Spatiotemporal Differentiation and Convergence of Urban Ecological Resilience in the Yellow River Basin: An Empirical Analysis of 61 Cities across Seven Major Urban Agglomerations (Postprint)

Authors: Wang Songmao

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Abstract

Scientifically measuring the development status and convergence trends of urban ecological resilience in urban agglomerations of the Yellow River Basin holds significant importance for urban ecological protection and high-quality development in the region. Utilizing panel data from 61 prefecture-level cities across seven major urban agglomerations in the Yellow River Basin from 2011 to 2020, this study adopts an evolutionary resilience perspective to construct an urban ecological resilience evaluation index system based on dimensions such as "resistance-response-innovation" . Kernel density estimation and natural breaks method are employed to examine the spatial differentiation of urban ecological resilience, while different types of convergence models are used to analyze its convergence trends. The findings indicate: (1) The overall mean value of urban ecological resilience in the Yellow River Basin is 0.093, exhibiting a slow development trend. (2) Urban ecological resilience demonstrates a spatial pattern characterized by "strong downstream urban agglomerations and weak upstream and midstream urban agglomerations" , with a decreasing spatial distribution of "core and provincial capital cities—peripheral and marginal cities" formed within urban agglomerations. (3) Both the Yellow River Basin and individual urban agglomerations exhibit absolute β-convergence, with the Jinzhong Urban Agglomeration converging at the fastest rate. After incorporating control variables, significant conditional β-convergence trends are observed in both the Yellow River Basin and internal urban agglomerations, with convergence speeds all showing improvement. Moreover, variables such as economic development level and population density exert significantly heterogeneous influences on the convergence of urban ecological resilience.

Full Text

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WANG Songmao, NING Wenping, NIU Jinlan, AN Kang
College of Economics & Management, Shandong Agricultural University, Tai'an 271018, Shandong, China

Abstract

Scientific measurement of the development status and convergence trends of urban ecological resilience in the Yellow River Basin urban agglomerations is of great significance for ecological protection and high-quality development in the region. This study selects panel data from 61 prefecture-level cities across seven major urban agglomerations in the Yellow River Basin from 2011 to 2020, adopts an evolutionary resilience perspective, and constructs an urban ecological resilience evaluation index system based on the dimensions of resistance-response-innovation. Using kernel density estimation and the natural breaks method, we examine the spatial differentiation of urban ecological resilience, and employ different types of convergence models to analyze convergence patterns. The findings reveal that: (1) The overall mean value of urban ecological resilience in the Yellow River Basin is 0.093, showing a slow development trend. (2) Urban ecological resilience exhibits a spatial pattern of "strong downstream urban agglomerations, weak upstream and midstream urban agglomerations," with an internal distribution pattern of "core and provincial capital cities—peripheral and marginal cities" decreasing within each agglomeration. (3) Absolute β convergence exists in both the Yellow River Basin as a whole and within individual urban agglomerations, with the Jinzhong urban agglomeration converging the fastest. After incorporating control variables, significant conditional β convergence emerges in the basin and within each agglomeration, with accelerated convergence speeds. Additionally, variables such as economic development level and population density exert significantly heterogeneous effects on the convergence of urban ecological resilience.

Keywords: Yellow River Basin; urban agglomeration; urban ecological resilience; spatiotemporal differentiation; spatial convergence

Introduction

Urban ecological resilience has become a critical direction for urban development and planning. The concept of resilience has undergone three important transformations from "engineering resilience" to "ecological resilience" and then to "evolutionary resilience." Both engineering and ecological resilience adopt an equilibrium perspective. From this viewpoint, foreign scholars define ecological resilience as the capacity of urban ecosystems to prevent, respond to, and recover from risk disturbances. From an evolutionary perspective, Hosseini et al. consider resilience as an inherent system property that no longer emphasizes the ability of urban ecosystems to return to pre-disturbance states, but rather stresses the capacity to achieve transformative development through structural adjustment and path alteration. Domestic scholars primarily define the concept from perspectives of urban ecological governance and risk prevention and control. Shen et al. view urban ecological resilience as the dynamic capacity of urban ecosystems to defend against disturbances before they occur, respond promptly when disturbances happen, and optimize after disasters subside. Zhou et al. emphasize the ability of ecosystems to absorb disturbances, reorganize, and achieve sustainable development.

