Spatiotemporal Evolution Characteristics and Influencing Factors of Urban Ecological Resilience in the Yellow River Basin (postprint)

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Date: 2024-04-01T00:00:00+00:00

Abstract

Scientific assessment of urban ecological resilience in the Yellow River Basin is crucial for shaping high-quality development advantages and creating resilient and livable environments in the basin. Based on a four-dimensional framework of "Pressure-State-Response-Innovation," an evaluation system for urban ecological resilience is constructed, employing methods such as kernel density estimation and Dagum Gini coefficient to examine the temporal evolution, spatial distribution, and spatial differentiation characteristics of urban ecological resilience in the Yellow River Basin from 2011 to 2020, and using a spatial Durbin model to analyze its influencing factors. The results indicate: (1) Urban ecological resilience in the Yellow River Basin has been effectively enhanced, with varying evolutionary processes and polarization characteristics across the upper, middle, and lower reaches. (2) The spatial pattern of urban ecological resilience exhibits a gradient decreasing from "lower reaches-middle reaches-upper reaches," with evident spatial agglomeration and regional differentiation features. (3) The overall and intra-regional differences in urban ecological resilience have shown a fluctuating decline, with inter-regional differences being the primary source of spatial disparity, contributing an average of 65.44% annually. (4) Precipitation, economic development level, and public safety construction exert positive impacts on the enhancement of urban ecological resilience in the Yellow River Basin, the level of opening-up demonstrates positive spillover effects, infrastructure construction and government intervention also exhibit positive spillover effects in the process of enhancing local urban ecological resilience, while land development intensity and environmental pollution level constrain the improvement of urban ecological resilience, and environmental pollution level also generates negative spillover effects. Moreover, the effects of influencing factors vary significantly across the upper, middle, and lower reaches of the Yellow River.

Full Text

Spatiotemporal Evolution Characteristics and Influencing Factors of Urban Ecological Resilience in the Yellow River Basin

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Abstract: Scientific assessment of urban ecological resilience in the Yellow River Basin is crucial for shaping high-quality development advantages and creating resilient, livable environments. Based on a four-dimensional "Pressure-State-Response-Innovation" framework, this study constructs an urban ecological resilience evaluation system. Using kernel density estimation and Dagum Gini coefficient methods, we examine the temporal evolution, spatial distribution, and spatial differentiation characteristics of urban ecological resilience in the Yellow River Basin from 2011 to 2020, and employ a spatial Durbin model to analyze its influencing factors. The results show that: (1) Urban ecological resilience in the Yellow River Basin improved effectively, with distinct evolution processes and polarization features across upstream, midstream, and downstream regions. (2) The spatial pattern exhibits a "downstream > midstream > upstream" gradient decline, with pronounced spatial agglomeration and regional differentiation. (3) Overall and intra-regional differences fluctuated downward, with inter-regional differences serving as the primary source of spatial disparity, contributing 65.44% annually on average. (4) Precipitation, economic development level, and public security construction positively influence urban ecological resilience improvement, while opening-up level demonstrates positive spillover effects. Infrastructure construction and government intervention also show positive spillover effects in enhancing local urban ecological resilience. Conversely, land development intensity and environmental pollution degree inhibit resilience improvement, with environmental pollution also exhibiting negative spillover effects. Moreover, the effects of influencing factors vary significantly across upstream, midstream, and downstream regions.

Keywords: urban ecological resilience; spatiotemporal evolution; spatial difference; influencing factors; Yellow River Basin

Introduction

The Industrial Revolution ushered humanity into an era of material abundance, yet boundless, unrestrained, and irreversible production and consumption patterns have subtly yet profoundly impacted ecosystems. Climate change, environmental pollution, ecological degradation, and resource shortages have emerged incessantly, severely weakening ecological carrying capacity, increasing ecological risks, threatening regional and overall ecological security, and consequently reducing ecological resilience. In response, China has proposed the concepts that "lucid waters and lush mountains are invaluable assets," the construction of a Beautiful China, and urban resilience development, explicitly stating the need to "continue fighting the battles to keep our skies blue, our waters clear, and our land pollution-free, promote ecological conservation and governance of major rivers, lakes, and reservoirs, and enhance ecosystem diversity, stability, and sustainability."

Since the 21st century, urban ecological resilience has attracted widespread academic and social attention to meet the demands of constructing wetland cities, ecological cities, and smart cities. However, it remains an emerging topic with ongoing debates and exploration space. Urban ecological resilience is based on the resilience of "social-ecological" systems, reflecting the dynamic capacity of ecosystems to maintain resistance, response, recovery, and learning innovation when facing pressures and disturbances, characterized by human impact dominance and socioeconomic drivers.

