

# Spatio-temporal Patterns and Driving Mechanisms of Coupling Coordination Between Urban Resilience and Low-Carbon Development in the Yellow River Basin

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## ABSTRACT

Against the dual backdrop of intensifying global climate change and the deepening of Sustainable Development Goals, the synergistic advancement of low-carbon transition and resilience building has emerged as a critical pathway for the international community to address complex environmental risks. This study constructs a comprehensive evaluation indicator system for urban resilience and low-carbon development in the Yellow River Basin. By employing the entropy-weighted TOPSIS model and the coupling coordination degree model, it quantifies the synergy level between urban resilience and low-carbon development in the Yellow River Basin from 2006 to 2021 and reveals its spatio-temporal evolution characteristics. Furthermore, Geographic Detector is utilized to identify key driving factors, and finally, the Spatial Durbin Model is applied to explore their spatial effects. The results indicate that from 2006 to 2021, the overall urban resilience level in the Yellow River Basin exhibited a fluctuating upward trend, displaying a spatial gradient pattern where the lower reaches surpass the middle reaches, which in turn exceed the upper reaches. Low-carbon development demonstrated phased acceleration, although the energy transition lagged, with a spatial pattern characterized as "high in the east and low in the central and western regions." The coupling coordination degree between the two increased from 0.29 to 0.45, with regional disparities widening; the lower reaches experienced the fastest improvement and formed high-value agglomeration areas, the middle reaches showed accelerated catch-up growth, while progress in the upper reaches remained sluggish. The effect of the "Low-Carbon City" pilot policy initially declined and subsequently increased, exhibiting siphonic spillovers. Gross Domestic Product and fiscal expenditure emerged as the most dominant driving factors, with the synergy between economy and resources constituting a key impetus. The spatial spillover effects of various factors differ significantly across the upper, middle, and lower reaches as well as among agglomeration types, and the interaction effects of paired factors are substantially stronger than those of single factors. Therefore, systematic synergistic governance represents a crucial pathway for enhancing the level of coupling coordination between urban resilience and low-carbon development in the Yellow River Basin.

## KEYWORDS

Regional coordinated development; Spatial heterogeneity; Mitigation and adaptation; Climate change

# 1. INTRODUCTION

Global climate change, as a serious environmental challenge, has had a profound impact on urban systems worldwide (Jin et al., 2026; Huang et al., 2026). As major sources of energy consumption and greenhouse gas emissions, cities' low-carbon development pathways are regarded as key measures for mitigating climate change (Shi et al., 2026). However, as the frequency of extreme weather events—such as droughts, heat waves, and heavy rainfall—continues to rise, relying solely on mitigation strategies is no longer sufficient to address increasingly complex climate risks, underscoring the urgent need to systematically enhance urban resilience. Cities currently consume approximately 75% of the world's energy and account for more than 70% of global greenhouse gas emissions. This energy-intensive, high-carbon development model not only exacerbates climate change itself but also exposes cities to more severe threats from climate-related disasters (Sharma et al., 2025). In the face of the dual challenges of emission reduction and adaptation, the response strategies of the international community are undergoing a transformation, shifting from single-target measures to a cooperative governance model (Wang & Chen, 2025; Shahmohammad et al., 2024). The United Nations Sustainable Development Goal 11 explicitly calls for building inclusive, safe, resilient, and sustainable cities. Moreover, the 2025 World Federation of Engineering Organizations Resilient Cities Forum has identified "Climate Change and Resilient City Construction" as a core theme. This global consensus indicates that integrating low-carbon transformation with resilience building has become a frontier issue and an inevitable pathway for cities striving towards sustainable development (Ai et al., 2025). As the world's largest carbon emitter, China is actively exploring a synergistic urban development path that integrates low carbon and resilience through top-down national strategies and bottom-up policy pilots, in response to the global agenda and to alleviate the dual pressures of domestic development and emission reduction (Wang & Chen, 2025). At the strategic level, the convergence of the "dual carbon" goals and major national strategies such as the "Ecological Protection and High-Quality Development of the Yellow River Basin" has charted the course for the green transformation of cities in the basin. At the practical level, China has successively established 36 low-carbon city pilots, and the latest research shows that synergistically promoting mitigation and adaptation policies can generate a governance effectiveness of '1+1>2', which provides important theoretical value and practical reference for exploring urban sustainable development pathway (Liu et al., 2025). Urban resilience research originally originated from the fields of ecology and engineering, after which its connotation evolved from a single engineering resilience to a comprehensive capacity encompassing social-ecological systems (Dakos & Kéfi, 2022; Pendall et al., 2010). The Resilience Alliance defines it as the ability of a city to absorb external disturbances and maintain its core characteristics, structure, and functions, which marks the deepening and expansion of adaptive capacity within complex urban systems (Sharifi et al., 2026). Relevant research has gradually progressed from conceptual analysis to level assessment, spatial differentiation, and the exploration of optimization strategies (Li et al., 2025; Zhang et al., 2024), assessment methods are also becoming increasingly integrated (Sun et al., 2026; Chen et al., 2026). In particular, the indicator system method has been widely applied due to its ability to effectively capture the performance of urban resilience across multiple dimensions such as the economy, society, and ecology. Meanwhile, the analysis of its driving factors has shifted from a single-factor perspective to a systemic one, encompassing multiple levels including economic structure, social capital, governance capacity, and infrastructure networks (Shi et al., 2025; Lu et al., 2025). Low-carbon development, as a specific pathway to mitigate climate change, emphasizes achieving a fundamental transformation of the urban development model through systemic changes in energy, industry, and lifestyle (Yu et al., 2025). The evaluation practice has evolved from an early reliance on single indicators such as carbon emission intensity to the adoption of data envelopment analysis and more inclusive composite index methods, with the latter becoming mainstream due to its greater flexibility and systematicness (Yu et al., 2023; Wu et al., 2023). Research on driving mechanisms also extensively involves factors such as technological innovation, industrial structure, and policy guidance (Wang et al., 2020; Liu et al.,

