slowly during the study period, with most districts and counties remaining in states of severe or moderate imbalance. (3) Economic structure shows strong positive correlations with economic potential, infrastructure, livelihood improvement, and natural environment. At the criterion level, population factors, environmental pressure, and economic vitality significantly impact composite ecosystem resilience enhancement. At the indicator level, comprehensive energy consumption and transportation, storage, and postal service personnel numbers substantially influence resilience improvement across most districts and counties. Future efforts should actively leverage the positive synergistic effects of various influencing factors to rapidly enhance Ningxia' s composite ecosystem resilience, thereby effectively supporting ecological protection and high-quality pilot zone construction in the Yellow River Basin.

Keywords: composite ecosystem resilience; coupling coordination degree; correlation analysis; obstacle degree model; ecologically fragile areas; upper reaches of the Yellow River

Introduction

Ecologically fragile areas typically occur at transition zones between different ecosystem types. In China, moderately or severely fragile ecological zones account for approximately 55% of total land area, predominantly distributed across northern arid and semi-arid regions, the Qinghai-Tibet Plateau, southwestern mountainous areas, southern hilly regions, and coastal land-water transition zones. These areas generally exhibit unstable internal structures under multi-source risks and variable disturbances, displaying strong sensitivity to external interference that exacerbates ecological problems, including accelerated soil erosion, desertification, biodiversity loss, and declining environmental carrying capacity. The inherent uncertainty of ecological issues in fragile areas can be investigated through ecological resilience theory, which emphasizes the capacity to absorb, resist, adapt to, and recover from shocks and disturbances.

Recent research on resilience concepts, resilience assessment, and disaster resilience response has provided theoretical foundations for ecological resilience studies. Common ecological resilience assessment models include pressure-conduction-potential, resistance-adaptation-recovery, and scale-density-morphology frameworks. However, most ecological resilience research has focused on urban areas, with few studies addressing ecologically fragile zones, particularly in the upper Yellow River region. Existing studies rarely incorporate economic and social indicators, seldom examine correlations between indicators, internal coupling coordination of ecological resilience, obstacle degrees, or spatio-temporal differentiation, thus limiting accurate revelation of ecological resilience mechanisms. Therefore, investigating spatio-temporal differentiation of composite ecosystem resilience in the upper Yellow River region can expand theoretical perspectives on ecological resilience and ecological civilization, while providing theoretical support for enhancing ecological resilience in fragile areas of the upper Yellow River basin.

Ningxia, located in the ecologically fragile zone at the intersection of agriculture and animal husbandry in northern China, experiences harsh natural conditions and frequent natural disasters that cause significant casualties and economic losses. As an important ecological security barrier for northwestern China and the upper Yellow River region, Ningxia bears a critical mission to maintain regional and national ecological security. As the only province entirely within the Yellow River basin and a pilot zone for ecological protection and high-quality development in the Yellow River basin, Ningxia must possess the capacity to resist uncertain risks and recover after disturbances. Ningxia' s geographical location, ecological environment, ecological fragility, and economic development share similarities with the broader upper Yellow River region, making it a representative case study. This research constructs a composite ecosystem resilience evaluation system for Ningxia, employing the entropy method, coupling coordination model, correlation analysis, and obstacle degree model to assess composite ecosystem resilience, explore its spatio-temporal evolution, and diagnose key factors influencing resilience enhancement. The findings provide decision-making support for countering uncertain risks, ecological restoration, and enhancing zonal governance capacity in ecologically fragile areas of the upper Yellow River.

1.1 Study Area and Data

Ningxia is situated in the upper reaches of the Yellow River, encompassing the Helan, Luoshan, and Liupan Mountains. Located between 104°17 -107°29 E and 35°14 -39°23 N, Ningxia features a temperate continental climate with arid conditions and low precipitation. Annual precipitation ranges from 166.9–647.3 mm, average annual temperature varies from 5.3–9.9°C, and annual evaporation reaches 1312–2204 mm. The region is dominated by dry steppe and desert steppe vegetation with low coverage, severe grassland degradation and desertification, water resource shortages, and serious soil erosion. Ningxia is surrounded by the Mu Us Sandy Land, Tengger Desert, Loess Plateau, and Ulan Buh Desert. Based on its ecological foundation, the region is divided into a northern green development zone, central conservation zone, and southern water source conservation zone.