Current research on urban ecological resilience mainly focuses on three aspects. First, regarding evaluation and measurement, scholars hold different views on the concept and thus construct varying indicator systems. Foreign research often analyzes from perspectives of ecosystem sustainability and services or urban socio-ecological systems, while domestic studies mostly quantify urban ecological resilience through multi-dimensional indicator systems, including scale-density-morphology systems based on landscape ecological patterns and resistance-response-recovery models built upon the DPSIR framework. Second, research on influencing factors examines both natural and human activity causes. Natural factors concentrate on ecosystem characteristics such as climate, hydrology, vegetation, and topography, while human activities primarily include urbanization, population agglomeration, and technological innovation. Some scholars note that identifying these constraints helps explain regional differences in urban ecological resilience. Third, regarding research content, existing studies focus on measuring levels and spatiotemporal evolution, analyzing driving mechanisms of different factors, and investigating coordinated development between urbanization and ecological environments through decoupling analysis, interactive responses, and coupling coordination models.

Recent research on the Yellow River Basin ecology has become increasingly rich, covering threshold effects of ecological efficiency, spatial analysis of ecological vulnerability, and ecological security focusing on influencing factors. However, theoretical and empirical studies exploring urban ecosystems from a resilience perspective remain relatively weak. Although a few scholars have examined the Yellow River Basin' s urban ecological resilience, such as Zhou et al. and Guo et al. investigating coupling coordination relationships and the impact of digital economy, research on the convergence of urban ecological resilience in Yellow River Basin urban agglomerations remains a significant gap. Given that resource endowments and development paths vary across the basin' s urban agglomerations, with different ecological resilience development patterns emerging in recent years, analyzing the spatiotemporal differentiation and convergence of urban ecological resilience is crucial for narrowing regional gaps and promoting coordinated ecological protection.

Against this background, this study makes three potential marginal contributions. First, while existing research mostly focuses on measuring urban ecological resilience levels, this paper deeply explores its convergence, providing a useful supplement to current studies. Second, from a methodological perspective, the evolutionary resilience perspective enables a shift from stable equilibrium to dynamic development, offering a more comprehensive assessment of urban ecosystems' essential characteristics and innovation capacity. Third, spatial factors are increasingly important in regional ecological environment research, yet literature incorporating spatial elements to study convergence trends remains insufficient. This paper includes spatial factors in econometric models to analyze convergence trends of urban ecological resilience in Yellow River Basin urban agglomerations.

1. Data and Methods

1.1 Study Area

The Yellow River Basin features a fragile ecological foundation, with energy-heavy industries along provincial regions and urban agglomerations accounting for over 80% of pollution emissions, facing dual challenges of ecological protection and high-quality development. The basin concentrates seven urban agglomerations: four regional-level agglomerations (Shandong Peninsula, Central Plains, Guanzhong Plain, and Jinzhong) and three local agglomerations (Lanzhou-Xining, Ningxia Yellow River Area, and Hohhot-Baotou-Ordos-Yulin). Following the "Yellow River Basin Ecological Protection and High-Quality Development Plan Outline," this study selects 61 prefecture-level and above cities across these seven major urban agglomerations as research subjects [Figure 1: see original paper].

1.2 Data Sources

Data were primarily collected from the *China City Statistical Yearbook* (2012–2021), provincial and municipal statistical yearbooks, and statistical bulletins of Yellow River Basin regions. Processed data (such as per capita water resources) were calculated through multiplication and division synthesis of indicators. Normalized Difference Vegetation Index (NDVI) data were obtained from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn/). Missing values were supplemented using linear interpolation based on average annual growth rates.