2020). As disciplinary integration and practice deepen, the synergies and trade-offs between adaptation and mitigation have attracted increasing attention, and the intrinsic link between urban resilience and low-carbon development has become a frontier issue. Existing studies have confirmed that low-carbon city pilot policies can not only improve performance in their respective fields, but also generate significant cross-sectoral synergistic gains and spatial spillover effects through technological innovation and industrial transformation (Tong et al., 2025). Empirical measurements also show that the resilience level and low-carbon transition process of Chinese cities are generally moving towards synergy, but their synergistic state exhibits significant spatiotemporal differentiation and nonlinear characteristics (Shi et al., 2022). There is an interaction between the two in terms of mechanisms. Resilient cities provide stable supporting conditions for low-carbon infrastructure and promote technological innovation, while low-carbon transition can also enhance urban resilience through means such as diversifying energy systems. Although challenges such as uncertainties associated with new technologies may arise during the transition process, their synergistic progress is driven by multiple factors, including technological innovation, industrial structure, institutional design, and spatial linkages (Zhou et al., 2025), and exhibits significant heterogeneity across regions and city types (Wang et al., 2024; Peng et al., 2025). In summary, urban resilience essentially represents the expansion and deepening of adaptive capacity within complex urban systems. It not only focuses on the defense against physical risks but also emphasizes the ability for social learning and transformation. Meanwhile, low-carbon development is a specific development path aimed at reducing emissions through structural changes under the framework of mitigation goals. Therefore, the coordinated advancement of urban resilience and low-carbon development can be regarded as the organic integration and practical implementation of the two major climate action processes at the urban level. This provides a comprehensive analytical framework and practical direction for building climate-responsive cities (Yan et al., 2026).

The Yellow River Basin, serving as both a vital ecological barrier and an energy base for China, is experiencing dual pressures from development and conservation on its urban systems (Fu et al., 2026). The spatial mismatch between water resource scarcity and energy development intensity within the basin is particularly prominent: ecosystem degradation and weakened soil and water conservation capacity in the upstream (Zhang et al., 2024). The midstream are dominated by loess landforms, characterized by fragmented terrain and severe soil erosion. The lower reaches, which have a high degree of urbanization and low ecological flow, constitute an important grain-producing area in China (He et al., 2025). This significant internal heterogeneity makes the Yellow River Basin an important empirical region for exploring the synergistic development pathways of low-carbon and resilient cities of different types. The research findings derived from this region hold significant theoretical value for understanding the complex human-environment system interactions in large river basins.

