



OPEN

Spatiotemporal characteristics of ecological resilience and its influencing factors in the Yellow River Basin of China

Fei Lu^{1✉}, Qi Liu² & Pengcheng Wang¹

Maintaining and improving ecological resilience is of great practical significance for the Yellow River Basin to reduce potential ecological risks and deliver sustainable development. Based on the essential characteristics of evolutionary resilience, this paper developed an ecological resilience index system of “resistance-recovery-reconstruction-renewal” and calculated the ecological resilience of 75 prefecture-level cities in the Yellow River Basin from 2007 to 2021 with the improved TOPSIS method. Then the spatiotemporal evolution characteristics of ecological resilience were analyzed using the gravity center-standard deviation ellipse, Dagum Gini coefficient decomposition, and spatial autocorrelation analysis. Furthermore, the dynamic spatial Durbin model (DSDM) was used to investigate the influencing factors of ecological resilience. The main results are as follows: (1) The ecological resilience of the Yellow River Basin showed an overall fluctuating upward trend, and the average annual growth rate in the downstream region was larger than in the upstream and midstream regions. (2) Cities with similar levels of ecological resilience were distributed in a “large settlement, small scattered” pattern. The center of gravity shifted to the southeast, and the spatial distribution exhibited a “northwest-southeast” pattern and a trend towards an “east–west” pattern. The primary source of spatial differences was the intensity of transvariation. (3) The ecological resilience in the Yellow River Basin showed significant spatial clustering, with the H–H clustering area shifting from the Hubao-Eyu urban agglomeration to the Shandong Peninsula urban agglomeration, and the L–L clustering area mainly distributed around the Central Plains city cluster. (4) The ecological resilience of the Yellow River Basin exhibited significant snowball, spillover, and siphon effects in time, space, and space-time dimensions, respectively. In the short and long term, population density and openness significantly positively affected the ecological resilience of local and surrounding cities. Urbanization had a long-term effect on ecological resilience without a short-term effect. GDP per capita and industrial structure only imparted a significant positive influence on local ecological resilience. The negative spatial spillover of the intensity of financial investment in technological innovation gradually turned into a positive effect.

Maintaining ecological security and emphasizing ecological restoration and management are the principal motivations behind attempts to achieve ecological protection and high-quality development in the Yellow River Basin. Despite the rapid social and economic development since the 18th CPC National Congress, the region continues to rely on an energy-dependent, inefficient, and environmentally polluting economic model. This has led to concerns about the future development of the Yellow River Basin, an ecologically fragile and fragmented area with a high risk of eco-environmental degradation. The area has also been grappling with widespread and prolonged air quality issues in recent years. Addressing these ecological risks while balancing economic development and environmental protection has become a pressing challenge for governments and scholars worldwide. The concept of ecological resilience offers a relevant and vital framework in this context. By maintaining and improving ecological resilience, the Yellow River Basin ecosystem can minimize the negative impacts of potential ecological risks, promote adaptive adjustment, and foster innovative development. In addition, the Yellow River Basin is a large area that has tremendous ecological diversity wherein development is unbalanced across

¹College of Literature and History (College of Culture and Tourism), Weifang University, Weifang 261061, Shandong, China. ²Weifang Municipal Cultural and Tourism Industry Development Center, Weifang 261061, Shandong, China. ✉email: wfuctlf2022@163.com

the region, and each region has distinct resource factor endowment. This inevitably leads to a discrepancy in the spatial distribution of ecological resilience. What is the pattern of spatiotemporal evolution characteristics of discrepancy among different regions? What are the influencing factors of ecological resilience? The answers to these questions have practical significance in guiding effective policymaking that strikes a balance between high-quality economic development and the realization of ecological civilization.

The concept of ecological resilience was introduced by Holling, who defined it as the capacity of natural systems to withstand or absorb perturbations resulting from environmental changes, whether natural or human-induced¹. From a human ecology perspective, Alberti et al. provide a widely accepted definition of ecological resilience, which refers to the ability of ecosystems to effectively resolve crises and recover promptly when subjected to acute shocks and long-term pressures². As ecosystems become increasingly complex, the equilibrium cognitive paradigm, which focuses solely on recovery from disturbances, has become less persuasive³. Instead, the evolutionary cognitive paradigm has gained prominence, emphasizing the ability of ecosystems to ensure regional ecological security and sustainable development through structural adjustments and trajectory changes. Folke further expanded on this idea, suggesting that ecological resilience encompasses the capacity to absorb disturbances, adapt, learn, and self-organize, thereby facilitating the coordinated development of human and environmental systems⁴. Consequently, ecological resilience has gained significant attention from scholars as it plays a crucial role in measuring the ability of natural systems to transition from an imbalanced state to equilibrium, maintain equilibrium in the face of perturbations, and self-organize their internal component hierarchy⁵.

Summarizing the contemporary scholarly literature surrounding ecological resilience, we note that the core issues have gradually expanded from evaluating measures to deeper dimensions such as spatial effects and influencing factors. In terms of research perspectives, with the ongoing deepening of research, ecological resilience has been presented as having the complex characteristics of a multidisciplinary intersection of disaster science, ecology, geography, management, and environmental science. For research on the spatial scale, the established studies have investigated the characteristics of ecological resilience at various spatial scales, ranging from provincial and municipal levels to regional levels^{3,6–9}, such as the Yangtze River Delta^{10,11}, the Pearl River Delta¹², the Beijing-Tianjin-Hebei region¹³, and the Upper Yellow River¹⁴. In terms of constructing evaluation models, several empirical studies have developed assessment systems based on the logic of the Pressure-State-Response (PSR) framework, which considers both the internal development needs (landscape background) and external risk responses of ecosystems within the context of landscape ecology. For example, Wang et al. and Zeng et al. constructed an evaluation system with three subsystems, namely “size-density-morphology”, drawing on ecological infrastructure and landscape security pattern theory, ecological footprint theory, and the “source-sink” theory^{12,15}. In a similar vein, Zhang et al. replaced “morphology” with “economy” to reflect the ability to cope with ecological risks¹⁶. Additionally, Xia et al. and Tong et al. developed an assessment model for ecological resilience that utilized land-use change data, considering resistance (habitat quality and the ESV), adaptability (landscape pattern factors), and restoring force or regeneration capacity (human-dominated land-use types)^{17,18}. From the perspective of the capacity of ecosystems to absorb disturbances, Xiao et al. attempted to establish a measurement model for ecological resilience based on the concepts of “risk-connectivity-potential”⁷. It should be noted that the landscape ecology perspective in ecological resilience evaluation does not fully account for the pressures and risks faced by ecosystems, nor does it adequately consider the interactions among subsystem ecosystems. Numerous scholars have undertaken the task of evaluating ecological resilience by developing comprehensive indicator systems. For instance, Tao et al. and Lv et al. have drawn upon Martin’s research¹⁹ to construct an analytical framework that incorporates various dimensions such as water, soil, gas, energy, industry, and agriculture^{11,18}. Furthermore, they have refined specific indicators within the dimensions of resistance, adaptation, and recovery. Yang, on the other hand, has proposed an evaluation index system for ecological resilience from the multidimensional perspectives of economy, society, and nature¹⁴. Further, Wang et al. and Niu et al. have introduced an urban ecological resilience index system, which operates under the principles of “resistance-response-innovation” within the context of “innovation adaptation” of the evolutionary cognitive paradigm^{3,20}. This system combines the dynamic evolution characteristics of the adaptive cycle model. To quantitatively measure ecological resilience, researchers have employed methods such as the entropy weight-synthetic index method and the entropy weight-TOPSIS method^{3,9–11,14}. Regarding the analysis of the evolution of spatial patterns, spatial differences, spatial dynamic evolution characteristics, and spatial agglomeration of ecological resilience have been analyzed using the Theil index, gravity center-standard deviation ellipse³, Dagum Gini coefficient²¹, and spatial autocorrelation analysis^{7,11}. When examining the influencing factors of ecological resilience, previous studies have utilized the STIRPAT model to investigate the impact of various factors^{11,22}, including land, capital, population, economic development, and technology. Factors such as the level of economic development, population agglomeration, industrial structure, environmental regulations, scientific and educational inputs, topographical factors, and soil and water conditions have been explored in relation to their influence on ecological resilience. To validate these findings, researchers have employed various methodologies, including correlation analysis¹⁴, multivariate linear regression¹³, the obstacle degree model^{18,21}, the geographic detector model, and the geographically and temporally weighted regression model (GTWR)¹⁰.

Existing studies on ecological resilience have been limited to date. First, the current ecological resilience measurement index system is primarily based on the evolutionary cognitive paradigm, which fails to reflect the essential characteristics of evolutionary resilience and does not sufficiently consider natural factors that need to be further deepened. Second, many studies currently examine the factors influencing ecological resilience using the traditional panel data model without considering spatial effects. In addition, previous studies on ecological resilience, as discussed above, have mainly focused on critical urban agglomeration scales, economic zone scales, or provincial scales. Nevertheless, limited literature systematically analyzes the characterization of spatiotemporal evolution and mechanistic issues of ecological resilience in the Yellow River Basin, which serves as a nationally significant ecological barrier and a rapidly transmutating economic-environmental system.

To address the knowledge gaps in existing research, we used panel data from 75 prefecture-level cities in the Yellow River Basin from 2007 to 2021, employed the “resistance-recovery-reconstruction-renewal” approach, and the improved TOPSIS method to measure ecological resilience in the Yellow River Basin. Additionally, we analyzed the spatiotemporal characteristics of ecological resilience in the Yellow River Basin using the gravity center-standard deviation ellipse, Dagum Gini coefficient decomposition, and spatial autocorrelation analysis to present ecological resilience from both static and dynamic perspectives. Finally, we investigated the spillover mechanism of ecological resilience and its influencing factors using the dynamic spatial Dubin model (DSDM). Accordingly, suggestions for improving ecological resilience are made. The results of this study would provide a reference for similar regions to select appropriate optimization policies for enhancing ecological resilience and exploring new approaches to ecological protection and environmental governance.

In the current study, the marginal contributions are as follows: First, considering natural factors such as land type, climate change, and biodiversity, and based on the essential characteristics of evolutionary resilience, the improved TOPSIS method is used to construct an evaluation index system for measuring the ecological resilience of the Yellow River Basin from four dimensions of resistance, recovery, reconstruction, and renewal, which helps to enrich the methodological and theoretical research and fill the research gap to some extent. Second, we comprehensively analyzed the spatial pattern of ecological resilience in the Yellow River Basin from the perspectives of spatial distribution, difference, and clustering and revealed the evolutionary trend of the spatial pattern, which can provide empirical evidence for policies based on local conditions. Finally, with regard to the spatial effects and dynamics of ecological resilience, we utilized the dynamic spatial Dubin model to analyze the direct and indirect effects, as well as the short-term and long-term effects of each influencing factor, which helps to facilitate the establishment of a new system for the development of ecological resilience.

