

## Analysis of Spatiotemporal Characteristics and Influencing Factors of Urban Ecological Resilience in China (Postprint)

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### Abstract

Systematic analysis of the factors influencing urban ecological resilience and the enhancement of urban ecological resilience levels are crucial for achieving sustainable urban development and constructing “resilient cities.” Based on panel data from 281 prefecture-level cities in China during 2005–2021, this study constructs evaluation indicators from three dimensions—resistance, adaptability, and recovery—to characterize the spatiotemporal evolution of urban ecological resilience, and comprehensively employs the Geographically and Temporally Weighted Regression (GTWR) model and global trend analysis to explore the influencing factors of urban ecological resilience in China and their spatiotemporal heterogeneity. The results indicate: (1) From 2005 to 2021, China’s urban ecological resilience level increased from 0.0207 to 0.0248, with an average annual growth rate of 1.140%. The center of gravity of ecological resilience migrated from northeast to southwest, and the disparity in ecological resilience levels exhibited a trend of first expanding and then contracting. (2) Economic development, industrial structure, topographic factors, environmental regulation, and human capital exert positive effects on urban ecological resilience; however, the influences of these factors demonstrate significant spatiotemporal heterogeneity, with the magnitude and direction of their effects varying across different regions. (3) The impacts of influencing factors on urban ecological resilience exhibit greater variation in the east-west direction than in the north-south direction. The effect of industrial structure level on urban ecological resilience is most sensitive in the east-west direction, while environmental regulation is most sensitive in the north-south direction.

## Full Text

# Spatiotemporal Characteristics and Influencing Factors of Urban Ecological Resilience in China

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## Abstract

Systematic analysis of the factors influencing urban ecological resilience and improvement in its levels are essential for achieving sustainable urban development and fostering “resilient cities.” Based on panel data from 281 prefecture-level cities in China between 2005 and 2021, this study constructed evaluation indexes across three dimensions: resistance, adaptability, and recovery. The spatial and temporal evolution of urban ecological resilience was characterized, and spatiotemporal geographically weighted regression (GTWR) models were applied alongside global trend analysis to explore the spatiotemporal heterogeneity of influencing factors. The results showed the following: (1) From 2005 to 2021, the ecological resilience level of Chinese cities increased from 0.0207 to 0.0248, with an average annual growth rate of 1.140%. The center of gravity for ecological resilience shifted from northeast to southwest. The difference in ecological resilience levels initially expanded but then narrowed. (2) Economic development, industrial structure, topographical factors, environmental regulations, and human capital all demonstrated positive effects on urban ecological resilience. However, the influence of these factors exhibited obvious spatiotemporal heterogeneity, with their effects varying significantly in magnitude and direction across different regions. (3) The impact of influencing factors on urban ecological resilience exhibited greater variation along the east-west direction compared to the north-south direction. Industrial structure showed the greatest sensitivity in the east-west direction, while environmental regulation was most sensitive in the north-south direction.

**Keywords:** urban ecological resilience; spatiotemporal geographically weighted regression model; influencing factors; spatiotemporal heterogeneity

## 1. Introduction

Urbanization and industrialization have brought economic development to cities while simultaneously posing severe challenges to resource utilization and environmental protection, necessitating greater attention to coordination and sustainability. In response, countries and organizations worldwide have introduced a series of policy measures aimed at enhancing urban resilience, strengthening cities’ capacity to adapt to various challenges and risks, and promoting more

sustainable and livable urban development. The concept of resilience originated in physics, where it described a system's ability to return to its original state after external disturbance [?]. Holling later introduced the concept of ecological resilience, suggesting that systems maintain a new stable state after shock [?]. As research has progressed, resilience thinking has evolved from natural ecology to socio-ecology and expanded into urban studies [?]. Scholars generally define urban resilience as a city's capacity to rapidly recover and maintain normal operations when facing pressures, shocks, or challenges [?]. Urban ecological resilience, as an important subsystem, has received widespread attention from scholars. Conceptually, it is generally defined as an ecosystem's ability to resist, adapt to, or transform after external disturbance [?]. In terms of evaluation and measurement, current assessments of urban ecological resilience typically adopt comprehensive indicator methods from resilience characteristics, measuring from social, economic, and natural perspectives [?], or constructing evaluation index systems from three dimensions: resistance, recovery, and adaptability [?], or relying on the Driver-Pressure-State-Impact-Response (DPSIR) framework [?].