This study conducts a systematic investigation into the synergistic relationship between urban resilience and low-carbon development in the Yellow River Basin. First, the entropy-weighted TOPSIS model is employed to comprehensively evaluate the development levels of both dimensions. On this basis, the coupling coordination degree model is applied to quantitatively reveal their synergistic development status. Then, global and local spatial autocorrelation methods are used to characterize the spatial agglomeration and differentiation patterns of the coupling coordination degree. Subsequently, the geographic detector is utilized to identify the key driving factors influencing the coupling coordination degree and their relative importance, while the geographically weighted regression model is adopted to analyze the spatial heterogeneity of these factors. To further explore interregional interactions and transmission mechanisms, the spatial Durbin model is employed to uncover the differentiated spatial effects and influence pathways of driving factors on different types of cities, thereby providing empirical evidence and strategic references for promoting the synergistic advancement of resilience enhancement and low-carbon development in the Yellow River Basin (Figure 1). The objectives of this study are as follows:

To comprehensively evaluate the urban resilience level and low-carbon development level of cities in the Yellow River Basin, accurately measure their coupling coordination degree, systematically analyze its spatiotemporal evolution patterns and spatial agglomeration patterns, and identify spatial correlation structures and regional differentiation characteristics.

To identify the key driving factors affecting the coupling coordination degree, and reveal the spatial heterogeneity and regional differences in the intensity of each factor's influence.

To uncover the spatial effects of different driving factors on the coupling coordination degree of various types of cities, clarify their spatial transmission mechanisms, and provide scientific support for formulating differentiated and targeted regional coordinated development policies.

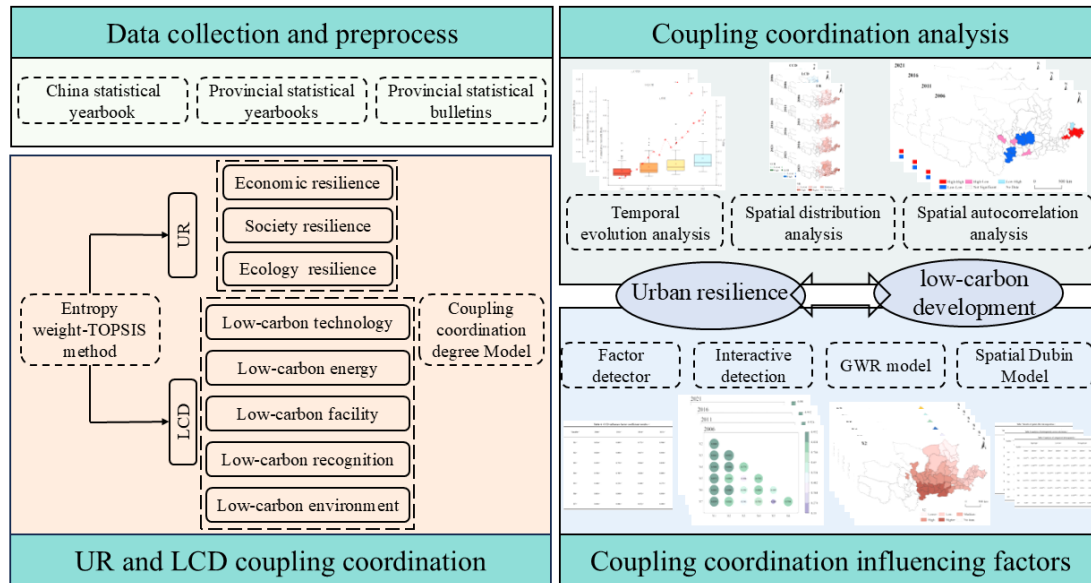


Figure 1. Research framework

## 2. MATERIALS

### 2.1. Study Area

The Yellow River Basin (32°N to 42°N, 96°E to 119°E) flows through nine provinces: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong. As of 2022, the basin had a permanent resident population of approximately 209 million, making it one of the most densely populated and economically dynamic regions in China (Zhang et al., 2024). To ensure a comprehensive and representative analysis, this study selected 60 prefecture-level cities within the basin as research subjects. The Yellow River Conservancy Commission divides the basin into three sections: the upper, middle, and lower reaches, with the boundary points being Tuoketuo County in Inner Mongolia Autonomous Region and Taohuayu Town in Zhengzhou City, Henan Province (Figure 2).