Materials and methods

Study area

The study focuses on the Yellow River Basin, which spans eastern, central, and western China. It encompasses nine provinces and autonomous regions, namely Qinghai, Sichuan, Gansu, Inner Mongolia, Ningxia, Shanxi, Shaanxi, Henan, and Shandong, covering a total area of 2.17 million square kilometers. According to data from the China Statistical Yearbook, the Yellow River Basin accounted for approximately 25.35% of China’s GDP in 2022. It is an essential ecological barrier and economic belt in China, with a complex and diversified ecosystem, and is also an important “energy basin” and industrial and mining enterprise agglomeration area, so the situation of ecological protection is grim. In 2019, the ecological protection and high-quality development of the Yellow River Basin became a primary national strategy, bringing significant opportunities for the ecological management of the basin. The research focuses on the natural watershed scope delineated by the Yellow River Conservancy Commission of the Ministry of Water Resources. A total of 75 prefecture-level cities within the Yellow River Basin were selected as the research object (Fig. 1). However, certain cities were excluded from the analysis due to their geographical location, regional connections, and missing data. Specifically, Sichuan cities (Hanzhong, Ankang, and Shangluo) are typically considered part of the Yangtze River Economic Belt, while Inner Mongolia cities (Hulunbeier, Chifeng, and Tongliao) are often classified as part of Northeast China. Additionally, Haidong

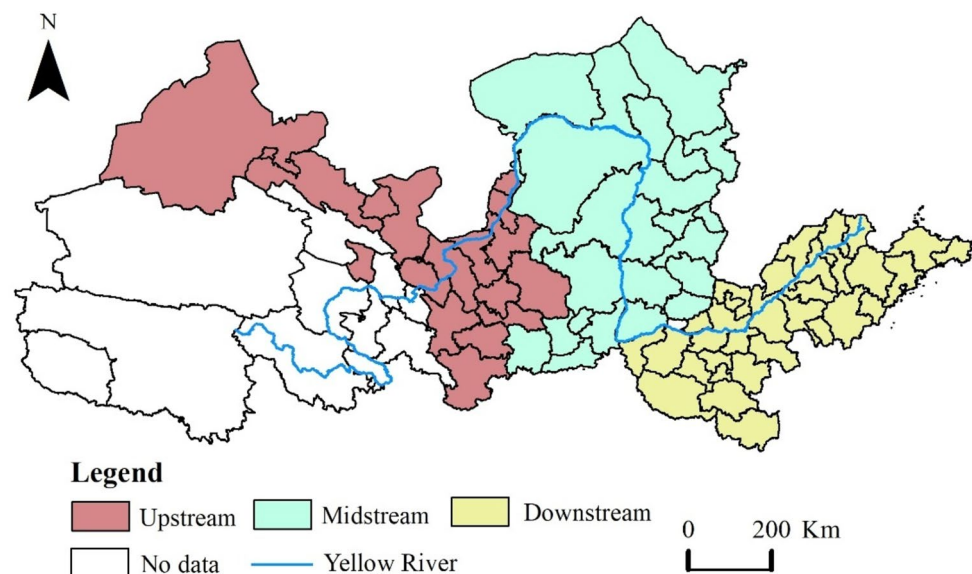


Figure 1. Study area. The figure is based on the standard map GS(2019)1822 in the Standard Map Service website of the Ministry of Natural Resources of the People’s Republic of China, with no modifications of the boundaries in the standard map.)

in Qinghai had a higher incidence of missing data. Consequently, these cities were not included in the analysis conducted in this paper. To facilitate regional comparisons, the Yellow River Basin was divided into three parts: upstream, midstream, and downstream. The upstream region comprises 18 cities located in Qinghai, Gansu, and Ningxia. The midstream region includes 24 cities located in Inner Mongolia, Ningxia, Shanxi, and Shaanxi. The downstream region encompasses the remaining 33 cities located in Henan and Shandong (Table 1).

Methodology

Indicator system construction

The evolutionary cognitive paradigm emphasizes that ecosystems are complex adaptive systems that continuously acquire new knowledge from the external environment and evolve accordingly. Ecological resilience, as a fundamental component of resilience, refers to the ability of ecosystems to adjust their structure and state continuously in response to changes in the external environment, enabling them to adapt and thrive²³. Within academic circles, several essential characteristics of evolutionary resilience have been identified, including “resistance-recovery-adaptation-transformation”¹⁹, “absorb-recovery-transformation”²⁴, and “resistance-recovery-reorganization-renewal”²⁵, which is also applicable to ecological resilience as a critical component of resilience. Based on the theoretical foundations and previous research findings, this study proposes an evaluation indicator system for ecological resilience encompassing four dimensions: resistance, recovery, reconstruction, and renewal. Resistance indicators represent the ability of an ecosystem to prevent or absorb disturbances from internal and external factors and to maintain its structure and functioning, which largely depends on the condition and endowment of the ecosystem^{15,26}. It is closely related to factors such as resource abundance and economic development. Recovery indicators refer to the ability of an ecosystem to return to its original state while maintaining its internal structure and function²⁷. This content includes, for example, pollution control, environmental quality, and physical resources. Reconstruction indicators focus on the ability of an ecosystem to reorganize its internal and external structures and functions in response to disturbances²⁸, which are characterized in terms of labor and capital. Renewal indicators guarantee ecosystems develop new development models and pathways driven by science, technology, and innovation, mainly in terms of “innovation adaptation”²⁹, as measured by innovation intensity, inputs, and outputs¹⁵. Table 2 describes the complete evaluation indicator system in this paper.

Improved TOPSIS method

The TOPSIS method is a decision-making method for multi-objective systems proposed by Hwang and Yoon³⁰. The model has been widely used to rank the evaluation objects according to their proximity to optimal and inferior solutions because it can make full use of data information³¹. Therefore, this paper introduces the improved TOPSIS method to calculate the ecological resilience of the 75 cities in the Yellow River Basin. The main steps of the improved TOPSIS method are as follows³²:

- (1) Standardize the evaluation indexes:

$$\text{Positive in : dex : } x'_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (1)$$

$$\text{Negative index : } x'_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (2)$$

In the formula, x_{ij} is the original index j in the region i ; x'_{ij} is the index after standardization processing; $\max x_{ij}$ and $\min x_{ij}$ are the maximum and the minimum values of index j , respectively.

- (2) Calculate the weight of the evaluation indexes based on entropy weight:

$$w_{ij} = \frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}}; e_j = -\frac{1}{\ln m} \sum_{i=1}^m w_{ij} \times \ln w_{ij} \quad (3)$$

Regions	Prefecture-level cities
Upstream	Lanzhou, Baiyin, Wuwei, Jinchang, Pingliang, Zhangye, Jiayuguan, Jiuquan, Qingyang, Dingxi, Longnan, Tianshui, Xining, Yinchuan, Guyuan, Wuzhong, Shizuishan, Zhongwei
Midstream	Hohhot, Baotou, Wuhai, Ordos, Ulanqab, Bayannur, Taiyuan, Datong, Yangquan, Changzhi, Linfen, Jinzhong, Yuncheng, Jincheng, Xinzhou, Shuozhou, Lvliang, Xi'an, Xianyang, Yulin, Baoji, Tongchuan, Weinan, Yan'an
Downstream	Zhengzhou, Kaifeng, Luoyang, Pingdingshan, Jiaozuo, Hebi, Xinxiang, Anyang, Puyang, Xuchang, Luohe, Sanmenxia, Nanyang, Shangqiu, Xinyang, Zhoukou, Zhumadian, Jinan, Qingdao, Zibo, Zaozhuang, Dongying, Yantai, Weifang, Jining, Tai'an, Weihai, Rizhao, Binzhou, Dezhou, Liaocheng, Linyi, Heze

Table 1. The division of prefecture-level cities in the upstream, midstream, and downstream of the Yellow River Basin.

Dimension	Sub-dimension	Indicators (Unit)	Attribute	Weight
Resistance	Resource abundance	Per capita water resources (m ³ /person)	+	0.0858
		Normalized difference vegetation index (NDVI)	+	0.0064
		Habitat quality index (HQI)	+	0.0590
		Public recreational green space per capita (m ²)	+	0.0377
	Economic development	Per capita GDP (CNY)	+	0.0203
		Disposable income per resident (CNY)	+	0.0150
		Ratio of tertiary industry to GDP	+	0.0065
Recovery	Pollution control	Industrial SO ₂ removal rate (%)	+	0.0058
		Wastewater treatment rate (%)	+	0.0010
		Industrial solid waste comprehensive utilization rate (%)	+	0.0074
		Domestic garbage harmless treatment rate (%)	+	0.0017
		Industrial smoke (dust) removal rate (%)	+	0.0006
		“Three waste” emissions per unit of output value (t/CNY 10, 000)	-	0.0003
	Environmental quality	Green coverage rate of the built-up area (%)	+	0.0016
		Green space rate of built-up area (%)	+	0.0054
		Number of days with Grade II air quality or better (day)	+	0.0030
	Physical resources	Number of wastewater treatment plant (unit)	+	0.0652
		Number of harmless treatment plants or grounds (unit)	+	0.0169
		Density of water supply pipelines in the built-up area (km/km ²)	+	0.0117
	Reconstruction	Labor	Number of employees in the environmental sector (person)	+
Capital		Investment in sewerage (CNY 10, 000)	+	0.0734
		Investment in landscaping (CNY 10, 000)	+	0.0754
		Investment in environmental sanitation (CNY 10, 000)	+	0.0919
Renewal	Innovation intensity	Number of college students per 10, 000 population (person)	+	0.0556
		R&D personnel per 10,000 labor force (person))	+	0.0747
	Innovation inputs	Public expenditures on education (CNY 10, 000)	+	0.0475
		Proportion of R&D investment in GDP (%)	+	0.1000
	Innovation outputs	Patent grants per 10, 000 GDP (piece)	+	0.0309
		Patent grants per 10,000 population (piece)	+	0.0616
		Proportion of patents for inventions to patents granted (%)	+	0.0147

Table 2. Comprehensive evaluation index system of ecological resilience in the Yellow River Basin.

$$\varphi_j = \frac{(1 - e_j)}{\sum_{j=1}^m (1 - e_j)} \tag{4}$$

In the formula, w_{ij} is the proportion of index j under the region i ; e_j is the entropy value of index j ; φ_j is the index weight.

(3) Calculate the weighting matrix:

$$R = (r_{ij})_{n \times m}; r_{ij} = \varphi_j x_{ij} \tag{5}$$

(4) Calculate the positive and negative ideal solutions:

$$Q_j^+ = (\max r_{i1}, \max r_{i2}, \dots, \max r_{im}) \tag{6}$$

$$Q_j^- = (\min r_{i1}, \min r_{i2}, \dots, \min r_{im}) \tag{7}$$

(5) Calculate the distance between each evaluation object to the positive and the negative ideal solutions:

$$d_i^+ = \sqrt{\sum_{j=1}^m (Q_j^+ - r_{ij})^2} \tag{8}$$

$$d_i^- = \sqrt{\sum_{j=1}^m (Q_j^- - r_{ij})^2} \tag{9}$$

(6) Determine the relative proximity:

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{10}$$

(7) Considering the harmonization of four dimensions of resistance, recovery, reconstruction, and renewal, this paper introduces the coefficient of variation k :

$$k = \sqrt{\sum_{n=1}^4 \frac{(R - V)^2}{4}} / V; V = \frac{1}{4} \sum_{n=1}^4 R \tag{11}$$

(8) Calculate the improved ecological resilience:

$$C'_i = C_i(1 - k) \tag{12}$$

Gravity-standard deviation ellipse

The standard deviation ellipse is a classical method of analyzing the distribution direction and characteristics of geographical elements^{33,34}. This paper introduces this method to present the directional spatial distribution of ecological resilience in the Yellow River Basin and quantitatively describe its dynamic evolution trend. Its expression is³⁵:

$$X = \sum_{i=1}^n w_i X_i / \sum_{i=1}^n w_i; Y = \sum_{i=1}^n w_i Y_i / \sum_{i=1}^n w_i \tag{13}$$

$$\theta_{j-i} = \frac{n\pi}{2} + \arctan((y_j - y_i) / (x_j - x_i)) \tag{14}$$

$$d_{j-i} = c \times \sqrt{(y_j - y_i)^2 + (x_j - x_i)^2} \tag{15}$$

$$\tan \beta = \frac{\left(\sum_{i=1}^n w_i^2 X_i^{*2} - \sum_{i=1}^n w_i^2 Y_i^{*2}\right) + \sqrt{\left(\sum_{i=1}^n w_i^2 X_i^{*2} - \sum_{i=1}^n w_i^2 Y_i^{*2}\right)^2 - 4 \sum_{i=1}^n w_i^2 X_i^{*2} Y_i^{*2}}}{2 \sum_{i=1}^n w_i^2 X_i^{*2} Y_i^{*2}} \tag{16}$$

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^n (R_i X_i^* \cos \theta - R_i Y_i^* \sin \theta)^2}{\sum_{i=1}^n R_i^2}}; \sigma_y = \sqrt{\frac{\sum_{i=1}^n (R_i X_i^* \sin \theta - R_i Y_i^* \cos \theta)^2}{\sum_{i=1}^n R_i^2}} \tag{17}$$

In the formula, X and Y are the center of gravity coordinates, respectively; θ_{j-i} represents the angle of shift of the center of gravity in year j with respect to year i ; d_{j-i} represents the distance that the center of gravity shifts in year j with respect to year i ; c is the conversion coefficient, which takes the value of 111.111; β is the rotation; σ_x and σ_y are the the semi-major axis and semi-major axis, respectively.

Dagum Gini coefficient

Dagum decomposed the Gini coefficient into the contribution of intra-regional difference (G_w), inter-regional difference (G_{nb}), and intensity of transvariation (G_t), which can effectively solve problems such as the overlap of sample data³⁶. This study reveals the composition and the source of the spatial differences in ecological resilience in the Yellow River Basin. Its expression is:

$$G = \frac{\sum_{j=1}^k \sum_{h=1}^k \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |y_{ji} - y_{hr}|}{2n^2 \mu} \tag{18}$$

$$G_w = \sum_{j=1}^k G_{jj} p_j s_j; G_{jj} = \frac{\sum_{i=1}^{n_j} \sum_{r=1}^{n_j} |y_{ji} - y_{jr}|}{2n_j^2 y_i} \tag{19}$$

$$G_{nb} = \sum_{j=2}^k \sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) D_{jh}; G_{jh} = \frac{\sum_{i=1}^{n_j} \sum_{r=1}^{n_h} |y_{ji} - y_{jr}|}{n_j n_h (\bar{y}_i + \bar{y}_h)}; p_j = n_j/n; s_j = n_j/n \quad (20)$$

$$G_t = \sum_{j=2}^k \sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)(1 - D_{jh}) \quad (21)$$

$$D_{jh} = \frac{(d_{jh} - p_{jh})}{(d_{jh} + p_{jh})}; d_{jh} = \int_0^\infty dF_j(y) \int_0^y (y-x)dF_h(x); p_{jh} = \int_0^\infty dF_h(y) \int_0^y (y-x)dF_j(x) \quad (22)$$

In the formula, G is the overall Gini coefficient; y_{ji} is the ecological resilience of the city i in region j ; μ is the average ecological resilience of all cities; \bar{y}_j (\bar{y}_h) is the average ecological resilience of region j (h); d_{jh} is the difference in gross ecological resilience influence between regions j and h ; p_{jh} is the first-order moment of transvariation.