Data sources (Table 1) primarily include the *Ningxia Statistical Yearbook* (2010-2020) and statistical yearbooks and bulletins from Ningxia' s counties (cities, districts). Missing data were supplemented using exponential smoothing methods. All natural data were converted to the county-level scale as the minimum unit. Elevation data were obtained from the Geospatial Data Cloud platform' s GDEMV2 30 m × 30 m resolution raster data.

[Figure 1: see original paper] Overview of the study area

1.2 Indicator System Construction

Based on theories of resilient cities, ecological vulnerability, and "ruralism-ecology" resilience, we selected indicators and criterion layers that can comprehensively evaluate Ningxia' s composite ecosystem resilience. Considering Ningxia' s actual conditions—such as its arid and semi-arid climate dominated by dry steppe and desert steppe—we converted the commonly used forestland indicator to grassland. Given Ningxia' s water scarcity, we included water conservancy and environmental infrastructure investment indicators to construct the composite ecosystem resilience evaluation system.

The indicator system comprises 27 indicators across three dimensions: economic resilience (8 indicators), social resilience (9 indicators), and natural resilience (10 indicators). Specific indicators include average wages of non-private enterprises, number of industrial enterprises above designated size, retail sales of consumer goods, fiscal budget revenue, GDP, per capita disposable income, proportion of tertiary industry, general public budget expenditure, transportation/storage/postal personnel, water conservancy and environmental infrastructure investment, crop yield, number of employees, villages with tap water benefits, permanent population, population growth rate, health technicians, industrial sulfur dioxide emissions, domestic wastewater discharge, domestic soot emissions, waste gas treatment facilities, industrial solid waste comprehensive utilization, domestic sewage treatment volume, and comprehensive energy consumption. "+" indicates positive indicators and "-" indicates negative indicators.

1.3 Composite Ecosystem Resilience Evaluation Model

Assuming the value of indicator j in year i for a county in the study area is x_{ij}, we construct an $m \times n$ matrix. The composite ecosystem resilience evaluation model is constructed as follows:

$$R_{eco} = \sum_{j=1}^{8} w_j p_{ij}, \quad R_{soc} = \sum_{j=9}^{17} w_j p_{ij}, \quad R_{nat} = \sum_{j=18}^{27} w_j p_{ij}, \quad R = R_{eco} + R_{soc} + R_{nat}$$

where R_{eco}, R_{soc}, R_{nat}, and R represent the economic resilience index, social resilience index, natural resilience index, and composite ecosystem resilience index, respectively. The natural breakpoint method is used to classify resilience levels into low, medium, and high categories.

The weight w_{j} for indicator j is determined using the entropy method:

$$e_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} p_{ij} \ln(p_{ij}), \quad d_j = 1 - e_j, \quad w_j = \frac{d_j}{\sum_{j=1}^{m} d_j}$$

where p_{ij} is the normalized value, and e_{j} and d_{j} are the entropy value and information entropy redundancy of indicator j, respectively.

To eliminate dimensional effects, the range standardization method is applied:

$$X_{ij} = \frac{x_{ij} - \min(x_{1j}, \cdots, x_{nj})}{\max(x_{1j}, \cdots, x_{nj}) - \min(x_{1j}, \cdots, x_{nj})} \quad \text{(for positive indicators)}$$

$$X_{ij} = \frac{\max(x_{1j}, \cdots, x_{nj}) - x_{ij}}{\max(x_{1j}, \cdots, x_{nj}) - \min(x_{1j}, \cdots, x_{nj})} \quad \text{(for negative indicators)}$$

1.4 Coupling Coordination Degree Model

Coupling coordination refers to the interaction and coordination degree among two or more subsystems under internal and external influences, used to evaluate the development quality of composite ecosystem resilience.