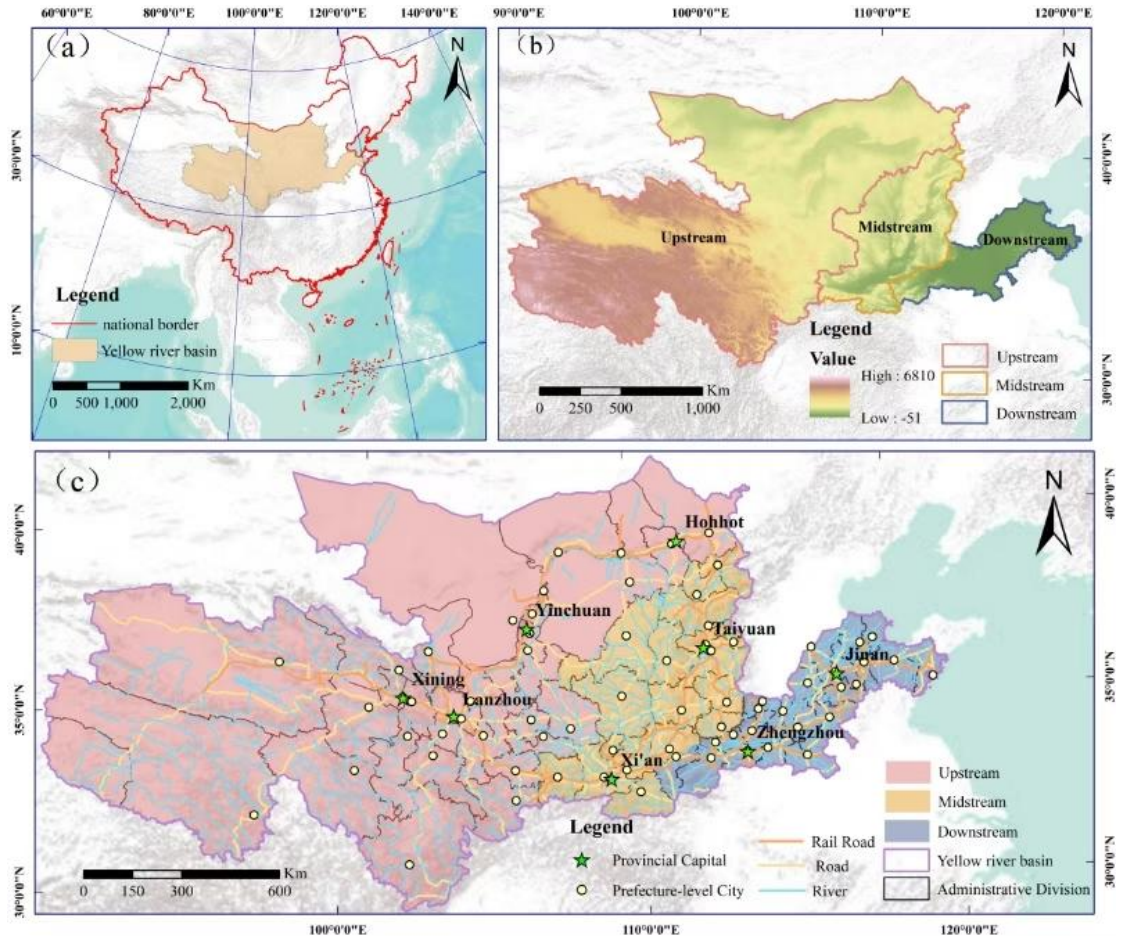


Figure 2. Study area

## 2.2. Data Sources

This study uses economic and social panel data, primarily sourced from the statistical yearbooks of prefecture-level cities from 2006 to 2021, the China City Statistical Yearbook, the China Urban Construction Statistical Yearbook, and the Statistical Bulletins of National Economic and Social Development of Prefecture-level Cities. The green patent data are obtained from the China National Intellectual Property Administration. The data on low-carbon city pilots are derived from the three batches of the "Low-carbon City Pilot Lists" published by the National Development and Reform Commission in 2010, 2012, and 2017. Missing data points are supplemented using the linear interpolation method.

## 2.3. Construction of the Indicator System

### 2.3.1. UR Evaluation Indicator System

This study constructs a three-dimensional urban resilience indicator system covering economic resilience, social resilience, and ecological resilience, aiming to comprehensively assess the resistance, adaptation, and recovery capabilities of cities in the Yellow River Basin when facing external shocks. Economic resilience is primarily measured from the perspectives of economic development quality, economic strength, and diversity, evaluating the rapid response and recovery ability of cities when encountering uncertain shocks. Five sub-indicators are selected to comprehensively characterize urban economic resilience at multiple levels, including individuals, governments, and enterprises (Yang et al., 2024). Social resilience focuses on a city's ability to integrate social resources, safeguard residents' livelihoods, and stimulate long-term potential. Based on relevant research, five indicators are selected: population density, urbanization level, medical