Spatial autocorrelation analysis

(1) Global spatial autocorrelation.

The global spatial autocorrelation analysis, frequently measured by the global Moran's I index, can effectively verify whether there is an overall spatial dependency between the neighborhood units³⁷. This paper adopts the global Moran's I index to detect whether the ecological resilience in the Yellow River Basin are spatially autocorrelated as a whole. Its expression is³⁸:

$$\text{Global Moran's } I = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n W_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (23)$$

In the formula, n is the number of cities; x_i and x_j are the ecological resilience of cities i and j , respectively; W_{ij} is the weight value of the spatial matrix corresponding to cities i and j .

(2) Local spatial autocorrelation.

The local spatial autocorrelation can effectively reveal the spatial clustering of ecological resilience in each city of the Yellow River Basin. The commonly used test statistic is the local Moran's I index³⁹. Its expression is:

$$\text{Local Moran's } I = \frac{(x_i - \bar{x}) \sum_j W_{ij}(x_j - \bar{x})}{\sum_{j=1, j \neq i}^n (x_j - \bar{x})^2 / (n-1)} \quad (24)$$

Dynamic spatial Durbin model

Given that ecological resilience has significant spatial spillover characteristics, this paper uses a spatial econometric model to test the influencing factors of ecological resilience. As a general form of both the spatial autoregressive model (SAR) and the spatial error model (SEM), the spatial Durbin model (SDM) produces more robust estimation results by introducing the spatial lag terms of explanatory variables and explained variables⁴⁰. Moreover, considering the path dependence and Matthew effect, the time lag term of the explained variable was added. The dynamic spatial Durbin model (DSDM) can be set as

$$y_{it} = \partial_0 + \partial_1 y_{i,t-1} + \eta \sum_{j=1}^n W_{ij} y_{j,t-1} + \rho \sum_{j=1}^n W_{ij} y_{jt} + \partial_2 X_{it} + \partial_3 \sum_{j=1}^n W_{ij} X_{jt} + \mu_i + \xi_t + \varepsilon_{it} \quad (25)$$

In the formula, y_{it} is the explained variable at time t in region i ; W_{ij} is the spatial weight matrix; α_1 is the time lag coefficient; ρ is the spatial autoregressive coefficient; η is the spatiotemporal lag coefficient; X is the explanatory variables (influencing factors for the selection); μ_i is the regional fixed effect; ξ_t is the time fixed effect; ε_{it} is the random error term.

The study of influencing factors behind environmental change has evolved through various stages, including the IPAT⁴¹, ImPACT⁴², and STIRPAT models^{43,44}. Among these, the STIRPAT model has gained popularity due to its flexibility, and the extended version of the STIRPAT model allows for the inclusion of additional drivers based on specific research scenarios. In many studies, the STIRPAT model incorporates fundamental variables such as population size, affluence, and technological level, which align with the IPAT model, along with additional variables relevant to the research context⁴⁵. Considering the unique characteristics of the Yellow River Basin and drawing upon existing research, this study adopts population density (PD) and urbanization rate (UR) as indicators of population size. Per capita GDP (PGDP) and openness (OPEN) are used to measure affluence, while industrial

structure (IS) and the intensity of financial investment in technological innovation (FIT) represent the technological level. Specifically, we employed the logarithm of population per square kilometer to reveal the influence of PD on ecological resilience. Population growth has always been closely connected to ecological problems⁴⁶, and thus, the number of people per square kilometer primarily reflects PD indicators⁴⁷. Rapid urbanization has been found to have a complex and influential relationship with the ecological environment^{9,48,49}. Therefore, the proportion of the urban population in the total population is used to measure UR in this study. The relationship between environmental quality and economic development is well-established. Hence, the logarithm of GDP per capita is used as a measure of PGDP. Theoretically, foreign direct investment inflows may have different ecological impacts under the hypotheses of a “pollution paradise” or “pollution halo”^{50,51}. Therefore, the proportion of foreign investment in GDP is employed to represent OPEN and explore its influence on ecological resilience. The secondary industry, particularly manufacturing, tends to consume more natural resources compared to the tertiary industry. Additionally, agriculture and industry may have distinct environmental impacts. To assess IS, the ratio of the proportion of the tertiary industry to the proportion of the secondary industry is introduced⁵². Furthermore, the proportion of expenditure for science and technology in public finance expenditure is used as an indicator of FIT^{53,54}, which is considered a major influencing factor ecological resilience.

Data sources

We used panel data from 75 prefecture-level cities in the Yellow River Basin from 2007 to 2021. The social and economic data were obtained from the China City Statistical Yearbook, the China Urban Construction Statistical Yearbook, the China Urban–Rural Construction Statistical Yearbook, as well as statistical yearbooks and bulletins of provinces and cities. The number of days with Grade II air quality or better was derived from the China Air Quality Online Monitoring and Analysis Platform (<https://www.aqistudy.cn/>). NDVI data were obtained from NASA’s regularly released MOD13A3 dataset (<https://search.earthdata.nasa.gov/search>), and the original data were in raster format. After calculating the average raster values within each prefecture-level city, year-by-year NDVI data were generated. Data on HQI were calculated according to the area of woodlands, grasslands, water wetlands, and cropland obtained from the second and third national land surveys and annual national land change surveys. The number of patents granted was obtained from the Chinese Research Data Services Platform (<https://www.cnrds.com/>). The data acquired were classified into the Yellow River Basin’s upstream, midstream, and downstream regions.

Results

The ecological resilience of the 75 cities in the Yellow River Basin was calculated based on Eqs. (1–12) and the proposed evaluation indicator system for ecological resilience. The analysis covered the period from 2017 to 2021.

Temporal evolution characteristics

The average ecological resilience of the Yellow River Basin increased from 0.087 in 2007 to 0.130 in 2021 (Fig. 2), showing an overall fluctuating upward trend with an annual increase of 3.57%. During the observation period, the implementation of policies by the Central Committee of the Communist Party of China (CPC) and the State Council, such as the National New-Type Urbanization Plan, the Overall Program of Ecological Civilization

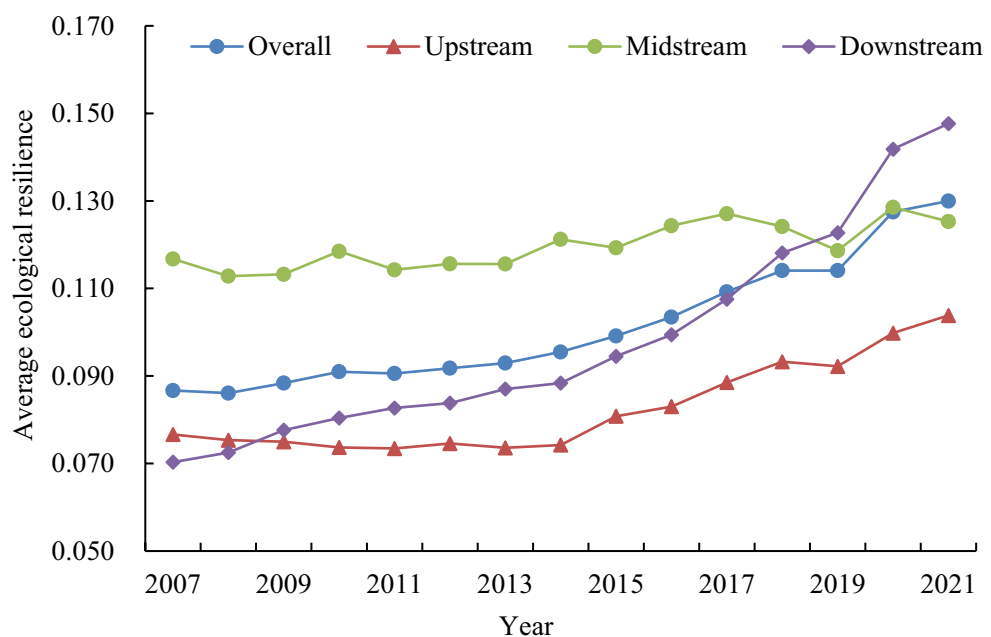


Figure 2. Trends of average ecological resilience by region.

System Reform, and the Outline of the Plan for the Ecological Protection and High-Quality Development of the Yellow River Basin, has played a significant role in driving this improvement. These policies have emphasized the importance of eco-environmental protection factors in the socio-economic development of the cities in the region. As a result of these efforts, the construction of ecological civilization has yielded significant results, leading to an evident enhancement in environmental carrying capacity and risk resistance. Consequently, the ecological resilience of the Yellow River Basin has been gradually optimized. However, it is important to note that the value of ecological resilience remains relatively small, with noticeable fluctuations. For instance, there were slight downward trends in 2008, 2011, and 2019, followed by subsequent rebounds. These fluctuations may be attributed to factors such as the limited economic strength of the cities in the Yellow River Basin, the presence of imperfect social systems, and the fragile nature of the ecological environment in the region. These findings suggest that enhancing ecological resilience in the Yellow River Basin is a complex and gradual process, requiring continued efforts to address the underlying socio-economic and challenges.

Figure 2 also presents the ecological resilience of each region in the Yellow River Basin. When comprehensively analyzed at the regional level, significant regional differences were observed among the three major regions in the upstream, midstream, and downstream of the Yellow River Basin. From 2007 to 2008, regional ecological resilience was ranked as midstream > upstream > downstream in the Yellow River Basin. The reason may be that the downstream region is more economically developed, with a high degree of industrialization, and affected by the global financial crisis and the domestic economic situation. The pressure to “maintain growth” has led to neglecting rational and sustainable resource development and environmental protection, resulting in lower ecological resilience. In terms of trends, all regions within the Yellow River Basin experienced improvements in ecological resilience, although the magnitude of these increases varied significantly. The upstream region saw an increase in ecological resilience from 0.077 to 0.104, with an annual growth rate of 2.54%. Specifically, ecological resilience showed a slight fluctuating downward trend from 2007 to 2014. This trend can be attributed to the initial stage of ecological civilization construction, where upstream cities focused on immediate administrative measures rather than long-term sustainability. However, with the implementation of the “14th Five-Year Plan”, the Chinese government recognized the upstream region’s role as an ecological barrier and increased investment in environmental protection. As a result, the upstream has experienced rapid growth, although the overall value remains relatively low. Notably, cities with better ecological environments, such as Zhangye, Wuwei, Xining, and Tianshui, exhibited lower ecological resilience, highlighting the presence of the “resource curse”. However, this curse can be alleviated by increasing investment in innovation and enhancing environmental regulations. The midstream region displayed a slow, fluctuating upward trend in ecological resilience during the study period, with an annual growth rate of just 0.52%. This region is characterized by abundant energy resources and a fragile ecological environment. The development model, which heavily relies on resources and labor, has resulted in significant contradictions within the industrial structure. In 2019, the downstream region surpassed the midstream region in terms of ecological resilience. In recent years, the downstream region has been actively promoting the conversion of old and new kinetic energy, implementing the concept of “vacating cage to change birds” in the industrial sector. Consequently, its ecological resilience has exhibited a rapid upward trend, with an average annual growth rate of 25.35%, eventually showing a spatial differentiation pattern of ecological resilience of downstream > midstream > upstream.

Spatial distribution characteristics

In this study, the ecological resilience of the Yellow River Basin was visualized using ArcGIS 10.2 software. The natural breakpoint method was employed to classify the contrasting outcomes into higher, high, medium, low, and lower levels, as depicted in Fig. 3.