Existing research on urban ecological resilience covers multiple scales, including national [?], urban agglomeration [?], and metropolitan area levels [?], examining spatiotemporal distribution characteristics, regional differences, convergence, and influencing factors. Methodologically, scholars have employed multiscale geographically weighted regression [?], geographic detectors [?], and spatial econometric models [?] for analysis. Influencing factors mainly include natural environmental factors [?] and socio-economic factors [?].

Overall, research on urban resilience is extensive, but studies on urban ecological resilience remain in their infancy, with no consensus reached on index system construction, weighting methods, or selection of influencing factors. Therefore, this paper uses panel data from 281 prefecture-level cities from 2005 to 2021 to evaluate urban ecological resilience levels based on resistance, adaptability, and recovery dimensions, analyze their spatiotemporal distribution characteristics, and finally employ GTWR models and global trend analysis to explore the spatiotemporal heterogeneity of influencing factors, aiming to provide new insights for urban ecological protection and construction.

### 1.1 Data Sources

The study area includes 281 prefecture-level cities in China; other cities were excluded from the analysis due to data unavailability. Data for each city's ecological resilience indicators across dimensions and influencing factors (economic development, industrial structure, human capital) from 2005 to 2021 were obtained from the *China City Statistical Yearbook*, local government bulletins, and statistical yearbooks of individual cities. Environmental regulation data were extracted from original government work reports downloaded from local government websites, which were processed into panel data, tokenized, and used to calculate the proportion of environmental protection-related word frequencies. Topographic data were extracted based on the Digital Elevation

Model (DEM) data from the 1:1,000,000 scale database using ArcGIS. Using 1 km  $\times$  1 km grids as measurement units, the relief degree of land surface was extracted data 10 km  $\times$  10 km scale. Missing values were supplemented using interpolation and extrapolation methods.

## 1.2 Indicator Selection

Ecological resilience is summarized as a system's ability to resist, adapt to, or transform when suffering external interference, comprising three characteristics: resistance, adaptability, and recovery [?]. Resistance represents a city's ability to withstand external disturbances, measured by population density and per capita built-up area to characterize population and urbanization conditions; industrial wastewater emissions, industrial smoke and dust emissions, and industrial SO<sub>2</sub> emissions per unit area to characterize industrial pollution. Adaptability represents the ecosystem's capacity to maintain stability, measured by harmless treatment rate of household waste, sewage treatment rate, and comprehensive utilization rate of general industrial solid waste to characterize urban ecological absorption effects. Recovery represents the ecosystem's ability to return to its pre-disturbance state after damage, measured by built-up area green coverage rate, per capita park green space, per capita water resources, and per capita land area to characterize urban greening construction [?]. Specific indicators are shown in Table 1.

### 1.3.1 Spatiotemporal Geographically Weighted Regression Model

Brunsdon et al. first proposed the geographically weighted regression (GWR) model, with its core objective being to deeply analyze the non-stationarity of spatial data [?]. To further enrich the model's dimensions and precision, the spatiotemporal geographically weighted regression (GTWR) model emerged, incorporating the time dimension to explore non-stationarity in both temporal and spatial dimensions. Therefore, this study employs the GTWR model to simultaneously examine the spatiotemporal relationships between influencing factors and urban ecological resilience from both temporal and spatial perspectives. The model is as follows:

$$y_i = \beta_0(u_i, v_i, t_i) + \sum_{k=1}^p \beta_k(u_i, v_i, t_i)x_{ik} + \varepsilon_i$$

where  $y_i$  is the dependent variable for city  $i$ ;  $(u_i, v_i, t_i)$  are the spatiotemporal coordinates of city  $i$ ;  $\beta_0(u_i, v_i, t_i)$  is the intercept term;  $\beta_k(u_i, v_i, t_i)$  is the estimated coefficient for the  $k$ th explanatory variable of city  $i$ ;  $x_{ik}$  is a set of explanatory variables;  $p$  is the number of explanatory variables; and  $\varepsilon_i$  is the residual.