insurance coverage, pension insurance coverage, and higher education penetration rate, to reflect the city's human capital reserves, the comprehensiveness of its social security system, and its capacity to mobilize human resources in response to crises (Sun et al., 2024). Ecological resilience focuses on a city's ability to maintain ecological balance and provide ecosystem services under environmental pressures such as industrial pollution. Drawing on existing frameworks, the urbanization rate, industrial soot emissions, industrial sulfur dioxide emissions, industrial wastewater discharge, and urban construction land area are selected as measurement indicators to comprehensively assess a city's self-regulation and restoration capabilities when facing environmental risks (Lu et al., 2025) (Table 1).

**Table 1.** Index system for evaluating urban resilience

Target layer	Rule layer	Index layer	Index (+/-)	Unit
Urban resilience	Economic resilience	Per-Capita GDP	+	CNY
		Per capita disposable income of urban residents	+	CNY
		Savings balance of urban and rural residents	+	CNY
		Proportion of added value of secondary industries	+	%
		Proportion of added value of tertiary industries	+	%
	Society resilience	Population density	-	persons/ $km^2$
		Natural population growth rate	-	%
		Education spending	+	CNY
		Average number of employees	+	people
		Number of participants in urban basic medical insurance	+	people
	Ecology resilience	Urbanization rate	+	%
		Industrial fumes emission	-	t
		Industrial sulfur dioxide emissions	-	t
		Industrial wastewater discharge	-	t
		Urban construction land area	+	$m^2$

### 2.3.2. LCD Evaluation Indicator System

To reflect the overall low-carbon development level of cities in the Yellow River Basin from multiple angles and comprehensively, this paper constructs a comprehensive evaluation index system comprising five dimensions: low-carbon technology, low-carbon energy, low-carbon facilities, low-carbon public acceptance, and low-carbon environment (Table 2). Low-carbon technology serves as the core driving force for urban low-carbon development; sufficient investment in scientific and technological innovation funds and human capital can provide solid hard support for the low-carbon transformation of cities. Low-carbon energy effectively measures a city's progress in energy cleaning and low-carbon transition. Low-carbon facilities constitute the material foundation supporting low-carbon transformation and help promote the construction of low-carbon cities. Low-carbon public acceptance assesses the depth of society-wide understanding of the low-carbon concept. Environmental quality is an intuitive manifestation of the outcomes of low-carbon city construction.

**Table 2.** Index system for evaluating low carbon

Target layer	Rule layer	Index layer	Index (+/-)	Unit
Low-carbon	Low-carbon technology	Industrial structure upgrade	+	/
		Scientific expenditure	+	CNY
		Number of AI enterprises	+	/
		Employees in the tertiary industry	+	people
	Low-carbon energy	Total amount of water resources	+	$m^3$
		Carbon emissions	-	t
		Energy efficiency	+	%
	Low-carbon facility	Actual number of public operated cars at the end of the year	+	/
		Annual electricity consumption	-	kWh
		Number of health institutions	+	/
	Low-carbon recognition	Total number of low-carbon related words	+	/
		Number of patents granted	+	/
	Low-carbon environment	Domestic sewage treatment rate	+	%
		Save water consumption	+	t
		Green coverage rate in built-up area	+	%
		Green area	positive	$km^2$
Harmless treatment rate of municipal solid waste		positive	%	

### 2.2.3. Selection of Driving Factors

This study comprehensively considers previous research findings, the availability of indicator data, and the collinearity among variables, focusing on selecting key factors from four dimensions: policy promotion, economic strength, ecological resources, and green innovation. The factors from each dimension together constitute a systematic analytical framework, comprehensively revealing the multiple driving mechanisms that influence the coupling and coordinated development of urban resilience and low-carbon development in the Yellow River Basin. (Table 3)

**Table 3.** Factors Influencing the CCD between UR and LCD

Type	Driving	Index
Policy impetus	"Low-Carbon City" pilot policy (X1)	Reflect a city's priority status and institutional advantages within national low-carbon strategies
Economic strength	Gross domestic product (X2)	Reflect a city's economic scale and the wealth level of its residents
	Year-end savings balance of urban and rural residents (X3)	
Ecological resources	Green space area (X4)	Represent the natural environment and resource endowment of a city
	Total water resources (X5)	
Green innovation	Technology investment (X6)	Embodies a city's capacity to transform scientific research resources into sustainable technological outcomes
	Total green patent grants (X7)	

## 2.3. Methods

(1) Evaluation of urban resilience and low-carbon development levels: The entropy weight-TOPSIS method is used to measure the resilience level and low-carbon development level of cities in the Yellow River Basin, respectively.