$$C = \frac{3 \times \sqrt[3]{R_{eco} \times R_{soc} \times R_{nat}}}{R_{eco} + R_{soc} + R_{nat}}, \quad T = aR_{eco} + bR_{soc} + cR_{nat}, \quad D = \sqrt{C \times T}$$

where D is the coupling coordination degree, C is the coupling degree (higher values indicate stronger interactions among subsystems), T is the coordination degree (higher values indicate better coordination), and a, b, c represent the weights of each subsystem' s resilience. Following Wang et al.' s revision of the coupling coordination degree model, we classify coupling coordination degrees into ten categories ranging from extreme imbalance [0, 0.1) to high-quality coordination [0.9, 1].

Grade classification of the coupled coordination degree model

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1.5 Obstacle Degree Model

The obstacle degree model diagnoses the criterion and indicator layers of composite ecosystem resilience to identify key factors hindering resilience enhancement.

$$V_j = 1 - X_j, \quad H_j = \frac{E_j \times V_j}{\sum_{j=1}^{m} (E_j \times V_j)} \times 100\%$$

where H_{j} is the obstacle degree (higher values indicate stronger hindrance), E_{j} is the factor contribution degree (i.e., the weight w_{j}), and V_{j} is the indicator deviation degree, representing the gap between the standardized value Y_{j} and the maximum value of indicator j.

2.1 Spatio-temporal Evolution Characteristics of Composite Ecosystem Resilience in Ningxia

During the study period, Ningxia' s composite ecosystem resilience showed an upward trend, increasing from 0.189 in 2010 to 0.312 in 2020, with an overall growth rate of 65.1%. Except for negative growth in 2015, all other years exhibited positive growth. The 2015 decline resulted from decreased social and natural resilience compared to 2014.

Economic, social, natural, and composite ecosystem resilience all showed upward trends, increasing by 0.111 (137.0%), 0.025 (19.7%), 0.015 (11.4%), and 0.123 (65.1%), respectively. Economic resilience grew fastest in 2016 (21.7%). Social resilience declined only in 2015, reaching its highest level in 2020. Natural resilience grew fastest in 2010 (11.4%), with slower growth in other years and a decline in 2015. Economic resilience exceeded social resilience after 2018, becoming the highest among the three subsystems.

Spatially, Ningxia’ s composite ecosystem resilience exhibited significant differentiation from 2010 to 2020 (Figure 3). For economic resilience, most northern counties upgraded from low to high resilience, while central and southern counties improved from low to medium resilience, with overall northern levels exceeding central and southern areas. For social resilience, northern and southern counties transitioned from low/medium to high resilience, while central counties showed minimal change, remaining at low/medium levels. High social resilience is distributed in contiguous patches centered on urban districts, with higher levels in the north and south than in the center. For natural resilience, peripheral eastern, western, southern, and northern areas upgraded from low/medium to high resilience, while central counties remained at low resilience, showing higher levels in peripheral than central areas. For composite ecosystem resilience, northern counties mainly upgraded from low to medium/high resilience, while central and southern counties improved from low to medium resilience, with Yongning and Hongsibu consistently showing low resilience. Northern composite ecosystem resilience exceeds that of central and southern regions.

[Figure 2: see original paper] Dynamic trends of resilience of the composite ecosystems in Ningxia from 2010 to 2020
[Figure 3: see original paper] Spatial distribution of economic, social and natural resilience in ecologically fragile areas of Ningxia

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2.2 Spatio-temporal Characteristics of Coupling Coordination in Ningxia’ s Composite Ecosystem

Table 3 presents the coupling degree, coordination degree, and coupling coordination degree of Ningxia’ s subsystems from 2010 to 2020. The average coupling degree was 0.978, indicating strong interactions among the three subsystems that remained at high levels throughout the study period.

The coordination degree declined annually from 2010 to 2015 but increased from 2015 to 2020, rising from 0.189 to 0.312, indicating gradually strengthening coordination among subsystems. The coupling coordination degree also increased from 0.431 to 0.553, but remained in a state of severe imbalance, suggesting that economic and social development intensified resource and environmental pressures. However, the increasing coupling coordination degree indicates the system is evolving toward greater order, necessitating strengthened coordination among economic, social, and natural systems in Ningxia’ s ecologically fragile areas.