Existing research primarily involves three aspects. First, evaluation models: Most scholars establish urban ecological resilience assessment systems from dimensions such as resistance, adaptability, and recovery, sensitivity and adaptability, or vulnerability and response capacity. Some scholars further propose that evaluating ecological resilience from an evolutionary perspective should also consider the innovative development capacity of urban ecosystems, while others use the DPSIR (Driver-Pressure-State-Impact-Response) model for quantitative assessment. Second, research scales and contents: Studies cover scales ranging from cities, urban agglomerations, and metropolitan areas to regions, examining temporal changes, spatial distribution, multidimensional differences, and driving mechanisms. Third, influencing factors and methods: Scholars employ models such as obstacle degree, multiple linear regression, dynamic regression, STIRPAT, and Shapley value decomposition, identifying factors including precipitation, temperature, construction land, economic development, opening-up, and environmental investment.

Reviewing existing literature reveals several gaps. Regarding evaluation systems, current research focuses on cities' capacity to resist disturbances and adaptively recover, rarely incorporating ecosystem learning and innovation capacity, making it difficult to align with the essential connotation of urban ecological resilience. Concerning research scales and contents, limited attention has been paid to the Yellow River Basin as a crucial ecological security barrier, lacking comprehensive analysis across the entire basin; studies focus more on the actual state of spatiotemporal evolution while neglecting spatial differences and their sources. Regarding methodology, few studies utilize spatial econometric models to analyze influencing factors, making it difficult to account for spatial spillover effects. Therefore, this study examines 58 prefecture-level and above cities in the Yellow River Basin, constructs an urban ecological resilience evaluation system based on a four-dimensional "Pressure-State-Response-Innovation" framework, reveals spatiotemporal evolution characteristics, employs the Dagum Gini coefficient to precisely reflect spatial differences and sources, and uses a spatial Durbin model to deeply analyze influencing factors, aiming to identify the driving mechanisms of spatiotemporal differentiation and provide empirical support for coordinated improvement of urban ecological resilience in the Yellow River Basin.

1.1 Study Area

Based on the natural extent of the Yellow River Basin and considering the integrity of research units and the direct relevance of regional development to the Yellow River, this study defines the research area as 9 provinces (autonomous regions) along the Yellow River: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, totaling 73 prefecture-level administrative units. Drawing on relevant research, we use Hekou Town in Inner Mongolia and Taohuayu in Henan Province as boundaries between upstream-midstream and midstream-downstream, dividing the basin into three regions. Due to severe data gaps in cities such as Alxa League, Wuhai, and Golog Tibetan Autonomous Prefecture, the final sample comprises 58 prefecture-level and above cities [Figure 1: see original paper].

1.2 Data Sources

Data primarily derive from the *China City Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, *National Economic and Social Development Statistical Bulletin*, and *Science and Technology Expenditure Statistical Bulletin* from 2011 to 2020, as well as statistical yearbooks of prefecture-level and above cities, government fiscal final accounts, and the China Economic Database (CEIC). The per capita patent authorization quantity index originates from the "China Regional Innovation and Entrepreneurship Index" released by Peking University' s Open Research Data Platform. Normalized Difference Vegetation Index (NDVI) and annual average precipitation data come from the Chinese Academy of Sciences Resource and Environmental Science Data Center. Annual average PM2.5 concentration data are from the Global Ground PM2.5 Concentration Annual Mean dataset released by Dalhousie University' s Atmospheric Composition Analysis Group, processed using ArcGIS software. Missing data for individual years are filled using interpolation methods. To eliminate price factor impacts, all price-related indicators are deflated using constant 2011 prices.

1.3 Research Methods

1.3.1 Evaluation Framework and Indicator System The DPSIR model reflects interactions between humans and the environment and has become a framework for ecological environment research. Meanwhile, the evolutionary resilience cognitive paradigm serves as a reference for urban resilience studies, where resilience represents regional adaptability, innovation, and sustainability, with innovation capacity being the most critical. For urban ecological resilience, the capacity to maintain long-term development and create new growth paths is as important as resisting short-term shocks and self-adjustment recovery.