1.3 Methods

1.3.1 Entropy-TOPSIS This study employs the entropy-TOPSIS method to evaluate urban ecological resilience. The procedure is as follows:

(1) Entropy method to determine standardized indicator weights:

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}\ln\frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}}$$

$$w_j = \frac{1-e_j}{\sum_{j=1}^{k}(1-e_j)}$$

where e_j is the information entropy of indicator j; w_j is the weight of indicator j; m is the number of evaluation years; y_{ij} is the original value of indicator j in year i; and k is the Boltzmann constant.

(2) Determine positive and negative ideal solutions and calculate Euclidean distances:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(f_{ij}-f_j^+)^2}, \quad i = 1, 2, \cdots, m; \quad j = 1, 2, \cdots, n$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(f_{ij}-f_j^-)^2}, \quad i = 1, 2, \cdots, m; \quad j = 1, 2, \cdots, n$$

where S_i^+ and S_i^- represent the distances from the ith evaluation object to the optimal and inferior solutions, respectively; f_j^+ and f_j^- represent the distances from indicator j to the optimal and inferior targets, respectively; f_{ij} is the weighted normalized value of the jth evaluation indicator for the ith object; and n is the number of sample observations.

(3) Calculate the closeness degree (C_j) to the ideal solution:

$$C_j = \frac{S_i^-}{S_i^+ + S_i^-}, \quad i = 1, 2, \cdots, m$$

where C_j is the closeness degree of the jth research object, ranging from [0, 1]. Higher values indicate better performance.

1.3.2 Urban Ecological Resilience Indicator System From an evolutionary perspective, urban ecological resilience represents an inherent property of urban ecosystems that undergoes non-deterministic dynamic evolution over time, independent of external disturbances, emphasizing system learning and innovation capacity. Under increasingly complex system development conditions, “evolutionary resilience” is more suitable for current urban ecological resilience research, facilitating the transition from stable equilibrium to dynamic development. Following Wang et al.’s research, this study constructs an urban ecological resilience indicator system from three dimensions: resistance, response, and innovation. Resistance capacity refers to the ability to withstand disturbances and maintain functional and structural integrity based on natural endowments. Response capacity represents diversified abilities to cope with shocks when disturbances occur. Innovation capacity signifies the ability to achieve new development through learning and innovation while responding to disturbances .

1.3.3 Kernel Density Estimation Kernel density estimation fits distributions based on data characteristics, avoiding errors from artificially specified functional forms. Its expression is:

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x - X_i}{h}\right)$$

where X_i is the ith independent and identically distributed observation; x is the mean of observations; k is the Gaussian kernel function; n is the number of sample observations; and h is the bandwidth.

1.3.4 Convergence Models Convergence mechanisms reveal whether attribute values of research objects narrow over time and space. β convergence indicates that urban agglomerations with lower urban ecological resilience (UER) gradually catch up to those with higher resilience through greater growth rates. Absolute β convergence refers to the trend of convergence across regions over time without considering macro-heterogeneity factors, while conditional β convergence incorporates macro-heterogeneity influences.

The absolute β convergence model is:

$$\frac{\ln UER_{i,t+1} - \ln UER_{i,t}}{T} = \alpha + \beta \ln UER_{i,t} + \mu_i + \eta_t + \varepsilon_{it}$$

where i denotes region; t denotes year; $\ln UER_{i,t+1}$ is the logarithm of urban ecological resilience in region i at period $t+1$; T is the time span from t to $t+1$; the left side represents the logarithm of the annual growth rate of urban ecological resilience; $\ln UER_{i,t}$ is the logarithm of urban ecological resilience in region i at period t; α is the constant term; μ_i and η_t represent regional and time fixed effects, respectively; ε_{it} is the random disturbance term; and β is the convergence parameter. If $\beta < 0$, urban ecological resilience exhibits β convergence; otherwise, it diverges.