The ecological resilience of the Yellow River Basin exhibits clustering characteristics, with regional central cities serving as the core and displaying distinct zonal differences. Cities with similar levels of ecological resilience are distributed in a “large settlement, small scattered” pattern. Figure 3 shows that cities with higher and high levels of ecological resilience are primarily situated in core provincial capitals such as Jinan, Xi’an, Taiyuan, and Hohhot. These cities possess a solid economic and social foundation and have made significant efforts in industrial transformation and ecological protection in recent years. Consequently, their ecological resilience surpasses that of other cities in the basin. For example, Jinan has prioritized green city construction as part of its “13th Five-Year Plan” and recently issued the “14th Five-Year Plan for Green Low-carbon Cycle Development”. Similarly, cities like Bayannur, Erdos, Baotou, Shuozhou, and Yizhou in the midstream region, as well as Linyi, Dongying, Qingdao, and Zibo in the downstream region, exhibit higher and high levels of ecological resilience. These cities benefit from their proximity to the core provincial capitals, which ensures their ecological resistance and recovery. Analyzing the evolution of spatial distribution reveals that cities with high ecological resilience in the Yellow River Basin exhibit a significant positive spillover effect. This effect radiates and drives neighboring cities to enhance their own ecological resilience. Conversely, cities such as Baiyin, Dingxi, Tianshui, Baoji, Pingliang, Pingdingshan, Xuchang, Luohe, Nanyang, Xinyang, and Zhumadian, which have lower and low levels of ecological resilience, are predominantly located in the southwestern and southeastern regions of the Yellow River Basin. These cities exhibit specific spatial solidification characteristics and face challenges in improving their basic infrastructure, economic growth momentum, and pollutant emissions, all of which hinder their ecological resilience.

To further understand the spatial dynamic evolution of ecological resilience in the Yellow River Basin, we employed the center of gravity-standard deviation ellipse analysis (Fig. 4 and Table 3).

As for the center gravity, it shifted from Zhongyang, Lvliang City (111.00°E, 37.19°N) to Qinyuan, Changzhi City (112.10°E, 36.57°N), with a cumulative displacement of 149.96 km between 2007 and 2021. Specifically, the center of gravity shifted 60.69 km to the southeast from 2007 to 2012, indicating a significant improvement in

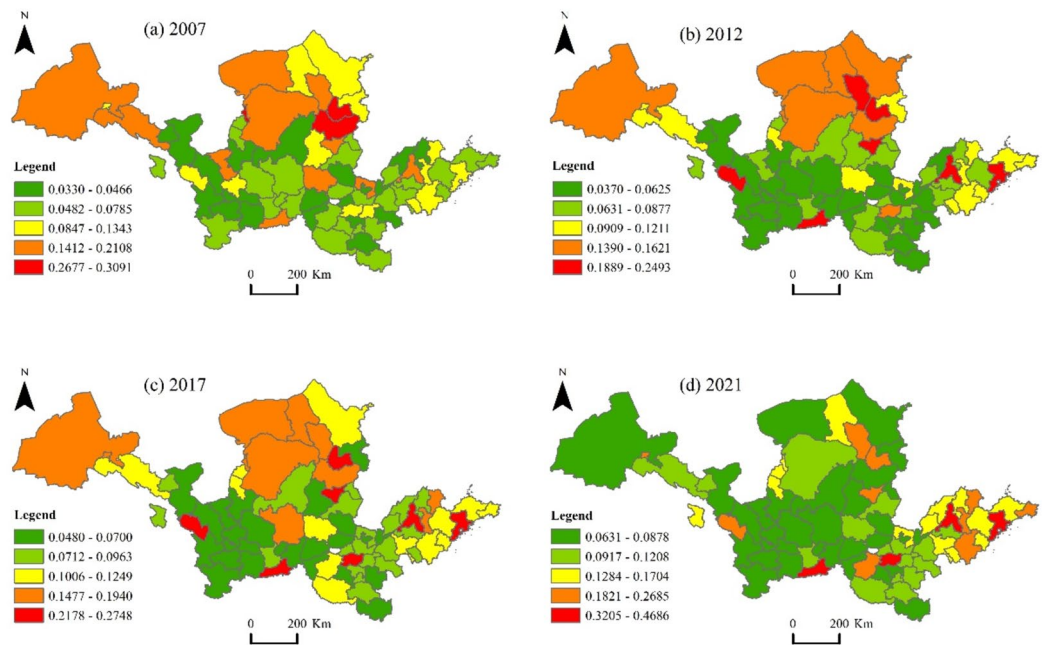


Figure 3. Spatial distribution of ecological resilience in the Yellow River Basin in 2007, 2012, 2017, and 2021.

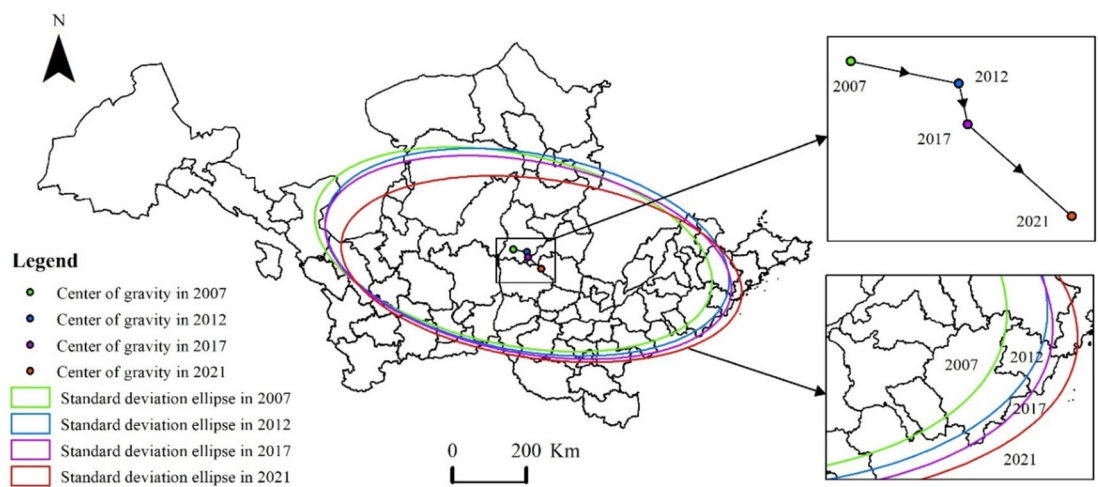


Figure 4. Center of gravity-standard deviation ellipse of ecological resilience in the Yellow River Basin in 2007, 2012, 2017, and 2021.

Year	Center	Direction	Rotation (°)	Semi-major (km)	Semi-minor (km)	Area (km ²)
2007	111.00°E, 37.19°N		101.86	882.81	416.29	115.44 × 10 ⁴
2012	111.54°E, 37.10°N	East by south 9.27°	100.35	894.01	430.23	120.82 × 10 ⁴
2017	111.59°E, 36.94°N	East by south 74.80°	100.94	900.42	417.32	118.04 × 10 ⁴
2021	112.10°E, 36.57°N	East by south 35.93°	98.12	882.94	390.84	108.40 × 10 ⁴

Table 3. Each parameter value in the center of gravity-standard deviation ellipse.

the ecological resilience of the southeast Yellow River Basin. From 2012 to 2015 and 2015 to 2021, the center of gravity further shifted 18.66 km and 70.61 km southeast, respectively, indicating a continued increase in ecological resilience in the southeast Yellow River Basin region. Overall, this phenomenon reflects a shrinking trend of the spatially concentrated distribution region of ecological resilience towards the southeast. This trend can be attributed to the gradual shift in the development strategy of the midstream and downstream Yellow River Basin regions, transitioning from a focus on economic growth to one centered on ecological development. Additionally, the core demonstration area for ecological protection and high-quality development, led by Zhengzhou, played a crucial role. Furthermore, strategic layouts and institutional guarantees, such as the “Shandong Peninsula Blue Economic Zone Development Plan” and the “Green Shandong” implemented by Shandong Province, have contributed to this trend.

Analysis of the standard deviation ellipse revealed that the coverage area of the ecological resilience space ellipse was primarily located in the midstream and downstream regions of the Yellow River Basin, with a shift towards the east. The spatial scope of cities with ecological resilience decreased. In terms of rotation, a distinct pattern of “decreasing-slightly increasing-and then decreasing” was observed. From 2007 to 2012, the rotation gradually decreased from 101.86° to 100.35°, indicating a shift of 1.51° in the spatial distribution of ecological resilience from a “northwest-southeast” pattern to an “east–west” pattern. The rotation slightly increased from 2012 to 2017, but the magnitude was minimal, suggesting relative stability in the spatial distribution. In the subsequent period, the rotation deflected by 2.82° in an “east–west” direction. Overall, the spatial distribution of ecological resilience in the Yellow River Basin exhibited a pattern of “northwest-southeast” initially, transitioning towards an “east–west” pattern. From the perspective of the standard distance of the ellipse, the semi-major axis of ecological resilience increased from 882.81 km in 2007 to 900.42 km in 2017, indicating a spreading tendency of ecological resilience in a “northwest-southeast” direction. Then, the semi-major axis decreased to 882.94 km from 2017 to 2021, and the spatial agglomeration phenomenon exhibited a trend in the “northwest-southeast” direction. Furthermore, the semi-minor axis increased from 416.29 to 430.23 km between 2007 and 2012, and then decreased to 390.84 km from 2012 to 2021. The results indicate a strengthening of the spatial agglomeration of ecological resilience in the “northeast-southwest” direction.

Spatial differences characteristics

We utilized the Dagum Gini coefficient and its decomposition method to describe the regional differences and sources of ecological resilience in the Yellow River Basin. The results of our calculations are presented in Table 4.

Overall and intra-regional differences

Figure 5 illustrates the overall Gini coefficient of ecological resilience in the Yellow River Basin, which decreased from 0.348 in 2007 to 0.282 in 2021, indicating a fluctuating downward trend. This suggests a reduction in spatial differences in ecological resilience over the observation period. The overall Gini coefficient exhibited a pattern of rising and falling, reaching its peak at 0.348 in 2007 and declining to 0.275 in 2019. For intra-regional differences, the average Gini coefficient values of ecological resilience in the upstream, midstream, and downstream regions were 0.263, 0.313, and 0.253, respectively. The largest difference was observed within the midstream region, while the smallest difference was within the downstream region. This can be attributed to the superior socio-economic foundation of the downstream region, comprehensive improvements in the human settlement environment, and the implementation of regional coordinated development strategies. In contrast, the midstream region faces ecological fragility and significant socio-economic and ecological conflicts. Variations in urban

Year	Overall	Intra-regional Gini coefficient			Inter-regional Gini coefficient			Contribution (%)		
		Upstream	Midstream	Downstream	Up- midstream	Up- downstream	Mid- downstream	Gw	Gnb	Gt
2007	0.348	0.337	0.362	0.269	0.371	0.298	0.348	31.436	34.111	34.453
2008	0.325	0.301	0.341	0.264	0.345	0.280	0.328	31.977	31.602	36.421
2009	0.317	0.289	0.329	0.272	0.335	0.280	0.320	32.618	29.329	38.053
2010	0.315	0.286	0.313	0.262	0.331	0.273	0.315	31.794	33.253	34.953
2011	0.295	0.287	0.296	0.244	0.318	0.263	0.289	32.089	31.990	35.921
2012	0.288	0.274	0.287	0.241	0.309	0.256	0.283	32.121	32.586	35.293
2013	0.282	0.238	0.301	0.237	0.307	0.243	0.282	32.631	33.021	34.349
2014	0.290	0.233	0.307	0.254	0.311	0.252	0.292	33.048	35.169	31.783
2015	0.280	0.245	0.288	0.255	0.294	0.256	0.280	33.649	28.459	37.893
2016	0.292	0.258	0.320	0.247	0.319	0.258	0.290	33.301	27.879	38.820
2017	0.286	0.265	0.301	0.243	0.307	0.260	0.281	33.153	24.749	42.098
2018	0.278	0.233	0.304	0.257	0.289	0.259	0.281	34.598	18.412	46.989
2019	0.275	0.226	0.310	0.247	0.286	0.253	0.279	34.610	18.612	46.778
2020	0.290	0.241	0.332	0.246	0.305	0.264	0.290	33.890	23.047	43.063
2021	0.282	0.232	0.297	0.259	0.278	0.269	0.285	34.360	25.688	39.953
Average	0.296	0.263	0.313	0.253	0.314	0.264	0.296	33.018	28.527	38.455

Table 4. Gini coefficient and decomposition results of ecological resilience in the Yellow River Basin.