- (2) Analysis of coupling coordination relationship: The coupling coordination degree model is employed to quantify the synergistic development relationship between urban resilience and low-carbon development.
- (3) Spatial pattern analysis: Global and local spatial autocorrelation analyses are applied to determine the overall agglomeration characteristics of the coupling coordination degree and to identify local spatial association patterns.
- (4) Identification of driving factor importance: The geographic detector model is used to investigate the key factors influencing the spatial differentiation of the coupling coordination degree and their interaction effects.
- (5) Spatial effect analysis: The spatial Durbin model is utilized to distinguish the direct and indirect effects of each driving factor.

**Table 4.** Research methods

Methodology	Function	Formula	Indicator	References
Entropy-weight TOPSIS method	evaluate UR and LCD levels	$x'_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}$ $x'_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}$ $e_j = -\frac{1}{\ln n} \sum_{i=1}^n p_{ij} \ln(p_{ij})$ $w_j = \frac{d_j}{\sum_{j=1}^m d_j}$ $I^+ = (\max z_{i1}, \max z_{i2}, \dots, \max z_{im})$ $I^- = (\min z_{i1}, \min z_{i2}, \dots, \min z_{im})$ $D_i^+ = \sqrt{\sum_{j=1}^n (I_j^+ - z_{ij})^2}$ $D_i^- = \sqrt{\sum_{j=1}^n (I_j^- - z_{ij})^2}$ $C_i = \frac{D_i^-}{D_i^+ - D_i^-}$	i: city j: indicator $x_{ij}$ : value of indicator $j$ for city $i$ $p_{ij}$ : proportion of indicator $j$ in year $i$ relative to the total indicator value $C_i$ : value of UR and LCD levels.	Chen, 2021
Coupling coordination degree (CCD) Model	measure the level of synergistic development between UR and LCD	$K = (MN)^{\frac{1}{2}}$ $N = \alpha F + \beta G$ $M = 2[FG/(F + G)^2]^{\frac{1}{2}}$	$K$ : coupling coordination degree $M$ : coupling degree $N$ : comprehensive coordination index $F/G$ : the UR index/the LCD index $\alpha/\beta$ : relative importance of the two systems	Ye et al., 2025
Spatial correlation analysis	characterizing spatial aggregation features of coupling coordination	$I = \frac{n \sum_{i=1}^n \sum_{j=1}^m W_{ij} (x_i - x')}{\sum_{i=1}^n \sum_{j=1}^m W_{ij} \sum_{i=1}^m (x_i - x')^2}$ $I' = \frac{n(x_i - x') \sum_{j=1}^m W_{ij} (x_j - x')}{\sum_{i=1}^n (x_i - x')^2}$	$I$ : global autocorrelation index $I'$ : local autocorrelation index $x_i, x_j$ : index value of attribute units $i$ and $j$ $x'$ : standard value $W_{ij}$ : spatial weight matrix	Xu et al., 2026
Geographical detector	detecting spatial heterogeneity and revealing its drivers	$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$	$N_h, N$ : number of cells in the stratum $h$ and the whole region $\sigma_h^2, \sigma^2$ : variances of the values of the dependent variable in stratum and the whole region, respectively	Sun et al., 2026
Spatial dubin model	Revealing the spatial effects of coupling coordination	$y = \phi W_1 y + X\beta + \lambda W_2 u + \varepsilon$	$W_1, W_2$ : spatial weight matrixes $\phi$ : spatial correlation coefficient $\mu$ : random error term $\lambda$ : spatial residual autocorrelation coefficient $\varepsilon$ : residuals	Wei et al., 2024