### 1.3.2 STIRPAT Model

The STIRPAT model can deeply analyze the environmental impacts of various influencing factors while allowing for decomposition and improvement of each factor [?]. Therefore, based on STIRPAT, this study comprehensively selects influencing factors of urban ecological resilience at economic, geographic, and social levels for empirical analysis. To eliminate heteroscedasticity, the model was log-transformed as follows:

$$I_{it} = aP_{it}^b A_{it}^c T_{it}^d X_{it}^e \varepsilon_{it}$$

where  $I_{it}$  is the ecological resilience level of city  $i$  in period  $t$ ;  $P_{it}$  represents population factors;  $A_{it}$  represents economic factors;  $T_{it}$  represents technological factors;  $X_{it}$  represents other potential factors;  $b, c, d, e$  are coefficients;  $a$  is the constant term; and  $\varepsilon_{it}$  is the residual.

## 2. Results

### 2.1 Spatiotemporal Evolution Characteristics of Urban Ecological Resilience

**2.1.1 Overall Temporal Characteristics** From 2005 to 2021, China's urban ecological resilience level showed a fluctuating upward trend, increasing from 0.0207 to 0.0248 with an average annual growth rate of 1.140% (Figure 1). Specifically, adaptability and recovery showed clear upward trends with average annual growth rates of 2.316% and 0.401%, respectively, while resistance changed minimally at only 0.186%. The gap between resistance and adaptability/recovery initially expanded before narrowing. With urbanization, population agglomeration, built-up area expansion, and environmental pollution intensified, increasing pressure on urban ecosystems to resist external interference. However, as environmental policies were improved and implemented, urban greening construction expanded, environmental governance capacity improved, and adaptability and recovery gradually strengthened.

[Figure 1: see original paper]

**2.1.2 Spatial Distribution Pattern** Using the natural breaks method, China's urban ecological resilience was classified into five levels: low, relatively low, medium, relatively high, and high (Figure 2). The number of cities with low and relatively low ecological resilience decreased, while those with medium and relatively high resilience increased, indicating improved urban ecological resilience and gradually enhanced capacity to resist internal and external disturbances. In 2005, few cities had high ecological resilience indices, accounting for only 3.559% of the total. By 2021, the proportion of medium-high level cities increased to 22.064%, showing agglomeration characteristics. This suggests that as ecological protection gained attention, many cities began upgrading their resilience indices, improving industrial structure levels, reducing demand

and consumption of natural resources, and decreasing environmental pollution while pursuing economic growth, thereby promoting urban ecological resilience.

[Figure 2: see original paper]

**2.1.3 Gravity Center Migration Trend** Standard deviational ellipse analysis revealed the gravity center migration trend of China's urban ecological resilience (Figure 3). From 2005 to 2021, the gravity center shifted gradually from Luohe City to Pingdingshan City in Henan Province, showing a northeast-to-southwest migration trend. Northeast China's traditional heavy industry and resource-intensive industries created significant environmental pressure, resulting in relatively lagging ecological resilience improvement. In contrast, the climate and geographic conditions in southwestern China were more conducive to ecosystem recovery and protection, facilitating higher urban ecological resilience levels.

[Figure 3: see original paper]

## 2.2 Analysis of Influencing Factors

**2.2.1 Indicator Selection** Given the complexity and broad scope of factors affecting urban ecological resilience, this analysis comprehensively considered economic, geographic, and social factors: economic development, industrial structure, topographic factors, environmental regulation, and human capital. Economic development provides a solid material foundation for urban ecological civilization construction [?]. Rational utilization and development of the economy facilitate better application of economic achievements to ecological civilization, achieving coordinated development among economy, population, resources, and environment, thereby enhancing resistance, adaptability, and recovery [?]. Therefore, per capita GDP was used to represent economic development, expected to positively affect urban ecological resilience.

Industrial structure upgrading can drive innovation and application of environmental protection technologies, promote high-tech and green industries, and improve resource utilization efficiency, thereby reducing urban environmental pollution and ecological damage and enhancing adaptability to external shocks [?]. Therefore, the ratio of tertiary industry added value to secondary industry added value was used to represent industrial structure, expected to positively affect urban ecological resilience.