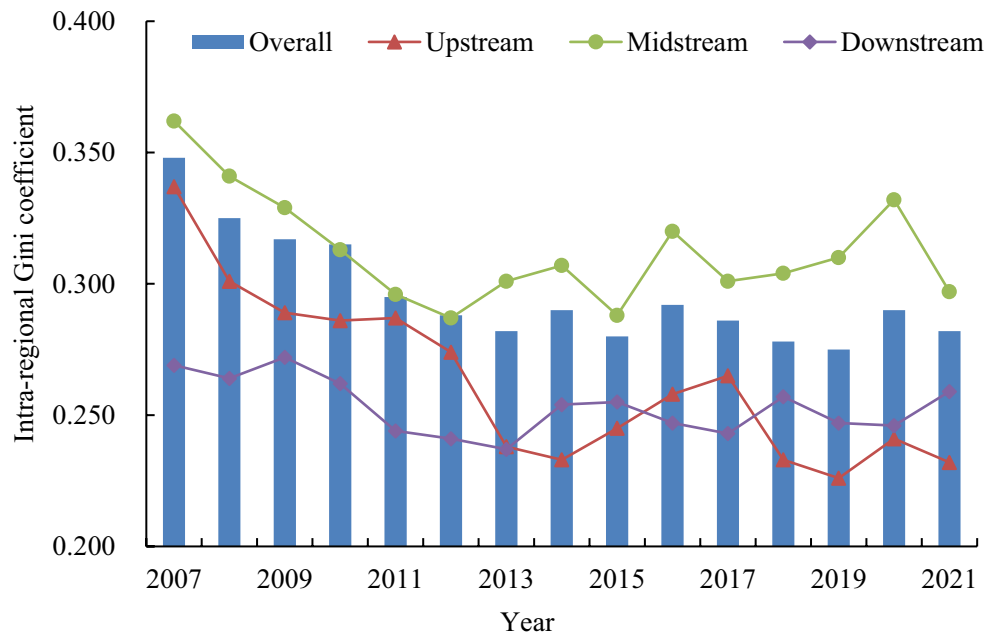


Figure 5. Trends in the overall and intra-regional Gini coefficient of ecological resilience.

economic levels, infrastructure development, and environmental monitoring and restoration efforts contribute to the larger intra-regional differences in ecological resilience within this region.

Specifically, the Gini coefficients of ecological resilience in the upstream and midstream regions also showed a fluctuating declining trend from 0.337 and 0.362 in 2007 to 0.232 and 0.297 in 2021, respectively. This represents a decrease of 31.16% and 17.96% in their respective Gini coefficients, indicating a convergence of cities with lower ecological resilience towards those with higher ecological resilience during the study period. In comparison, the Gini coefficient of the downstream region displayed an evolutionary pattern of alternating increases and decreases, maintaining a relatively stable state. These findings suggest positive outcomes in terms of ecological restoration and industrial restructuring in the upstream and midstream regions, driven by the transformation of resource-based economies. However, attention should be paid to the radiation and demonstration effects of ecological construction in core cities within the downstream region.

Inter-regional differences

Figure 6 illustrates the trend of Gini coefficients of ecological resilience in the upstream-midstream, upstream-downstream, and midstream-downstream regions. These coefficients displayed a fluctuating declining trend from 0.371, 0.298, and 0.348 in 2007 to 0.278, 0.269, and 0.285 in 2021, respectively. This represents a decrease of 25.06%, 9.73%, and 18.10% in their respective Gini coefficients, indicating an evolution characterized by alternating increases and decreases. Moreover, the average Gini coefficient value of ecological resilience in the upstream-midstream was 0.314, signifying the most significant inter-regional difference. This disparity can be attributed to variations in geographic location, ecological maintenance, industrial structure, resource development, and other factors between the upstream and midstream regions. Furthermore, the trend demonstrates a narrowing of differences in the upstream-midstream, upstream-downstream, and midstream-downstream regions, indicating a gradual convergence of inter-regional differences.

Sources of regional differences and their contributions

Figure 7 presents the average contribution rates of intra-regional difference (Gw), inter-regional difference (Gnb), and intensity of transvariation (Gt), which were calculated to be 33.018%, 28.527%, and 38.455%, respectively. The primary source of spatial differences in ecological resilience is the contribution rate of the intensity of transvariation, followed by intra-regional and inter-regional differences. Therefore, the main reason for spatial differences in ecological resilience is the overlapping problems between regions. In other words, regions with high levels of ecological resilience contain cities that have lower levels of ecological resilience than some cities in regions with lower levels. For the evolution trend, the contribution rate of intra-regional difference remained relatively stable, while the contribution rate of the intensity of transvariation exhibited an increasing trend, and the contribution rate of inter-regional difference showed a decreasing trend. The contribution rates of intra-regional difference and intensity of transvariation displayed a complementary fluctuating relationship. Specifically, the former reached its minimum value of 18.412% in 2018, while the latter reached its maximum value of 46.989%.

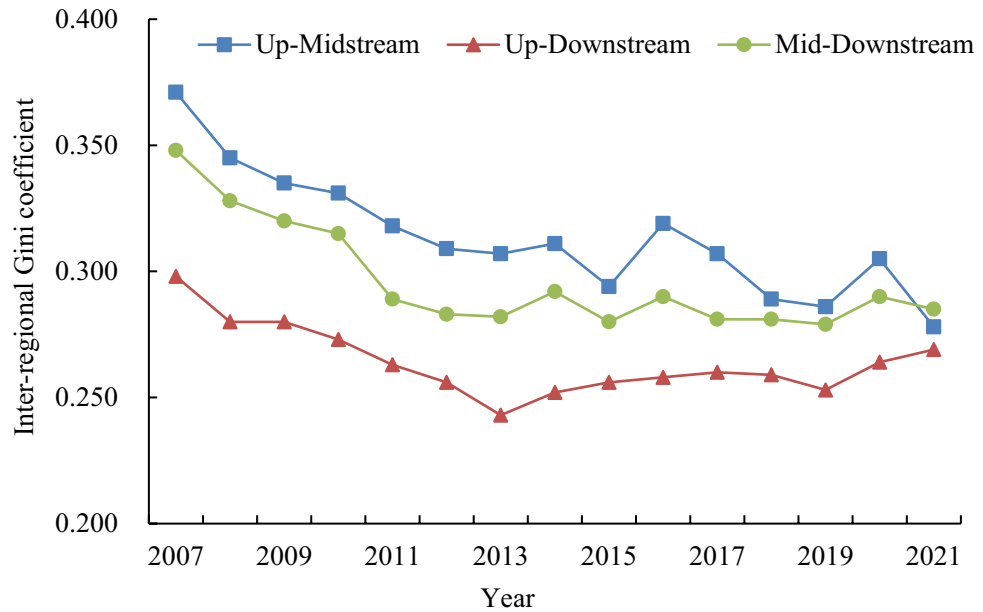


Figure 6. Trends in the inter-regional Gini coefficient of ecological resilience.

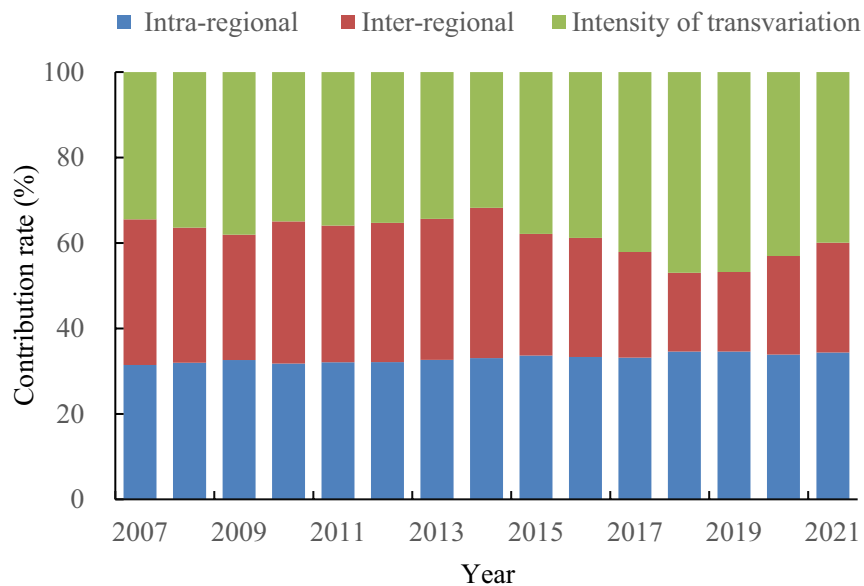


Figure 7. Sources of regional differences and contribution rates.

Spatial clustering characteristics

Global spatial autocorrelation analysis

To account for the spatial clustering effect of ecological resilience in the Yellow River Basin, we conducted a spatial autocorrelation analysis using the Rook adjacency method. Specifically, we calculated the Global Moran's I index and its related parameters to assess the ecological resilience in the Yellow River Basin. The primary objective is to determine whether there is an overall clustering trend in the spatial distribution of ecological resilience. The Global Moran's I values are illustrated in Table 5. During the observation period, the values of Moran's I index for ecological resilience in the Yellow River Basin were significantly positive at the 0.05 confidence level, except for 2007. This provides evidence that the ecological resilience in the Yellow River Basin displays a significant positive spatial autocorrelation. In other words, cities with similar levels of ecological resilience were often spatially adjacent. High ecologically resilient cities are adjacent to other cities with high ecological resilience, while low ecologically resilient cities are adjacent to other cities with low ecological resilience. In addition, a city's ecological resilience is influenced by its environment and the radiation-driven activities of neighboring cities. Furthermore, the level of economic development, industrial layout, and environmental policies will further strengthen the spatial autocorrelation. As shown in Fig. 8, the Moran's I index presented a fluctuating increased tendency that

Year	Moran's I	Zscores	P-Value
2007	0.1353	1.9351	0.0530
2008	0.1571	2.2072	0.0273
2009	0.1603	2.2398	0.0251
2010	0.2169	2.9870	0.0028
2011	0.2677	3.6140	0.0003
2012	0.2753	3.7187	0.0002
2013	0.2772	3.7474	0.0002
2014	0.2660	3.5793	0.0003
2015	0.1889	2.5974	0.0094
2016	0.1805	2.5005	0.0124
2017	0.1996	2.7374	0.0062
2018	0.2126	2.9419	0.0033
2019	0.2270	3.1190	0.0018
2020	0.2989	4.0296	0.0001
2021	0.2027	2.8328	0.0046

Table 5. Global Moran's I and test results of ecological resilience in the Yellow River Basin from 2007 to 2021.

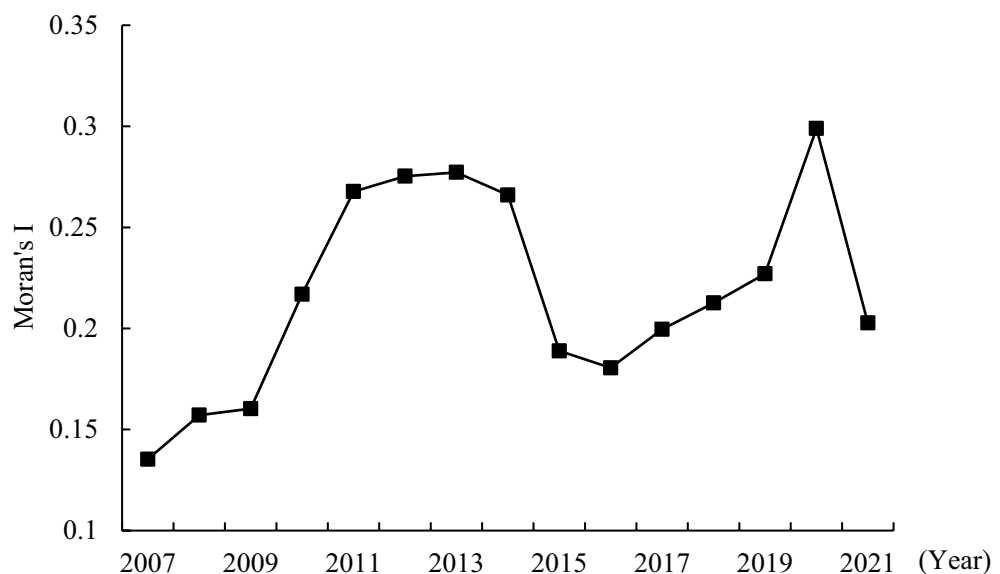


Figure 8. The trend of Moran's I of ecological resilience in the Yellow River Basin from 2007 to 2021.

first rises, then falls and rises again. In 2020, the Moran's I index value was the highest at 0.2989, indicating that the spatial clustering of ecological resilience in the Yellow River Basin continues to increase. This suggests that the geospatial background has become a critical contributor to ecological resilience in the Yellow River Basin.

Local spatial autocorrelation analysis

In order to further analyze the spatial effects on ecological resilience, we adopted a local spatial autocorrelation analysis method, namely Local Moran's I. This method reflects the degree of spatial autocorrelation between the ecological resilience of each city and that of its neighboring cities in the Yellow River Basin. The Local Moran's I values are calculated and analyzed with the LISA clustering map (Fig. 9).