Considering cross-regional flows of macro-influencing factors and varying degrees of spatial dependence among regions, this study incorporates spatial factors. The spatial Durbin model (SDM) transformed absolute β convergence model is:

$$\frac{\ln UER_{i,t+1} - \ln UER_{i,t}}{T} = \alpha + \rho W_{ij} \frac{\ln UER_{j,t+1} - \ln UER_{j,t}}{T} + \beta \ln UER_{i,t} + \theta W_{ij} \ln(UER_{j,t}) + \mu_i + \eta_t + \varepsilon_{it}$$

where ρ is the spatial autoregressive coefficient of urban ecological resilience, indicating influence from neighboring regions; θ is the spatial autoregressive coefficient of explanatory variables; and W_{ij} is the spatial weight matrix between regions i and j. This study constructs a comprehensive nested matrix combining geographic and economic weights to capture spatial correlation effects involving both distance and economic factors.

The spatial econometric model selection procedure involves: first, constructing a general panel model and using robust Lagrange Multiplier (LM) statistics to test for spatial autocorrelation; second, constructing spatial panel models and using Wald and Likelihood Ratio (LR) statistics for testing. If both null hypotheses for θ are rejected, the SDM model is selected. If the null hypothesis holds and LM tests support the spatial autoregressive (SAR) model, the SAR model is used:

$$\frac{\ln UER_{i,t+1} - \ln UER_{i,t}}{T} = \alpha + \rho W_{ij} \frac{\ln UER_{j,t+1} - \ln UER_{j,t}}{T} + \beta \ln UER_{i,t} + \mu_i + \eta_t + \varepsilon_{it}$$

If the null hypothesis holds and LM tests support the spatial error model (SEM), the SEM model is applied:

$$\frac{\ln UER_{i,t+1} - \ln UER_{i,t}}{T} = \alpha + \beta \ln UER_{i,t} + \mu_i + \eta_t + \varphi_{it}, \quad \varphi_{it} = \lambda W_{ij} \varphi_{jt} + \sigma_{it}$$

where λ is the spatial autoregressive coefficient of error terms, indicating random shocks; and σ_{it} is the random disturbance term in region i at period t.

The conditional β convergence model using the SDM framework is:

$$\frac{\ln UER_{i,t+1} - \ln UER_{i,t}}{T} = \alpha + \rho W_{ij} \frac{\ln UER_{j,t+1} - \ln UER_{j,t}}{T} + \beta \ln UER_{i,t} + \theta W_{ij} \ln(UER_{j,t}) + \delta \ln CV_{i,t} + \gamma W_{ij}$$

where $\ln CV_{i,t+1}$ is the set of control variables in region i at period $t+1$; $\ln CV_{j,t}$ is the set of control variables in region j at period t; δ represents the estimated parameters of control variables; and γ is the spatial autoregressive coefficient of control variables.

Following existing research, this study uses economic development level (ECO), population density (PDE), industrial structure (IND), technological progress (TEC), and environmental regulation (ER) as control variables. Economic development level is measured by per capita GDP; population density is represented by the ratio of year-end permanent population to administrative land area; industrial structure is expressed by the proportion of secondary industry output in GDP; technological progress is measured by the share of science expenditure in public fiscal expenditure; and environmental regulation intensity index is constructed using industrial wastewater, SO_2, and smoke (dust) emissions relative to secondary industry output:

$$Polu_{i,t} = \frac{1}{3}\sum_{j=1}^{3}\frac{Polu_{ij,t}/Y_{i,t}}{Polu_{j,t}/Y_t}$$

where $Polu_{i,t}$ is the environmental regulation intensity index for city i in year t; $Polu_{ij,t}$ is the emission of pollutant j for city i in year t; $Polu_{j,t}$ is the emission of pollutant j for all samples; $Y_{i,t}$ is the secondary industry output of city i in year t; and Y_t is the total secondary industry output for all samples in year t.