Areas with high relief degree of land surface experience less human interference, have stronger ecosystem resistance, and better environmental quality, thus exhibiting higher regional ecological resilience [?]. Therefore, relief degree of land surface was used to represent topographic factors, expected to positively affect urban ecological resilience.

Environmental regulation achieves environmental governance through government supervision and market incentives, limiting enterprise pollutant emissions

through laws, regulations, and emission standards, encouraging investment in green technologies and renewable energy, and facilitating sustainable urban development [?]. Therefore, the proportion of environmental protection-related word frequencies in local government work reports was used to represent environmental regulation, expected to positively affect urban ecological resilience.

High-level human capital can bring advanced technologies and concepts to cities, promote clean production technologies, and effectively reduce environmental pollution, thereby enhancing urban ecosystem resistance [?]. Therefore, the number of regular higher education institution students was used to represent human capital, expected to positively affect urban ecological resilience.

As the GTWR model has strict requirements regarding multicollinearity, variance inflation factor (VIF) tests were conducted on all influencing factors (Table 2). All VIF values were below 10, indicating no serious multicollinearity among influencing factors, making them suitable for GTWR analysis.

**2.2.2 Model Selection** Using the GTWR plugin in ArcGIS with a spatiotemporal distance parameter ratio of 0.5 and automatic bandwidth optimization, the influencing factors of urban ecological resilience were analyzed. Results are shown in Table 3. The GTWR model achieved an  $R^2$  of 0.892, significantly higher than the ordinary least squares (OLS) model's 0.411, with a lower corrected Akaike information criterion (AICc), demonstrating the GTWR model's superior fit. Therefore, this model provides more accurate analysis for explaining urban ecological resilience.

Descriptive statistics of regression coefficients for urban ecological resilience influencing factors in China based on the GTWR model are shown in Table 4. The significance proportion of influencing factors far exceeded 50%, indicating strong explanatory power. Based on mean coefficient values, industrial structure had the greatest impact on urban ecological resilience, followed by economic development and environmental regulation. Human capital and topographic factors had relatively smaller impacts. Except for environmental regulation, other factors showed large coefficient spans between minimum and maximum values, indicating temporal and spatial instability and heterogeneity. Therefore, further analysis from temporal and spatial dimensions is warranted.

**2.2.3 Temporal Trend Analysis of Influencing Factors** The GTWR model was used to analyze influencing factors of urban ecological resilience across 281 cities from 2005 to 2021. Temporal trends of regression coefficients were examined using box plots (Figure 4). Economic development consistently showed positive effects on urban ecological resilience, with median coefficients between 0.161 and 0.175. Although urban economic growth inevitably damages the environment, technological progress and industrial structure optimization have prompted many cities to transform traditional development models, driving transformation of high-pollution, high-energy enterprises and reducing adverse

environmental impacts, gradually forming a new trend of coordinated economic growth and ecological development.

Industrial structure showed a clear positive correlation with urban ecological resilience, with median coefficients between 0.650 and 0.886. Industrial structure transformation and upgrading improved resource utilization efficiency, promoted transformation of traditional high-energy-consuming and high-polluting industries, and reduced environmental pressure. High-end industries typically accompany technological innovation with higher environmental standards and lower energy consumption, helping reduce pollution emissions and promote green development. Additionally, industrial structure upgrading promotes stable economic development and improves urban environmental protection facilities, thereby enhancing urban ecological resilience.

Topographic factors showed an increasing positive impact on urban ecological resilience over time, with median coefficients between 0.011 and 0.023. Relief degree significantly influences landforms; areas with high relief degree typically have high altitudes, relatively pristine ecological environments, and less human interference. These areas can better maintain and restore original ecological conditions and resist external uncertainties, thus possessing high ecological resilience.

Environmental regulation showed overall positive correlation with urban ecological resilience, with median coefficients between 0.007 and 0.032. Strict environmental regulation can optimize resource allocation, eliminate backward production capacity, reduce negative externalities from environmental pollution, and effectively decrease environmental pollution and resource waste. Additionally, environmental regulation drives green innovation by setting environmental standards, promoting green technology development, and enhancing cities' capacity to address environmental challenges, thereby improving overall ecological resilience.