### 3. RESULT

#### 3.1. Spatio-Temporal Patterns of Urban Resilience, Low-Carbon, And Coupling Coordination in the Yellow River Basin

##### 3.1.1. Temporal Evolution Analysis

As illustrated in the figure, the temporal evolution characteristics of the Urban Resilience (UR), Low-Carbon Development (LCD), and Coupling Coordination Degree (CCD) indices from 2006 to 2021 exhibit pronounced differences. Although all three indices maintain an upward trajectory, their growth paths diverge considerably. Overall, urban resilience rose from approximately 0.13 to above 0.24 over the 15-year period—a substantial increase—with only a minor decline observed in 2015; all other years recorded sustained growth. This indicates a continuous enhancement of cities' capacity to withstand various risks and maintain stability and development during this period, with particularly notable increases in 2014 and 2018. Concurrently, low-carbon development displays a generally steady upward trend. Following minor fluctuations between 2006 and 2008, its growth rate accelerated significantly from 2020 to 2021, suggesting that the momentum and effectiveness of low-carbon advancement intensified markedly in the later phase. Collectively, these trends reflect the gradual implementation and efficacy of relevant measures from 2006 to 2021. The coupling coordination degree between urban resilience and low-carbon development in the Yellow River Basin also shows a sustained upward trajectory, albeit with a relatively moderate rate of increase. This signifies a continuous optimization of their coordination level over the period, with an overall positive developmental trend and a discernible acceleration in growth during the later years. The compound annual growth rate (CAGR) of UR surged to 84.2% in 2021, with a notably accelerated pace between 2016 and 2021, achieving sustained high-speed growth. The CAGR of LCD exhibits a classic "J-shaped" non-linear pattern: after a brief negative growth in 2007, it peaked in 2021, with the growth slope steepening considerably after 2012. The CAGR of CCD, in contrast, has maintained a steady increase without any evident deceleration phase. Furthermore, the increasing length of the boxes in the box plots for UR, LCD, and CCD from 2006 to 2021 indicates a widening disparity among cities across these three indicators. In the UR box plot for 2006, the median line is positioned towards the upper part of the box; by 2021, it resides closer to the center, reflecting a gradual diminution in the proportion of lower-level values over time. Meanwhile, the median lines in the box plots for both LCD and CCD remain consistently positioned towards the upper part throughout the 2006–2021 period, indicating the persistent prevalence of lower-level characteristics in these two dimensions.