2. Results and Analysis

2.1 Temporal Evolution of Urban Ecological Resilience in Yellow River Basin Urban Agglomerations

From 2011 to 2020, the mean value of urban ecological resilience in the Yellow River Basin was 0.093, with an annual growth rate of 2.25%. Since the proposal of ecological civilization construction at the 18th Party Congress, the basin’ s traditional “development-through-pollution” model has improved, though the transformation remains difficult and slow. At the urban agglomeration level, the Shandong Peninsula urban agglomeration leads with a mean value of 0.108 and an annual growth rate of 2.25%, maintaining its lead throughout the study period. The Guanzhong Plain urban agglomeration follows with a mean value of 0.095 and an annual growth rate of 5.19%. The Central Plains urban agglomeration lags behind with a mean value of 0.083, while other agglomerations show relatively weak development.

Kernel density analysis reveals the evolution trajectory of urban ecological resilience differences in the basin and its agglomerations [Figure 3: see original paper]. In terms of distribution location, the kernel density curve for the entire basin shows a rightward shift, indicating effective improvement in urban ecological resilience levels. Among urban agglomerations, all except the Ningxia Yellow River Area show rightward shifts, suggesting certain improvements. Regarding distribution shape, the basin’ s kernel density curve exhibits continuously rising main peaks with insignificant width changes. Among urban agglomerations, the Central Plains and Jinzhong agglomerations show increased main peak heights with decreasing widths, indicating gradually improving internal non-equilibrium. The Lanzhou-Xining and Ningxia Yellow River Area agglomerations display similar patterns of declining main peaks and increasing widths, suggesting growing internal absolute differences. In terms of distribution extension, all curves show significant right tails, indicating prominent high-value cities within agglomerations. At the agglomeration level, the Central Plains, Jinzhong, and Hohhot-Baotou-Ordos-Yulin agglomerations demonstrate converging extensions, with decreasing probabilities of extreme values, while the remaining agglomerations show the opposite trend.

2.2 Spatial Differentiation of Urban Ecological Resilience in Yellow River Basin Urban Agglomerations

Using the natural breaks method, we obtained spatial visualization results for urban ecological resilience in Yellow River Basin urban agglomerations from 2011 to 2020 [Figure 4: see original paper]. At the urban agglomeration scale, the overall pattern shows "strong downstream urban agglomerations, weak upstream and midstream urban agglomerations," with the Shandong Peninsula urban agglomeration consistently leading. In 2011, the Central Plains urban agglomeration was relatively weak, ranking last at 0.075, while the Lanzhou-Xining urban agglomeration' s ecological resilience increased to 0.088 in 2020. The Jinzhong urban agglomeration showed a declining trend.

At the prefecture-level city scale, internal patterns within urban agglomerations reveal "highlands" of urban ecological resilience centered on provincial capitals and "lowlands" represented by boundary areas. Specifically, provincial capital cities including Lanzhou (0.101), Zhengzhou (0.116), and Xi' an (0.112) exhibit mean values significantly higher than the basin average (0.093), forming a decreasing spatial distribution pattern of "core and provincial capital cities—peripheral and marginal cities." Among these, Zhengzhou shows the most significant change, with its mean value increasing by 208.5% from 2011 to 2020. The Shandong Peninsula urban agglomeration has formed a "dual-core leadership" pattern with Jinan and Qingdao, with mean values of 0.112 and 0.109, respectively.

2.3 Convergence Analysis of Urban Ecological Resilience in Yellow River Basin Urban Agglomerations

2.3.1 Absolute β Convergence Table 2 presents absolute β convergence analysis results for urban ecological resilience in Yellow River Basin urban agglomerations. LM statistics confirm spatial autocorrelation in urban ecological resilience, necessitating spatial econometric models. Robust LM statistics determine model selection. Results show that only the Guanzhong Plain, Ningxia Yellow River Area, and Shandong Peninsula urban agglomerations are suitable for spatial panel models. Specifically, robust LM tests support the SAR model for Guanzhong Plain and the SEM model for Ningxia Yellow River Area and Shandong Peninsula. For these three agglomerations, spatial lag terms are significantly positive at the 1% level, indicating that neighboring urban agglomerations' ecological resilience improvements generate positive spatial spillover effects, and that the basin' s urban ecological resilience convergence includes spatial correlation effects.