Human capital primarily showed positive effects on urban ecological resilience, with median coefficients between 0.015 and 0.030. Higher human capital means greater knowledge, skills, and innovation capacity, enabling better understanding and application of sustainable development concepts, environmental technologies, and policies. Highly educated and skilled labor can more effectively manage resources, reduce pollution, and promote green economies, thereby improving urban ecosystem adaptability and recovery when facing environmental challenges.

[Figure 4: see original paper]

**2.2.4 Spatial Heterogeneity Analysis of Influencing Factors** To further analyze spatial heterogeneity, average regression coefficients of each influencing factor were visualized (Figure 5) following Zhang et al.'s approach [?]. Economic development's promoting effect showed a trend of first weakening then strengthening from north to south. Specifically, it had the strongest effect on

cities in Gansu, Inner Mongolia, Heilongjiang, and Guangxi, with coefficients of 0.219–0.354. For economically developed provinces facing more severe infrastructure deficiencies and environmental governance issues, economic growth can provide more adequate financial, human, and technical support for environmental protection and governance, laying a good foundation for constructing environmental infrastructure, introducing advanced technologies, and implementing effective policies, thereby significantly enhancing ecological resilience. In contrast, economically developed areas already have relatively complete ecological infrastructure and management systems, leaving limited room for further improvement.

Industrial structure showed mostly positive correlation with urban ecological resilience, with positive effects increasing from northeast to southwest. Specifically, industrial structure had strong promoting effects on cities in Hainan, Guangdong, and Guangxi, with coefficients reaching 1.717–3.829. These regions reduced dependence on traditional high-pollution industries through transformation to high-tech and green industries, thereby reducing environmental pressure, improving resource utilization efficiency, and enhancing urban ecosystem stability. Industrial structure showed inhibitory effects on urban ecological resilience in Northeast China (Heilongjiang and Jilin), where cities face significant pressure transitioning away from heavy industry and resource-intensive industries, potentially experiencing lagging environmental governance and increased pollution in the short term, which is not conducive to improving ecological resilience.

Topographic factors' enhancement of urban ecological resilience was particularly prominent in Heilongjiang, Hainan, and Guangxi, with coefficients of 0.064–0.238. These regions have high vegetation coverage, superior natural environments, and large relief degree, experiencing less interference from urbanization and human activities, with relatively stable ecosystems that significantly promote urban ecological resilience.

Environmental regulation' s positive effects increased from west to east. High-value areas were mainly in Heilongjiang, Jilin, and Liaoning, with coefficients of 0.044–0.120. These regions effectively achieved energy conservation and emission reduction through environmental regulation, reducing urban ecological resilience pressure. Inhibitory effects of environmental regulation were mainly observed in western cities such as Sichuan and Shaanxi, where relatively weak economic foundations meant environmental regulation could increase enterprise production costs and hinder local innovation and production technology improvement, thereby affecting urban ecological resilience enhancement.

Human capital' s promoting effect on urban ecological resilience gradually increased from north to south, with strong effects on Hainan, Zhejiang, Jiangsu, and Guangdong, with coefficients of 0.090–0.168. These cities typically have high education levels and skill reserves. With the improvement of human capital, high-quality talent can drive innovation and application of environmentally friendly technologies, improve urban resource management and environmental protection capabilities, enhance ecosystem adaptability and stability, and in-

crease urban ecological resilience.

[Figure 5: see original paper]

### 2.3 Trend Analysis of Urban Ecological Resilience Influencing Factors

Further trend analysis of influencing factors was conducted using 3D perspective plots to explore spatial evolution patterns (Figure 6). In the east-west direction, environmental regulation, economic development, and human capital showed increasing trends, while industrial structure and topographic factors showed inverted U-shaped distributions with greater impacts on eastern regions. In the north-south direction, economic development and environmental regulation showed U-shaped distributions, while industrial structure and human capital showed inverted U-shaped distributions. Topographic factors' impact decreased from north to south, showing the lowest sensitivity. Overall, influencing factors exhibited more pronounced variation trends in the north-south direction than in the east-west direction. Environmental regulation was most sensitive in the north-south direction, while industrial structure was most sensitive in the east-west direction.