Drawing on the DPSIR model and evolutionary resilience perspective, this study constructs a four-dimensional evaluation system of "Pressure-State-Response-Innovation" for urban ecological resilience . This framework considers both the causal relationship between human activities and ecological environment and the basic functions and social attributes of learning and innovation in urban ecosystems. "Pressure" refers to the load and interference caused by human resource extraction and economic activities on ecosystems. Under resource degradation and environmental pollution pressures, biological resources, ecological environment, and ecological space change, while human society responds through diverse measures, ultimately achieving ecological resilience evolution through innovation adaptation. The four dimensions are closely linked, constituting the internal mechanism and evolution process of urban ecological resilience.

1.3.2 Combination Weighting Method To incorporate both subjective and objective information, this study employs a combination of subjective and objective weighting methods for scientific measurement. Subjective weighting uses equal weight assignment, as urban ecological resilience enhancement is a systematic evolution process of multi-dimensional composite transformation, with each dimension potentially being equally important. Objective weighting adopts the entropy method, which assigns weights based on information entropy to reflect indicator discrimination capability. The combination weighting method avoids the decisive role of subjective factors in subjective weighting and the disadvantage of entropy method ignoring indicator importance, achieving optimized weighting. Specific formulas are available in the literature.

1.3.3 Kernel Density Estimation Kernel density estimation uses continuous density curves to describe random variable distribution characteristics, with advantages of weak model dependence and strong robustness. This method analyzes the temporal evolution of urban ecological resilience in the Yellow River Basin. Specific formulas are available in the literature.

1.3.4 Dagum Gini Coefficient Traditional inequality measures such as Theil index and classic Gini coefficient strictly assume no overlap between grouped samples, while the Dagum Gini coefficient and its decomposition by subgroups effectively solve this problem. This study uses the Dagum Gini coefficient to reveal spatial differences in urban ecological resilience and analyze their specific sources and contributions. Specific formulas are available in the literature.

1.3.5 Spatial Durbin Model Urban ecological resilience exhibits significant spatial correlation. Ignoring spatial factors would affect result accuracy. Therefore, this study uses the spatial Durbin model to analyze influencing factors:

$$\ln CER_{it} = \rho \sum_{j=1}^{n} W_{ij} \ln CER_{it} + \beta X_{it} + \gamma \sum_{j=1}^{n} W_{ij} \ln X_{jt} + \mu_i + \lambda_t + \varepsilon_{it}$$

where CER_{it} represents the ecological resilience level of city i in year t; n is the number of cities; ρ is the spatial autocorrelation coefficient; X represents influencing factors; β and γ are regression coefficients for influencing factors and spatial lag terms, respectively; W_{ij} is the second-order adjacency matrix between cities i and j; μ_i and λ_t are individual and time fixed effects; and ε is the error term. To reduce heteroskedasticity and multicollinearity, variables are log-transformed.

2 Results

2.1 Temporal Evolution Characteristics of Urban Ecological Resilience in the Yellow River Basin

Kernel density estimation was conducted using MATLAB R2020a to illustrate temporal evolution characteristics [Figure 2: see original paper]. The analysis reveals four key features:

First, **main peak and distribution pattern**: Distribution curves for the entire basin and upstream, midstream, and downstream regions all shifted rightward, indicating effective improvement in urban ecological resilience. The main peak height showed an inverted "U" shape ("rise-fall-rise"), while main peak width exhibited a "narrow-wide-narrow" pattern, indicating a "U-shaped" evolution in resilience disparity.

Second, **distribution extension characteristics**: The basin-wide distribution initially showed both left and right tails. Over time, the right tail remained stable while the left tail shortened annually, indicating a contraction trend in distribution extension. This suggests "club convergence" among low-resilience cities and "class locking" among high-resilience cities. Upstream and downstream regions showed no tail phenomena, while the midstream region exhibited a prominent right tail with widening distribution extension, indicating an "advantage accumulation effect" where leading areas become increasingly superior.

Third, **peak number and polarization characteristics**: The basin transitioned from bimodal to unimodal distribution, though main peak height generally increased, indicating an unclear polarization trend. The upstream region evolved from multimodal (2011) to bimodal (2020), while the midstream region consistently showed "multimodal to bimodal" alternation. Both upstream and midstream regions exhibited bipolar or multipolar regional agglomeration characteristics, with the midstream showing more pronounced polarization due to higher main peaks and larger peak distances. The downstream region alternated between unimodal and bimodal, ultimately showing slight bipolar polarization in 2020.