The convergence coefficient β is significantly negative for the entire Yellow River Basin, indicating absolute β convergence. At the urban agglomeration level, all agglomerations exhibit significantly negative β coefficients, demonstrating absolute β convergence trends. This suggests that cities with relatively lagging ecological resilience within each agglomeration grow faster than leading cities, eventually developing at identical growth rates, with the Jinzhong urban agglomeration converging the fastest.

2.3.2 Conditional β Convergence Table 3 presents conditional β convergence analysis results. Spatial econometric model selection follows the same procedure as absolute β convergence. Results show that: First, conditional β convergence exists in the Yellow River Basin and all urban agglomerations, with significantly negative convergence coefficients, meaning that after considering heterogeneous socioeconomic factors such as economic development, convergence trends toward stable levels persist. Second, convergence speeds accelerate across all agglomerations, with the Hohhot-Baotou-Ordos-Yulin agglomeration showing the most obvious change (6.95%), demonstrating the scientific rationality of selected control variables. Third, different spatial effects emerge. Unlike absolute β convergence, Hohhot-Baotou-Ordos-Yulin exhibits spatial error effects, while Ningxia Yellow River Area shows the opposite pattern. The Yellow River Basin, Guanzhong Plain, and Shandong Peninsula maintain unchanged spatial effect types with significantly positive spatial lag coefficients, indicating positive spatial spillovers.

Control variables exert significantly heterogeneous effects on convergence. Economic development level, for instance, has significantly negative effects on the Central Plains, Hohhot-Baotou-Ordos-Yulin, and Shandong Peninsula agglomerations, consistent with the overall basin pattern, but significantly positive effects on Jinzhong and Ningxia Yellow River Area. This suggests that economic growth drives ecological resilience convergence toward lower values in the former group but promotes convergence toward higher values in the latter, possibly because the former groups neglected ecological sustainability during economic development, while the latter, with weaker ecological foundations and lagging resilience, emphasize green development.

Discussion

By constructing a rational urban ecological resilience evaluation system, this study accurately measures development levels and trends in the Yellow River Basin. The analysis of urban ecological resilience aligns with existing research. Urban agglomerations urgently need to strengthen inter-agglomeration synergistic linkages, shaping themselves as bonds for basin-wide ecological resilience development while creating internal assistance chains to address uneven development patterns. This study’ s main contribution lies in deeply analyzing the spatial differentiation and convergence of urban ecological resilience in the Yellow River Basin, supplementing existing research and providing important implications for scientifically improving resilience and exploring new models for coordinated ecological protection in large river basins.

This study has several limitations. First, due to data availability, prefecture-level cities were used; future research could employ more micro-level county data for more accurate reflections. Second, urban ecological resilience development may be influenced by multiple factors, and exploring its driving mechanisms represents an important direction for future research.

Conclusion

This study reaches the following conclusions: (1) Urban ecological resilience in the Yellow River Basin shows a fluctuating and slow growth trend, with significant ecological governance and protection pressures. Kernel density curves exhibit rightward shifts with continuously rising main peaks and stable widths, indicating improved resilience and narrowing overall dispersion. (2) At the urban agglomeration level, urban ecological resilience displays a spatial pattern of "strong downstream, weak upstream and midstream." Provincial capital cities significantly exceed the basin average, forming a "core and provincial capital cities—peripheral and marginal cities" gradient pattern. (3) Absolute β convergence exists in both the basin and individual agglomerations, with Jinzhong converging fastest. After adding control variables, significant conditional β convergence emerges with accelerated speeds. Moreover, variables such as economic development level exert significantly heterogeneous effects on convergence.

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