The LISA clustering map revealed that the ecological resilience of the Yellow River Basin mainly consists of two types of localized agglomerations: H–H clustering and L–L clustering. This further confirms the initial assessment of positive spatial autocorrelation, as indicated by the Global Moran's I index mentioned above. Specifically, the H–H clustering area was mainly concentrated in the Hubao-Eyu urban agglomeration in 2007, which includes locations such as Ordos, Hohhot, Shuozhou, Xinzhou, and Ulanqab. The scope of the H–H clustering area expanded in subsequent years, including Baotou and Datong in 2012. In 2017, Ordos, Hohhot, Shuozhou, Xinzhou, Ulanqab, and Datong transitioned from H–H clustering to non-significant clustering. This change may be attributed to factors such as the level of economic development, the absence of reasonable and practical regulatory measures such as resource allocation, the concentration of labor-intensive industries, and

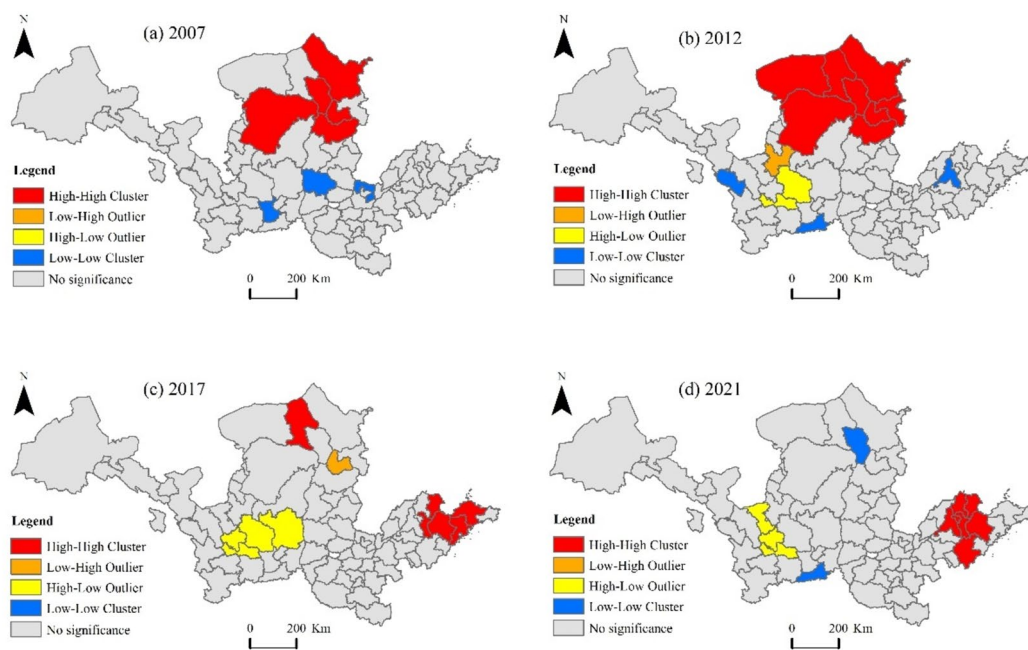


Figure 9. LISA Clustering Map of the ecological resilience in the Yellow River Basin for selected years.

the backwardness in production capacity and technology. Meanwhile, Zibo, Weifang, Dongying, Qingdao, and Yantai in the Shandong Peninsula urban agglomeration have become the new H–H clustering area. In 2021, the H–H clustering area expanded its scope from north to south. These cities have solid regional coordination and connectivity advantages, and the spillover effect from significant cities like Jinan and Qingdao will stimulate economic growth and infrastructure development. Ecological resilience has improved due to the gradual enhancement of the cross-regional synergistic governance pattern. The L–L clustering area was mainly distributed around the Central Plains city cluster, including Qingyang, Pingliang, Guyuan, Zhongwei, and Yan’an. These cities need more substantial infrastructure and adequate regional development resources. Constrained by location, transportation, resources, and other factors, they have formed “depressions” for ecological resilience. The future of this area should focus on improving the low-level concentration of ecological resilience by adjusting the industrial structure and enhancing the operational efficiency of green infrastructure. The H–L clustering cities, such as Hohhot, Lanzhou, and Xi’an, strongly influence the neighboring cities, creating a siphon effect. The L–H agglomeration area, which includes only Shuozhou and Wuzhong, has lower ecological resilience than neighboring cities due to natural conditions, resource status, and other factors. This area should promote transforming and upgrading specialized industries with an advantage while adhering to and strictly abiding by ecological protection measures. It is essential to avoid becoming a “pollution paradise” by implementing effective environmental regulations.

Influencing factors

Model selection

Based on Moran’s I index test, selecting a spatial econometric model is necessary. The specific test results are shown in Table 6. The Hausman test statistic was 72.90 and was significant at the 1% confidence level. The results showed that the fixed-effect spatial econometric model should be adopted. Then we established the SDM and conducted the Wald test to assess whether this model could be simplified to a spatial autoregressive model (SAR) or a spatial error model (SEM). The results showed that the SAR or SEM is strongly rejected, and the spatial lag

Test	Statistic	P value	Conclusion
Hausman test	72.90	0.0000	Fixed effects were used
Wald-SAR	37.91	0.0000	Reject SDM degradation to SAR
Wald-SEM	55.41	0.0000	Reject SDM degradation to SEM
LR-both-ind	38.60	0.0000	There is a individual effect
LR-both-time	1353.99	0.0000	There is a time effect

Table 6. Test results of selecting models.

term and error term exist at the same time. From the results of the Likelihood Ratio (LR) test, the SDM with both time and individual fixed effects is selected for discussion.

Empirical analysis

The empirical analysis was carried out using the fixed-effect spatial econometric model and the dynamic spatial Durbin model (DSDM). The results, presented in Table 7, revealed that the DSDM exhibited a higher degree of fit compared to the static spatial Durbin model (SDM), as evidenced by the improved R-squared value. Moreover, the spatial autocorrelation coefficient (ρ) in the DSDM was smaller than that in the SDM, suggesting that the SDM model overestimated the effect of the explanatory variables. Thus, the DSDM was deemed as the final model for the empirical analysis. The inclusion of time and space-time lag terms of the explained variable in the DSDM enhanced the explanatory power of the model.

From the results set out in Table 7, it was found that the spatial autocorrelation coefficient ρ was significantly positive, proving that ecological resilience has a positive spatial spillover effect and indicating that the improvement in one city's ecological resilience drives the rapid development of ecological resilience in its surrounding cities during the current period. This finding aligns with the outcomes of the global spatial autocorrelation analysis. The coefficient of $L.InER$ was found to be statistically significant at the 1% level, indicating the presence of "time inertia" and path-dependent characteristics in the ecological resilience of the basin. This implies that cities with higher ecological resilience in the previous period are likely to continue improving their ecological resilience in the current period, exhibiting a snowball effect. Furthermore, the coefficient of $L.W*InER$ was negative and significant at the 1% level, suggesting that cities with higher ecological resilience in the previous period may have an adverse impact on the current-period ecological resilience of their neighboring cities. This could be attributed to a "siphon effect" at the municipal level, where cities with higher ecological resilience attract resources from neighboring cities, potentially compromising their future ecological resilience. Considering the absolute values of ρ , $L.InER$, and $L.W*InER$ coefficients, it can be concluded that spatial spillover effects play a dominant role in shaping the ecological resilience of the Yellow River Basin.

Due to spatial dependence in the spatial econometric model, the coefficients in Table 7 do not accurately reflect the marginal effect of each explanatory variable. Therefore, the partial differentiation method proposed by LeSage and Pace was used to classify the marginal effect of each explanatory variable into direct, indirect, and total effects. Then, the spatial econometric model should be explained accordingly. Table 8 presents the short-term and long-term direct, indirect, and total effects of the DSDM.

As listed in Table 8, the long-term effect of each explanatory variable was more significant than the short-term effect (in absolute value), whether it was a direct or indirect effect, indicating that the explanatory variables have a cumulative effect on ecological resilience in the Yellow River Basin, demonstrating their long-term impact.

In the short and long term, the impact of population density showed significant positive direct and indirect effects. This result demonstrates that when other conditions remain unchanged, an increase in population density in the Yellow River Basin can positively impact the local and its neighboring cities, and the indirect effect was greater than the direct effect. On the one hand, the spatial spillover effect of population density on improvements

Variable	Static spatial Durbin model	Dynamic spatial Durbin model		
		Model(1)	Model(2)	Model(3)
$L.InER$		0.688(28.25)***		0.683 (28.17)***
$L.W*InER$			-0.301(-4.76)***	-0.220(-4.15)***
$\ln PD$	0.032(2.65)***	0.046(5.01)***	0.040(3.52)***	0.045(4.99)***
UR	-0.010(0.31)	-0.010(-0.41)	-0.031(-1.66)**	-0.010(-0.45)
$\ln PGDP$	-0.065(-1.14)	-0.081(-1.62)	-0.207(-3.37)***	-0.100(-1.99)**
OPEN	0.019(5.88)***	0.040(1.11)	0.019(4.90)***	0.030(1.04)
IS	0.231(2.51)**	0.115(1.66)*	0.187(2.19)**	0.195(1.37)
FIT	0.023(3.01)***	0.052(0.87)	0.021(2.95)***	0.024(0.64)
$W* \ln PD$	0.054(1.31)	0.026(1.38)	0.053(2.25)**	0.036(1.86)*
$W* UR$	0.052(3.04)***	-0.030(-1.44)	-0.040 (-1.46)	-0.020(-0.82)
$W* \ln PGDP$	-0.107(-1.16)	0.194(2.63)***	0.463(5.12)***	0.190(2.59)**
$W* OPEN$	0.049(1.18)	-0.007(1.05)	0.013(1.62)	0.005(0.74)
$W* IS$	-0.3486(-2.38)**	0.127 (1.24)	0.258(2.04)**	0.059(0.58)
$W* FIT$	0.096(-0.54)	0.015(1.64)	0.027(2.39)**	0.010(1.01)
Spatial rho	0.841(3.32)***	0.464(0.33)***	0.492(1.02)***	0.706(1.99)***
Σ^2	0.0006(23.48)***	0.0004(24.54)***	0.0006(24.54)***	0.0005(24.55)***
Time-fixed effect	Yes	Yes	Yes	Yes
Individual-fixed effect	Yes	Yes	Yes	Yes
R^2	0.6249	0.7932	0.7190	0.8128

Table 7. Regression results of the SDM and DSDM models. Figures-in () are the t-values. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively.

Variable	Short-term effects		Long-term effects	
	Direct effects	Indirect effects	Direct effects	Indirect effects
lnPD	0.034(1.70)*	0.047(5.37)***	0.158 (5.32)***	0.160(1.84)*
UR	-0.031(-1.62)	-0.004(-1.50)	-0.004(-1.90)*	-0.007(-2.04)**
lnPGDP	0.080(-1.68)*	-0.220(-2.73)***	0.234(1.55)**	-0.700(-2.62)***
OPEN	0.014(1.73)*	0.019(5.14)***	0.021(5.30)***	0.028(2.39)**
IS	0.016(1.73)*	0.014(1.35)	0.039(1.82)*	0.062(1.54)
FIT	0.005(0.99)**	-0.017(-1.67)*	0.020(1.09)*	0.067(1.71)*

Table 8. Estimation results of the decomposition effects. Figures-in () are the t-values. ***, **, and * indicate the significance at the 1%, 5%, and 10% levels, respectively.

to ecological resilience in neighboring cities is greater than the promotion of population density to ecological resilience in this region. On the other hand, in the long term, the positive impact and spatial spillover effect of population density on ecological resilience will be more significant and noticeable. This is similar to the findings of Tao et al., who demonstrated that the increase in population density has brought about an economic agglomeration effect. This effect has increased the demand on the ecosystem, resulting in significant improvements in local ecological resilience.

The short-term direct and indirect effects of urbanization were negative but not significant, while the long-term direct and indirect effects were obviously negative, indicating that urbanization has a long-term effect on ecological resilience without a short-term effect. Our results indicate that the current urbanization of the Yellow River Basin has failed to have a significant effect on ecological resilience in the short term. However, in the long term, the process of urbanization promotes the spatial agglomeration of factors and enhances regional innovation capacity, but it also leads to increased ecological resource loss and pollution discharge, which puts pressure on the ecological resilience of a local city. In addition, an increase in urbanization inhibits ecological resilience in neighboring cities through negative spillover effects such as resource absorption and pollution externalities.

In both the short and long term, the direct effects of GDP per capita on ecological resilience were significantly positive, while the indirect effects were negative, manifesting the way in which economic growth was beneficial to accelerating local ecological resilience but could not enhance the ecological resilience of neighboring cities. This may be attributed to the improvement of the economic level, which has led to a shift in the high-pollution and high-emission economic development of cities in the Yellow River Basin. This transition from crude to intensive development can promote local ecological resilience. At the same time, the economic growth in the region will result in a siphoning effect on the population and resources from neighboring cities. This will diminish the scale effect of resource elements in the neighboring areas, sacrificing economic benefits for ecological benefits. Consequently, the ecological resilience of neighboring cities will be inhibited.