2.2 Spatial Distribution and Difference Characteristics

2.2.1 Spatial Distribution Characteristics Using ArcGIS 10.8 with natural breaks classification, urban ecological resilience was divided into low, medium-low, medium-high, and high levels [Figure 3: see original paper]. The spatial pattern shows a clear "downstream > midstream > upstream" gradient decreasing from coastal to inland areas, with distinct spatial agglomeration and regional differentiation.

In 2011, high-resilience cities were concentrated in Shandong' s downstream region (except Heze). Medium-high levels clustered in Henan' s mid-downstream region. Medium-low levels were contiguously distributed in the midstream region, with 68.42% of cities in Shanxi and Shaanxi at this level. Approximately half of upstream cities, particularly in Ningxia and Gansu, showed low resilience. By 2020, high-resilience areas extended from downstream to upstream and from coastal to inland regions.

The upstream region displayed a "north-high, south-low" pattern, with low-level city ranges expanding significantly (76.92% in 2011) but contracting by 2020 (only Baiyin and Wuwei remaining low-level). The midstream region consistently showed an "east-high, west-low" distribution, evolving from a three-tier to two-tier gradient pattern. The downstream region developed from a "single-center" to "dual-center" structure, with high-resilience areas radiating outward from Jinan and Zhengzhou, reaching 81.25% high-level cities by 2020 (only Anyang, Puyang, and Heze at medium-high level).

2.2.2 Spatial Difference Characteristics The Dagum Gini coefficient was calculated using MATLAB R2020a to reveal sources and contributions of spatial differences [FIGURE:4, FIGURE:5].

Overall and intra-regional differences: The basin-wide Gini coefficient decreased from 0.1418 to 0.0976 (31.20% reduction) since the 18th Party Congress launched ecological protection initiatives. Intra-regional differences also declined across all regions, with the upstream region showing the fastest reduction (56.73%), followed by midstream (31.78%) and downstream (26.42%). The mean intra-regional Gini coefficients ranked as: midstream (0.1078) > upstream (0.0916) > downstream (0.0679), indicating the largest internal disparity in the midstream region.

Inter-regional differences: Inter-regional Gini coefficients ranked as: upstream-downstream (0.1681) > midstream-downstream (0.1162) > upstream-midstream (0.0891), revealing inherent gaps between regions, particularly between upstream and downstream. All inter-regional differences narrowed over time, with upstream-midstream differences declining most rapidly (7.14% annually).

Difference source decomposition: The mean contribution rates ranked as: inter-regional differences (65.44%) > intra-regional differences (25.30%) >

transvariation density (9.26%). Inter-regional differences constitute the primary source of spatial disparity, making them key to addressing spatial imbalance in urban ecological resilience across the Yellow River Basin.

2.3 Influencing Factors of Urban Ecological Resilience

2.3.1 Factor Selection Urban ecological resilience is influenced by multiple factors. Based on its connotation and previous research, we select representative factors from ecological space environment and socioeconomic environment dimensions .

2.3.2 Factor Analysis Spatial Durbin model estimation results show significant positive spatial autocorrelation ( ), indicating strong positive spatial spillover effects where high-resilience cities can exert demonstration and driving effects on surrounding areas .

Ecological space environment: Precipitation shows significant positive direct effects, while infrastructure construction demonstrates significant positive direct and spillover effects. Land development intensity and environmental pollution degree show significant negative direct effects, with environmental pollution also exhibiting negative spillover effects. Increased precipitation benefits vegetation growth and improves ecological quality in the Yellow River Basin, enhancing soil and water conservation. Infrastructure development improves local traffic conditions and urban efficiency while reducing transport costs and accelerating regional factor flows, promoting coordinated resilience improvement in neighboring cities. However, growth-oriented land development has expanded construction land faster than population growth, while industrial emissions harm water and air quality, exacerbating ecological-economic imbalances. Air and water pollutants also cross administrative boundaries, inhibiting surrounding cities' resilience.

Socioeconomic environment: Economic development level and public security construction show significant positive direct effects. Opening-up level demonstrates significant positive spillover effects. Government intervention shows significant positive direct and spillover effects. Economic development empowers high-quality basin development, providing material support for disaster resistance and recovery. Public security construction helps prevent risks and maintain healthy ecosystem operation. Economic openness creates favorable competition environments, and the "pollution halo effect" improves surrounding cities' ecological quality through knowledge and technology spillovers. Local governments enhance ecological governance capacity through policies and funding, while "race-to-the-top" competition among governments creates demonstration effects that radiate to surrounding cities.