[Figure 6: see original paper]

## 3. Discussion

This study constructed an urban ecological resilience evaluation index system from resistance, adaptability, and recovery dimensions to analyze spatiotemporal distribution characteristics and influencing factors. Urban ecological resilience showed an overall fluctuating upward trend, with comprehensive improvement primarily driven by adaptability and recovery, consistent with existing research [?]. The analysis of influencing factors from economic, social, and geographic perspectives revealed that economic development, industrial structure, topographic factors, environmental regulation, and human capital all positively promoted urban ecological resilience [?, ?], helping clarify how different factors affect different regions and enabling targeted recommendations. The main contribution of this study lies in analyzing the heterogeneity of influencing factors from spatiotemporal dimensions. However, due to data availability limitations, the indicator system selection has shortcomings, and more natural environment variables and biodiversity variables should be incorporated in future research to construct a more comprehensive evaluation system. Additionally, current research only analyzes single influencing factors, and future studies should examine interactions between factors.

## 4. Conclusions and Recommendations

### 4.1 Conclusions

This study analyzed the spatiotemporal characteristics and influencing factors of urban ecological resilience in China, yielding three main conclusions. (1)

From 2005 to 2021, China's urban ecological resilience level showed a fluctuating upward trend with agglomeration characteristics in spatial distribution, with overall differences first expanding then narrowing. In terms of dimensional changes, the improvement in comprehensive ecological resilience mainly benefited from enhanced adaptability and recovery. Spatially, the number of medium-high value cities increased, showing agglomeration distribution. Temporally, differences in urban ecological resilience first expanded then narrowed, with the resilience gravity center migrating from northeast to southwest. (2) Influencing factors of urban ecological resilience exhibited obvious spatiotemporal heterogeneity. GTWR results showed that urban ecological resilience is affected by economic, social, and geographic factors. Economic development, industrial structure, topographic factors, environmental regulation, and human capital all positively promoted urban ecological resilience, but with obvious spatiotemporal differences. Each factor showed different effect intensities and fluctuation directions due to differences in urban resource endowments, development conditions, and geographic locations. (3) The degree of influence of various factors showed regional differences in trend changes. Trend analysis revealed that factors exhibited greater variation in the east-west direction than in the north-south direction. Industrial structure was most sensitive in the east-west direction, while environmental regulation was most sensitive in the north-south direction.

#### 4.2 Recommendations

Based on these conclusions, three policy recommendations are proposed. (1) Promote spatial protection of ecological resilience and continue implementing environmental pollution control and green development measures to consolidate achieved results. Focus on the overall improvement of urban ecological resilience levels. Given significant differences in development levels, resource and environmental factor allocation, and ecological resilience across prefecture-level cities and regions, strengthen experience exchange and division of labor among cities, adopt targeted measures, and promote coordinated regional development to improve national urban ecological resilience and reduce regional disparities. (2) Considering uneven urban development, economic development, industrial structure, topographic factors, environmental regulation, and human capital have differential effects on urban ecological resilience. Therefore, when formulating ecological resilience protection measures, each city's actual development conditions must be fully considered. For cities where economic factors such as industrial structure inhibit ecological resilience development, promote green industrial transformation, eliminate backward technologies, and optimize industrial structure upgrading. For regions where human capital shows negative effects, formulate reasonable population planning strategies and enhance local human capital levels and environmental protection awareness to effectively improve ecological resilience. (3) When formulating urban ecological resilience improvement strategies, fully consider regional conditions and implement differentiated measures. Pay special attention to industrial structure levels in western and northeastern regions, enhance ecological resilience by encouraging green in-

dustry development and promoting technological innovation and industrial upgrading. Simultaneously, improve regional cooperation mechanisms, strengthen inter-regional exchange and interaction, and promote rational flow of technology, talent, and capital between urban and rural areas. By selecting effective paths suited to regional characteristics, urban ecological resilience gaps can be effectively narrowed, the resilience of the entire ecosystem optimized, and sustainable development goals achieved.

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