All districts and counties showed varying degrees of improvement in coupling coordination degree (Figure 4). Lingwu showed the greatest improvement (0.178), while Hongsibu showed the smallest (0.056). In 2020, Yinchuan urban district had the highest coupling coordination degree, while Hongsibu had the lowest. Although Hongsibu’ s economic and social resilience improved, its natural resilience remained low, requiring greater attention to environmental protection alongside economic and social development. From 2010 to 2020, Yinchuan urban district’s coupling coordination degree shifted from moderate to mild imbalance, Lingwu shifted from severe to moderate imbalance, and Shizuishan urban district remained in moderate imbalance, while other counties remained in severe imbalance.

[Figure 4: see original paper] Radar diagram of coupling coordination degree of subsystem of districts and counties in Ningxia

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2.3 Spatio-temporal Characteristics of Obstacle Degrees in Ningxia’ s Composite Ecosystem

Correlation analysis at the criterion layer is crucial for identifying factors influencing composite ecosystem resilience (Table 4). Ningxia’s composite ecosystem resilience shows extremely significant positive correlations between economic resilience and infrastructure (0.847), economic potential (0.807), livelihood improvement (0.807), and natural environment (0.804) at $p < 0.01$, indicating that higher economic resilience promotes these dimensions. Lower economic resilience inhibits them. The correlation coefficient between natural and social resilience is 0.794 ($p < 0.01$), reflecting that natural resilience is significantly influenced by economic and social resilience, with mutual interactions among all three dimensions.

Based on correlation analysis, obstacle degree analysis was conducted at both criterion and indicator layers. At the criterion layer, all obstacle degrees showed fluctuating increases except for economic structure, which fluctuated downward (Table 5). Population factors (B7) showed the highest obstacle degree (17.46%), while environmental pressure (B9) showed the greatest variation coefficient (0.23), though overall variation across years and criteria remained limited. Average obstacle degrees ranked as: population factors (17.46%) > economic vitality (13.58%) > natural environment (12.89%) > livelihood improvement (12.52%) > infrastructure (11.96%) > economic potential (11.83%) > ecological governance (10.98%) > economic structure (9.24%) > environmental pressure (8.53%).

At the indicator layer, the top five obstacle factors in 2020 were: comprehensive energy consumption (18.21%), transportation/storage/postal personnel (11.34%), health technicians (9.87%), retail sales of consumer goods (8.93%), and crop yield (8.21%). Comprehensive energy consumption, from the natural environment criterion layer, consistently ranked first across years, significantly impacting Ningxia' s composite ecosystem resilience. Districts and counties must utilize resources rationally and pursue sustainable development. Transportation/storage/postal personnel, from social resilience, ranked highly and increased in proportion and ranking compared to 2010, reflecting growing social factor influence. Retail sales of consumer goods, from economic resilience, decreased in proportion and ranking, indicating diminishing economic factor influence relative to Ningxia' s economic resilience improvement.

Spatially, obstacle factors show significant variation across Ningxia' s districts and counties (Figure 5). In 2020, the top three obstacle factors were distributed as follows: comprehensive energy consumption ranked first in 15 counties, mainly in Yinchuan, central, and southern Ningxia; transportation/storage/postal personnel ranked second in 13 counties, mainly in Wuzhong; and health technicians ranked third in 11 counties, distributed across central and southern areas. This indicates that natural factors most significantly impact resilience improvement, followed by social factors. In Yinchuan urban district, the top five obstacle factors all originated from natural resilience, suggesting that environmental protection must be prioritized alongside economic development and social stability.

[Figure 5: see original paper] Spatial distribution of the top 3 obstacle factors in Ningxia in 2020

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3 Discussion

During the 12th Five-Year Plan period, Ningxia seized opportunities from the Western Development Strategy and Belt and Road Initiative, achieving a new level of comprehensive opening-up. The 13th Five-Year Plan represented the decisive stage in building a moderately prosperous society, during which Ningxia maintained steady progress while deepening Minning poverty alleviation cooperation. By 2020, all districts and counties reached medium resilience or above, laying a solid foundation for synchronized moderate prosperity.