2.3.3 Heterogeneity Analysis Significant spatial heterogeneity exists in urban ecological resilience across the Yellow River Basin. Grouped regressions for the three regions reveal distinct effects .

Precipitation shows significant positive direct effects in upstream and midstream regions, particularly benefiting arid and semi-arid areas like Ningxia and Inner Mongolia. Infrastructure construction and economic development have the most pronounced direct effects in the upstream region, where economic growth and improved connectivity provide crucial material support for enhancing adaptive capacity. However, economic development in upstream and midstream regions creates siphon effects, hindering surrounding cities'resource integration and innovation ecosystem construction. Land development intensity and environmental pollution have the most significant inhibitory effects in the midstream region, which encompasses major grain production and heavy chemical energy zones where construction land expansion and coal mining activities severely threaten ecological resilience.

Public security construction shows significant direct effects across all regions. Government intervention exhibits significant negative direct effects in upstream and downstream regions and negative spillover effects in the midstream region. Upstream regions tend toward artificial intervention while neglecting natural restoration, focusing on short-term rather than long-term prevention. Downstream regions, with high economic density and marketization, suffer from market distortions and rent-seeking when government intervention is excessive. Midstream local governments tend to adopt competitive policies that hinder coordinated resilience improvement in surrounding cities.

Opening-up level shows significant negative direct effects but positive spillover effects in upstream regions, where foreign trade focuses on low-value-added, resource-intensive products that increase vulnerability to external shocks but also facilitate regional cooperation and technology spillovers. In downstream regions (Shandong and Henan), higher-quality opening-up promotes high-quality development and strengthens risk resistance capacity.

3 Discussion

This study investigates spatiotemporal evolution and influencing factors of urban ecological resilience in the Yellow River Basin based on the "Pressure-State-Response-Innovation" framework. Regarding the indicator system, while previous research focused on ecosystems' capacity to recover to stable states after disturbances, this study incorporates indicators reflecting innovation capacity such as R&D expenditure as a proportion of GDP and per capita patent authorization index, highlighting the importance of innovation for long-term sustainability.

Regarding spatiotemporal evolution, contrary to findings of continuously decreasing ecological resilience in the Pearl River Delta region, the Yellow River Basin shows overall annual improvement and a spatial pattern decreasing from coastal to inland and downstream to upstream. This study further reveals the sources of spatial differences. Concerning influencing factors, previous research rarely addressed spatial correlation, while this study employs the spatial Durbin model to consider both spatial spillover effects and heterogeneity, providing in-depth analysis for the entire basin and sub-regions.

Nevertheless, this study has limitations. First, the indicator system emphasizes human activity impacts; future research should incorporate natural disturbance pressures and ecosystem health status, such as drought, soil erosion, biodiversity, and landscape diversity. Second, urban agglomerations are important carriers for ecological protection and high-quality development in the Yellow River Basin. The seven major urban agglomerations along the Yellow River demonstrate higher-level, higher-quality cross-regional coordination. Future research should explore spatial relationships of urban ecological resilience at different spatial scales of these urban agglomerations.

4 Conclusions

This study reaches the following conclusions:

(1) Urban ecological resilience in the Yellow River Basin improved effectively, with distinct evolution processes and polarization characteristics across regions. Upstream and midstream regions exhibit bipolar or multipolar regional agglomeration features, with more pronounced polarization in the midstream, while the downstream shows slight bipolar polarization.

(2) The spatial pattern demonstrates a "downstream > midstream > upstream" gradient decline with obvious spatial agglomeration and regional differentiation. The upstream region shows a "north-high, south-low" distribution, the midstream evolved from a three-tier to two-tier gradient pattern, and the downstream shifted from a "single-center" to "dual-center" structure.

(3) Spatial differences in urban ecological resilience fluctuated downward, with a 31.20% decrease from 2011 to 2020. Intra-regional differences in all three regions also decreased, with the upstream region showing the fastest reduction (56.73%). Inter-regional differences constitute the primary source of spatial disparity, with an average annual contribution rate of 65.44%, with the largest gap between upstream and downstream and the smallest between upstream and midstream.

(4) Precipitation, economic development level, and public security construction positively affect urban ecological resilience improvement. Opening-up level shows positive spillover effects. Infrastructure construction and government intervention demonstrate positive spillover effects in enhancing local resilience. Land development intensity and environmental pollution degree inhibit resilience improvement, with environmental pollution also showing negative spillover effects. Additionally, the effects of influencing factors differ significantly across upstream, midstream, and downstream regions.

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