The direct and indirect effects of openness on ecological resilience were both significantly positive in the short and long term, indicating that openness plays a significant role in improving ecological resilience in both local and neighboring cities, with the indirect effect being greater than the direct effect. This shows that increased openness can realize the spillover of advanced knowledge and technologies through the optimal allocation of innovation resources between cities, promoting ecological resilience. Moreover, openness can drive improvements in ecological resilience over time, with the long-term effect being greater than the short-term effect. This is mainly due to the Yellow River Basin's rapid optimization of the business environment and vigorous promotion of ecological protection in recent years. As a result, trade activities and resource integration between cities have become more convenient. The relatively unimpeded flow of innovative resources and the spillover of advanced technologies between cities provide a solid foundation for improving ecological resilience.

Referring to the industrial structure, we found that the short-term and long-term direct effects on ecological resilience were significantly positive, while the indirect effect was insignificant. Results show that the effect of industrial structure upgrading has obvious localized characteristics. Because the Yellow River Basin is constrained by its agricultural production and energy development base, the industrial structure upgrading of the local city has yet to be able to produce close input–output correlations with neighboring cities. As a result, it does not have a significant impact on enhancing ecological resilience in neighboring cities.

The intensity of financial investment in technological innovation has a positive direct effect on ecological resilience in the short and long term, but its indirect effect is negative in the short term and gradually transforms into a positive effect in the long term. This implies that increasing financial investment in technological innovation within a region can enhance its ecological resilience. However, when neighboring cities increase their investment in technological innovation, it initially has a negative impact on their ecological resilience. Over time, this negative effect diminishes and eventually turns into a positive effect. This suggests that the positive spillover effects of technological innovation gradually outweigh the negative spillover effects, leading to an overall improvement in ecological resilience in the region.

Discussion and policy implications

Discussion

A resilient ecosystem is a rational choice to promote paradigm innovation in the construction of an ecological civilization and explore new paths to sustainable development. Resilience thinking originates from complex

systems theory, which provides a perspective for analyzing how ecosystems continuously adjust their structure and state to adapt to changes in the external environment and continue to grow. Ecosystem services reflect patterns of ecological spatial security, minimize external disturbances, and maintain natural ecological processes, which are influenced by a variety of factors and are an important means of increasing ecological resilience. The reliable provision of ecosystem services over the long term requires that ecosystems be managed in a manner that is adaptive to changing environmental factors, whether natural or human-induced. Ecological resilience could be utilized to assess the level of ecosystem development in the Yellow River Basin from multiple perspectives, which is more specific than the general method of analyzing ecosystem development and can reveal deep-level features. This study considers natural factors such as land type, climate change, and biodiversity, and constructs a complete evaluation indicator system to measure ecological resilience based on the essential characteristics of evolutionary resilience. Comparing the TOPSIS method with previous studies, this paper introduces the coefficient of variation to rectify the results of the weights of each indicator. In this work, the degree of dispersion of resistance, recovery, reconstruction, and renewal indices is included in the weights of the indicators, taking into account the harmonization between the ecological resilience modeling systems. The traditional method of assigning weights according to the gap between ecological resilience and positive and negative ideal solutions was improved to ensure more realistic research results.

Policy implications

The findings of this study have significant policy implications for enhancing ecological resilience in the Yellow River Basin. The following recommendations are put forth based on the conclusions drawn from the analysis:

- (1) Optimization of ecological resilience spillover. The government should play a pivotal role in resource regulation and policy guidance, ensuring the effective implementation of ecological construction in neighboring cities through intergovernmental strategies for joint prevention and control of ecological and environmental issues. This involves leveraging the government's influence to stimulate ecological preservation and high-quality development in local and neighboring cities. Additionally, collaboration in regional economic development and synchronizing urbanization processes should be fostered to mitigate the long-term economic "siphon effect" on neighboring cities. The objective is to redirect adverse spillover effects and enhance environmental resource factors and green infrastructure in adjacent cities. Lastly, ecological development should be aligned with regional strategic positioning, ensuring a coherent supply of land, finance, taxation, and ecological compensation. This requires a comprehensive evaluation of resource and environmental capacities, ecological characteristics, foundational development, and location advantages in each region. Harmonizing economic development, environmental protection, and resource utilization at the spatial level while addressing cross-cluster intersections is necessary to ensure ecological resilience upgrading within and between regions.
- (2) Cultivating a novel model of ecological resilience development. Information sharing mechanisms and the free flow of talent should be enhanced to bolster talent attraction and the assimilation and application of technology. This harnesses the catalytic potential and demonstrative effects of ecological development in core provincial capitals. Streamlining the business environment and reducing congestion costs should be prioritized, while promoting a mindset of resource conservation and environmental friendliness during investment attraction processes. Industrial structure optimization should be advanced through integrated planning and specialized division of labor, fostering innovation and the proliferation of new kinetic energy in a larger spatial context. Finally, scientific and technological innovation should be prioritized in fiscal expenditure, intensifying efforts to cultivate innovation hubs and high-capacity platforms. This amplifies the mechanism of long-term ecological resilience enhancement through substantial financial investment in technological innovation.
- (3) Implementation of environmental and ecological governance at the sub-district level. In the upstream region, an emphasis on ecological protection synergy and ecosystem integrity within the Yellow River Basin should guide green transformation and the enhancement of ecological resilience. Greater support for environmental management is essential to break free from the "resource curse" in cities with high ecological risks. In the midstream region, sharing experiences and divisions of labor between cities, bolstering ecological environment co-insurance, and collaborative governance mechanisms should be the focus. Swift relocation of highly polluting enterprises, accelerated industrial restructuring, and intensified environmental and ecological quality monitoring are critical for reducing local ecological risks and preventing their spread throughout the entire region. Additional labor, technology, and capital investments are required in cities near the ecological resilience core. In the downstream region, increased investment in regularized environmental management and ecological conservation is necessary. This involves protecting and restoring natural wetlands in the Yellow River Delta and advancing characteristic marine industries. The differentiated spatial pattern of ecological resilience should be eliminated in future national territory planning by strengthening the protection and development of ecological space in cities in the southeastern region.

This study is of great importance for the ecological protection and high-quality development of countries and regions. In the context of increasingly close regional social and economic geographical ties, the spatial spillover effect of ecological resilience between regions continues to grow, as demonstrated in this study. After going through the stage of "separate government" development, coordination of economic development, environmental protection, and resource utilization at the spatial level will be a new development idea to improve regional ecological resilience. In addition to the changes in the direct and indirect effects,

as well as the short-term and long-term effects of the same influencing factors, reasonable and effective policies and measures can be formulated based on the results of this paper.

Conclusions

Based on the essential characteristics of evolutionary resilience, this paper developed an ecological resilience index system of “resistance-recovery-reconstruction-renewal” and calculated the index weight value, which describes the ecological resilience values of 75 cities in the Yellow River Basin from 2007 to 2021. We then analyzed the spatiotemporal evolution characteristics of the Yellow River Basin’s ecological resilience using the gravity center-standard deviation ellipse, Dagum Gini coefficient decomposition, and spatial autocorrelation analysis. Further, we employed a dynamic spatial Dubin model to investigate the influencing factors of ecological resilience, including the direct and indirect effects, and the short-term and long-term effects. The main conclusions are summarized as follows:

- (1) The results of the temporal evolution indicated that the ecological resilience of the Yellow River Basin showed an overall fluctuating upward trend. In terms of trends, the ecological resilience of each region in the Yellow River Basin improved, although the increases varied significantly. The average annual growth rate of ecological resilience in the downstream region was larger than in the upstream and midstream regions, eventually showing a spatial differentiation pattern of downstream > midstream > upstream.
- (2) From the perspective of spatial distribution, the ecological resilience of the Yellow River Basin exhibited clustering characteristics, with regional central cities serving as the core and displaying distinct zonal differences. Cities with similar levels of ecological resilience were distributed in a pattern of “large settlement, small scattered”. As for the center of gravity, it shifted to the southeast. In terms of rotation, the spatial distribution of ecological resilience in the Yellow River Basin exhibited a “northwest-southeast” pattern and a trend towards an “east-west” pattern. Regarding changes in the length of the semi-major and semi-minor axes, ecological resilience was spread and then polarized in the “northwest-southeast” direction, while polarization continued in the “northeast-southwest” direction.
- (3) Given the Dagum Gini coefficient and its decomposition, the spatial difference in ecological resilience of the Yellow River Basin showed a fluctuating downward trend. For intra-regional differences, the upstream and midstream regions showed a fluctuating declining trend, while the downstream region experienced a relatively stable state, with the largest difference in the midstream region and the smallest difference in the downstream region. For inter-regional differences, the upstream-midstream, upstream-downstream, and midstream-downstream regions showed a fluctuating declining trend, with the largest difference between the upstream and midstream regions. The primary source of spatial differences in ecological resilience was the contribution rate of the intensity of transvariation.
- (4) Concerning global spatial autocorrelation, we found that the ecological resilience in the Yellow River Basin showed a significant positive spatial autocorrelation, with the spatial clustering continuing to increase. From the perspective of local spatial autocorrelation, the estimation results indicated that the ecological resilience of the Yellow River Basin mainly consisted of two types of localized agglomerations: H-H clustering and L-L clustering. Among them, the H-H clustering area was shifted from the Hubao-Eyu urban agglomeration to the Shandong Peninsula urban agglomeration, and the L-L clustering area was mainly distributed around the Central Plains city cluster.
- (5) The results of the DSDM indicated that the ecological resilience of the Yellow River Basin exhibited significant snowball, spillover, and siphon effects in time, space, and space-time dimensions, respectively. By analyzing the marginal effect of each influencing factor, we found that population density and openness significantly positively affected the ecological resilience of local and surrounding cities in both the short and long term. Urbanization had a long-term negative effect on ecological resilience without a short-term effect. GDP per capita imparted a significant positive influence on local ecological resilience in both the short and long term, and a negative effect on the ecological resilience of surrounding cities. The industrial structure was found to have a positive effect in relation to local ecological resilience in both the short and long term, while the indirect effect was not significant. In addition, the intensity of financial investment in technological innovation was beneficial to improving local ecological resilience in the short term, and the negative spatial spillover gradually turned into a positive effect in the long term.

In conclusion, the findings of this study provide valuable insights into the spatiotemporal evolution and influencing factors of ecological resilience in the Yellow River Basin. The policy recommendations put forth can guide policymakers and stakeholders in their efforts to enhance ecological resilience and promote sustainable development in the region. However, further research is needed to explore the specific mechanisms and interactions between different factors influencing ecological resilience, as well as to assess the long-term of policy interventions.

Data availability

Data is provided within the manuscript or supplementary information files.