Concurrently, Ningxia vigorously promoted livelihood projects and infrastructure connectivity, substantially improving infrastructure levels. However, these facilities concentrated in urban districts, leaving some counties with low social resilience. Among the three subsystems, natural resilience had the most counties at high resilience levels in 2020. With ecological civilization integrated into the "Five-Sphere Integrated Plan," Ningxia vigorously promoted ecological construction, scientifically planning production, living, and ecological spaces, implementing "ecological priority" strategies, demarcating ecological protection red lines, and coordinating mountain protection, water management, afforestation, farmland conservation, lake preservation, grass cultivation, and desertification control, achieving remarkable ecological progress.

Ningxia’ s central region serves as a conservation zone located in an arid belt with harsh natural conditions and consistently low natural resilience, where the primary task remains sand fixation. While each subsystem developed well, contributing to composite ecosystem resilience improvement, low coupling coordination among subsystems slowed overall resilience enhancement.

Ecologically fragile areas represent extremely complex giant systems with integrity, complexity, openness, and dynamic characteristics, wherein subsystem elements develop not linearly in parallel but through mutual interactions. Given limited understanding of ecological resilience connotations and predominant focus on natural aspects in indicator selection, this study incorporates economic and social dimensions to construct a composite ecosystem assessment model. Limited by data availability, the analysis period is relatively short and lacks horizontal comparison with other regions. Long-term temporal and regional difference studies would optimize resilience enhancement in ecologically fragile areas of the upper Yellow River basin. Future research should establish relevant models to objectively and comprehensively select evaluation indicators, obtain accurate values through field surveys and multi-source data fusion, and explore coupling relationships between composite ecosystem resilience and urbanization or industrial development.

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4 Conclusion

This study constructs a composite ecosystem resilience evaluation system for Ningxia from economic, social, and natural multidimensional perspectives. Using econometric models and spatial analysis methods, we assess Ningxia’ s composite ecosystem resilience from 2010 to 2020, analyze coupling coordination among subsystems, and diagnose key influencing factors through correlation analysis and obstacle degree models.

Ningxia’ s composite ecosystem resilience shows a steady upward trend but remains at a relatively low overall level, with economic resilience growing fastest. High economic resilience is densely distributed in the north, high social resilience is distributed in contiguous patches centered on urban districts, and high natural resilience is primarily located in peripheral eastern, western, southern, and northern areas. Northern composite ecosystem resilience exceeds that of central and southern regions.

The coupling degree of Ningxia’ s composite ecosystem is high, while the coordination degree shows an upward trend but remains relatively low overall. Coupling coordination among subsystems increased slowly, staying in severe imbalance, with most districts and counties in severe or moderate imbalance states.

At the criterion level, population factors, economic vitality, and ecological restoration significantly impact composite ecosystem resilience enhancement. At the indicator level, comprehensive energy consumption and transportation/storage/postal personnel numbers substantially influenced resilience improvement in 2020.

Economic resilience: Ningxia should leverage its strategic positioning as a pilot zone and the Yellow River "Ji" character bend metropolitan area hub to develop the inland open economy experimental zone.

Social resilience: Construct a "one core, one belt, one sub-center" spatial pattern, with Yinchuan as the core radiating to the Yellow River "Ji" character bend regional center, promoting development of the Yellow River urban belt, and establishing Guyuan as the southern sub-center and tourism city.

Natural resilience: As a pilot zone for ecological protection and high-quality development, Ningxia should build the Yellow River ecological corridor and the Helan-Luoshan-Liupan mountain ecological barriers, forming a "one river, three mountains" ecological pattern.

Composite ecosystem resilience: Develop the Yellow River ecological economic belt to radiate and drive high-quality development in the northern green development zone, central conservation zone, and southern water source conservation zone, forming a "one belt, three zones" development and protection pattern with mutual promotion and benign interaction.

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