Received: 4 February 2024; Accepted: 15 July 2024

Published online: 23 July 2024

References

1. Holling, C. S. Resilience and stability of ecological systems. *Ann. Rev. Ecol. Syst.* **4**, 1–23 (1973).

2. Alberti, M. *et al.* Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. *BioScience* **53**, 1169–1179. [https://doi.org/10.1641/0006-3568\(2003\)053\[1169:lhieoa\]2.0.Co;2](https://doi.org/10.1641/0006-3568(2003)053[1169:lhieoa]2.0.Co;2) (2003).
3. Wang, S. M. & Niu, J. L. Dynamic evolution and obstacle factors of urban ecological resilience in Shandong Peninsula Urban Agglomeration. *Econ. Geogr.* **42**, 51–61. <https://doi.org/10.15957/j.cnki.jjdl.2022.08.006> (2022).
4. Folke, C. Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environ. Chang.* **16**, 253–267. <https://doi.org/10.1016/j.gloenvcha.2006.04.002> (2006).
5. Yan, H. M., Yan, Z. J. & Tao, Z. Review of ecosystem resilience research progress. *Prog. Geogr.* **31**, 303–314. <https://doi.org/10.11820/dlxxjz.2012.03.005> (2012).
6. Qiu, L. X. & Yue, H. F. Spatial-temporal evolution and driving effect of ecological welfare performance in the Yellow River Basin. *J. Qingdao Univ. Sci. Technol. (Soc. Sci.)* **38**, 41–51. <https://doi.org/10.16800/j.cnki.jqstss.2022.04.015> (2022).
7. Xiao, S., Duo, L. H. & Li, Z. Z. Assessment of ecological resilience in Nanchang based on “risk-connectivity-potential”. *Chinese J. Appl. Ecol.* **34**, 733–741. <https://doi.org/10.13287/j.1001-9332.202303.022> (2023).
8. Guo, H. H. The coupling and coordinated development of new-type urbanization and ecological resilience in Qingdao: Based on the comparison of the central cities along the Yellow River. *J. China Univ. Petroleum Ed. Nat. Sci.* **39**, 22–31. <https://doi.org/10.13216/j.cnki.upcjess.2023.02.0003> (2023).
9. Guo, H. H. & Liu, X. M. Coupling and coordination mechanism of new urbanization and ecological resilience in central cities along the Yellow River. *East China Econ. Manage.* **37**, 101–109. <https://doi.org/10.19629/j.cnki.34-1014/f.220821006> (2023).
10. Tao, J., Dong, P. & Lu, Y. Spatial-temporal analysis and influencing factors of ecological resilience in Yangtze River Delta. *Resour. Environ. Yangtze Basin* **31**, 1975–1987. <https://doi.org/10.11870/cjlyzyyhj202209010> (2022).
11. Lv, T. G., Hu, H., Fu, S. F. & Kong, A. N. Spatio-temporal differentiation and influencing factors of urban ecological resilience in the Yangtze River Delta. *Areal Res. Dev.* **42**, 54–60. <https://doi.org/10.3969/j.issn.1003-2363.2023.01.010> (2023).
12. Wang, S. J., Cui, Z. T., Lin, J. J., Xie, J. Y. & Su, K. Coupling relationship between urbanization and ecological resilience in the Pearl River Delta. *Acta Geogr. Sin.* **76**, 973–991. <https://doi.org/10.11821/dlxb202104013> (2021).
13. Shi, C. C., Zhu, X. P., Wu, H. W. & Li, Z. H. Assessment of urban ecological resilience and its Influencing factors: A case study of the Beijing-Tianjin-Hebei Urban Agglomeration of China. *Land* **11**, 921. <https://doi.org/10.3390/land11060921> (2022).
14. Yang, H., Hou, J. W., Ma, C. H., Yang, C. & Wang, Y. J. Spatio-temporal differentiation of the composite ecosystem resilience in the ecologically fragile area in the upper reaches of the Yellow River: A case study in Ningxia. *Arid Zone Res.* **40**, 303–312. <https://doi.org/10.13866/j.azr.2023> (2023).
15. Zeng, F. S., Feng, X. H., Tang, Y., Xiao, Z. P. & Bi, M. Y. Evolution of ecological resilience space pattern at county level in Poyang lake basin. *Geogr. Geo-Info. Sci.* **38**, 29–35. <https://doi.org/10.3969/j.issn.1672-0504.2022.06.005> (2022).
16. Zhang, Q. R., Huang, T. & Xu, S. J. Assessment of urban ecological resilience based on PSR framework in the Pearl River Delta Urban agglomeration China. *Land* **12**, 1089. <https://doi.org/10.3390/land12051089> (2023).
17. Xia, C. Y., Dong, Z. Y. Z. & Chen, B. Spatio-temporal analysis and simulation of urban ecological resilience: A case study of Hangzhou. *Acta Geogr. Sin.* **42**, 116–126. <https://doi.org/10.5846/stxb202101030007> (2022).
18. Tong, Y. J. *et al.* Analysis of the spatial and temporal variability and factors influencing the ecological resilience in the urban agglomeration on the northern slope of Tianshan Mountain. *Sustainability* **15**, 4828. <https://doi.org/10.3390/su15064828> (2023).
19. Martin, R. Regional economic resilience, hysteresis and recessionary shocks. *J. Econ. Geogr.* **12**, 1–32. <https://doi.org/10.1093/jeg/lbr019> (2012).
20. Niu, D. W., Wang, L. C., Li, W. & Ma, Y. C. An international comparative study on the resilience of urban communities after COVID-19 pandemic: A one-year case study between Lanzhou, China and Sarajevo, Bosnia and Herzegovina. *Int. J. Env. Res. Pub. He.* **19**, 14458 (2022).
21. Huang, J., Zhong, P. S., Zhang, J. Z. & Zhang, L. Spatial-temporal differentiation and driving factors of ecological resilience in the Yellow River Basin. *China. Ecol. Indic* **154**, 110763. <https://doi.org/10.1016/j.ecolind.2023.110763> (2023).
22. Lv, T. G. *et al.* Spatial spillover effects of urbanization on carbon emissions in the Yangtze River Delta urban agglomeration. *China Environ. Sci. Pollut. R.* **29**, 33920–33934. <https://doi.org/10.1007/s11356-021-17872-x> (2022).
23. Boschma, R. Towards an evolutionary perspective on regional resilience. *Reg. Stud.* **49**, 733–751. <https://doi.org/10.1080/00343404.2014.959481> (2014).
24. Nunes, D. M., Tomé, A. & Pinheiro, M. D. Urban-centric resilience in search of theoretical stabilisation? A phased thematic and conceptual review. *J. Environ. Manage.* **230**, 282–292. <https://doi.org/10.1016/j.jenvman.2018.09.078> (2019).
25. Sun, C. Z., Cao, Q. & Zou, W. Assessment of marine economy resilience of coastal cities in Bohai Sea Ring Area based on entropy efficiency model. *J. Ningbo Univ. (Nat. Sci. Eng.)* **33**, 10–18 (2020).
26. Xu, Y. & Zhang, L. L. The economic resilience of Chinese cities and its origin: From the perspective of diversification of industrial structure. *Financ. Tr. Econ.* **40**, 110–126. <https://doi.org/10.19795/j.cnki.cn11-1166/f.2019.07.008> (2019).
27. Zhao, L. M., Jiao, S. S. & Yao, Z. G. Distributional dynamic and evolution of China’s tourism economic development. *J. Arid Land Resour. Environ.* **32**, 181–188. <https://doi.org/10.13448/j.cnki.jalre.2018.028> (2018).
28. Wang, Z. Y. & Wang, Y. X. Spatial and temporal differentiation and influencing factors of the marine economy resilience in China. *Econ. Geogr.* **39**, 139–145. <https://doi.org/10.15957/j.cnki.jjdl.2019.02.017> (2019).
29. Martin, R. & Sunley, P. On the notion of regional economic resilience: conceptualization and explanation. *J. Econ. Geogr.* **15**, 1–42. <https://doi.org/10.1093/jeg/lbu015> (2015).
30. Lai, Y.-J. & Hwang, C.-L. *Fuzzy multiple objective decision making: Methods and applications* (Springer, 1994).
31. Stewart, T. J. A critical survey on the status of multiple criteria decision making theory and practice. *Omega* **20**, 569–586. [https://doi.org/10.1016/0305-0483\(92\)90003-P](https://doi.org/10.1016/0305-0483(92)90003-P) (1992).
32. Lin, Y. Z., Peng, C., Chen, P. & Zhang, M. J. Conflict or synergy? Analysis of economic-social- infrastructure-ecological resilience and their coupling coordination in the Yangtze River economic Belt. *China. Ecol. Indic.* **142**, 109194. <https://doi.org/10.1016/j.ecolind.2022.109194> (2022).
33. Wong, D. W. S. Several fundamentals in implementing spatial statistics in GIS: Using centrographic measures as examples. *Geo. Inf. Sci.* **5**, 163–174. <https://doi.org/10.1080/10824009909480525> (1999).
34. Lefever, D. W. Measuring geographic concentration by means of the standard deviational ellipse. *Am. J. Sociol.* **32**, 88–94. <https://doi.org/10.1086/214027> (1926).
35. Chen, S. Y. *et al.* Spatial and temporal evolution of synergizing the reduction of pollution and carbon emissions and examination on comprehensive pilot effects—evidence from the national eco-industrial demonstration parks in China. *Environ. Impact Assess. Rev.* **101**, 107147. <https://doi.org/10.1016/j.eiar.2023.107147> (2023).
36. Dagum, C. A new approach to the decomposition of the Gini income inequality ratio. *Empir. Econ.* **22**, 515–531. <https://doi.org/10.1007/BF01205777> (1997).
37. Moran, P. A. P. Notes on continuous stochastic phenomena. *Biometrika* **37**, 17–23. <https://doi.org/10.1093/biomet/37.1-2.17> (1950).
38. Lu, F., Ren, H. G. & Zhai, X. L. Dynamic evolution characteristics and driving factors of tourism ecosystem health in China. *Front. Public Health* **11**, 1127980. <https://doi.org/10.3389/fpubh.2023.1127980> (2023).
39. Anselin, L. Local indicators of spatial association—LISA. *Geogr. Anal.* **27**, 93–115. <https://doi.org/10.1111/j.1538-4632.1995.tb00338.x> (1995).
40. Elhorst, J. P. *Spatial econometrics: From cross-sectional data to spatial panels* (Springer, 2014).
41. Ehrlich, P. R. & Holdern, J. P. Impact of population growth. *Obstet. Gynecol. Surv.* **171**, 1212–1217 (1971).

42. Waggoner, P. E. & Ausubel, J. H. A framework for sustainability science: A renovated IPAT identity. *P. Natl. Acad. Sci. USA* **99**, 7860–7865 (2002).
43. Dietz, T. & Rosa, E. A. Effects of population and affluence on CO₂ emissions. *P. Natl. Acad. Sci. USA* **94**, 175–179 (1997).
44. York, R., Rosa, E. A. & Dietz, T. STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* **46**, 351–365. [https://doi.org/10.1016/s0921-8009\(03\)00188-5](https://doi.org/10.1016/s0921-8009(03)00188-5) (2003).
45. Huang, Y., Duan, M. J., Yang, J. & Wen, Y. L. Research on spatial effects of environmental ethics in provinces of China based on improved STIRPAT. *Stat. Inform. Forum* **36**, 95–106. <https://doi.org/10.3969/j.issn.1007-3116.2021.03.008> (2021).
46. Dietz, T., Rosa, E. A. & York, R. Driving the human ecological footprint. *Front. Ecol. Environ.* **5**, 13–18. [https://doi.org/10.1890/1540-9295\(2007\)5\[13:DTHEF\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[13:DTHEF]2.0.CO;2) (2007).
47. Chang, X. F. & Guan, X. Spatial and temporal evolution of eco-efficiency and its influencing factors in the Yangtze River Delta urban agglomeration in the process of new urbanization. *Econ. Geogr.* **40**, 185–195. <https://doi.org/10.15957/j.cnki.jjdl.2020.03.021> (2020).
48. Zhao, J. J. *et al.* Spatiotemporal differentiation and influencing factors of the coupling and coordinated development of new urbanization and ecological environment in the Yellow River Basin. *Resour. Sci.* **42**, 159–171. <https://doi.org/10.18402/resci.2020.01.16> (2020).
49. Zhao, R. D., Fang, C. L., Liu, H. M. & Liu, X. X. Evaluating urban ecosystem resilience using the DPSIR framework and the ENA model: A case study of 35 cities in China. *Sustain. Cities Soc.* **72**, 102997. <https://doi.org/10.1016/j.scs.2021.102997> (2021).
50. Peng, R. X., Liu, T. & Cao, G. Z. Spatial pattern of urban economic resilience in eastern coastal China and industrial explanation. *Geogr. Res.* **40**, 1732–1747. <https://doi.org/10.11821/dlyj020200486> (2021).
51. Du, Z. W., Jin, L. X. & Liu, Q. H. Industrial diversity, innovation, and economic resilience: Empirical analysis of the Pearl River Delta in the post-financial crisis era. *Trop. Geo.* <https://doi.org/10.13284/j.cnki.rddl.003126> (2019).
52. Chen, Q., Zhou, J. X., Li, X. M. & Xiao, R. B. Analysis on the driving force of environmental impact in Wuhan based on STIRPAT model. *Resour. Environ. Yangtze Basin* **20**, 100–104 (2011).
53. Xu, J., Xu, H. L. & Jin, C. Spatial evolution and spillover effects of tourism economy in Yangtze River Delta. *Areal Res. Dev.* **40**, 94–99. <https://doi.org/10.3969/j.issn.1003-2363.2021.06.016> (2021).
54. Xue, F., Zhou, M. L. & Liu, J. Q. Can Industrial transformation and upgrading reduce carbon emissions? Evidence from national Industrial transformation and upgrading demonstration zones. *Ind. Eco. Res.* <https://doi.org/10.13269/j.cnki.ier.2023.02.002> (2023).

Acknowledgements

We thank all the reviewers of this manuscript for their helpful comments and valuable suggestions.

Author contributions

F.L.: Conceptualization; Funding acquisition; Methodology; Writing-original draft; Writing-review & editing. Q.L.: Data curation; Writing-original draft; Writing-review & editing; Software; Visualization. P.W.: Data curation; Writing-original draft; Writing-review & editing.

Funding

This work was supported by the Social Science Planning Research Project of Shandong Province (NO. 21CLYJ52) and the Humanities and Social Sciences Project of Shandong Province (NO. 2021-YYGL-33).

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-024-67628-z>.

Correspondence and requests for materials should be addressed to F.L.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2024