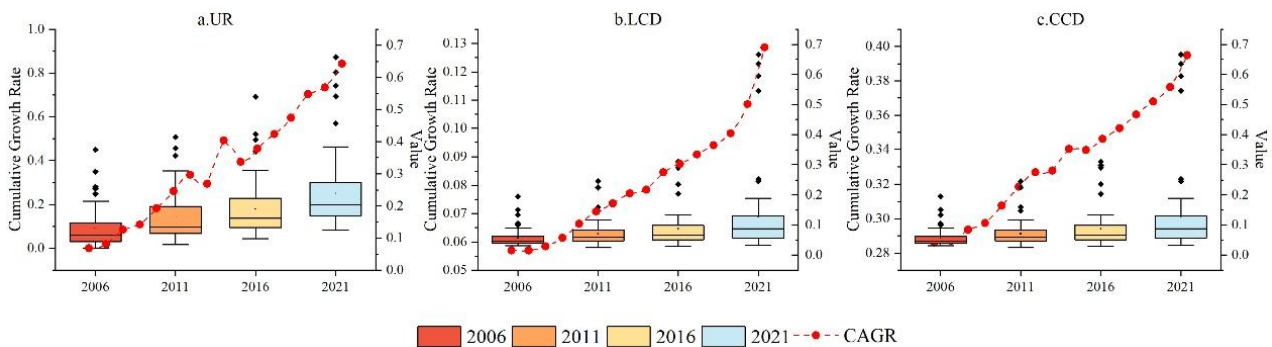


Figure 3. Spatial evolution characteristics

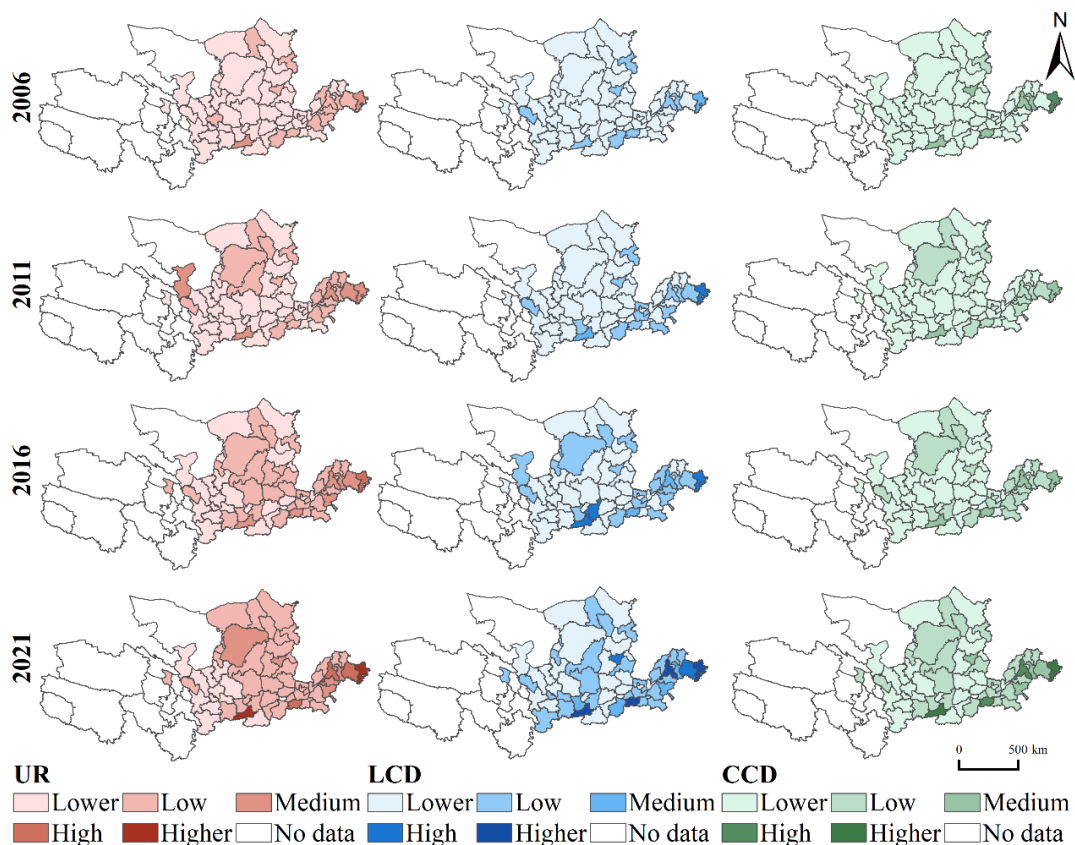
##### 3.1.2. Spatial Distribution Analysis

The overall urban resilience in the Yellow River Basin has shown an upward trend, yet regional disparities remain pronounced. In 2006, approximately 75% of cities were at the lower level; by 2021, the proportion of lower resilience cities had dropped to around 18%, while 65% of cities had advanced to the low level. Specifically, Qingdao has consistently maintained a leading position, rising from the medium level to a higher level of 0.663. Provincial capitals such as Zhengzhou, Xi'an, and Jinan have

made rapid progress, whereas cities in the northwest, including Zhongwei and Longnan, have experienced slow growth and remain at low levels, presenting an overall spatial pattern of higher resilience in the east and lower in the west. Analyzed by river section, the upper reaches have consistently exhibited low resilience, with an average value of only 0.185 in 2021, still in the nascent stage. The middle reaches have developed at a moderate pace, achieving an average of 0.227 in 2021. The lower reaches have consistently led, starting from 0.166 in 2006 and rising to 0.307 by 2021, thereby entering the medium-level range.

Low-carbon development across the entire basin has been relatively slow but has accelerated in recent years. In 2006, 85% of cities were at the lower level, whereas by 2021 this proportion had decreased to 42%, with an equivalent 42% of cities advancing to the low level. Benchmark cities such as Xi'an have emerged with values exceeding 0.6, and Jinan, Zhengzhou, and Qingdao have also attained relatively high levels. However, resource-dependent cities like Baiyin and Qingyang have remained at the lower level of approximately 0.03, facing considerable transformation pressure. By section, the upper reaches have encountered the greatest difficulty in low-carbon transition, with an average of only 0.075 in 2021, never surpassing the 0.08 threshold. The middle reaches have achieved a leap from 0.053 to 0.114, while the lower reaches have performed best, rising from 0.063 to 0.192 and entering the medium-level range.

Systemic coordination across the entire basin has steadily strengthened. In 2006, 75% of cities were in the lower coordination range, but by 2021, 68% of cities had progressed into the preliminary coordination range of 0.3 to 0.5, with a few cities—most notably Qingdao—attaining a high coordination level of 0.806. In terms of sectional performance, the upper reaches exhibited the lowest coordination degree, standing at merely 0.336 in 2021, indicative of barely coordinated status. The middle reaches have steadily improved to 0.375. The lower reaches have continued to lead, increasing from 0.311 to 0.468, approaching the moderate coordination level, thereby demonstrating a leading position in systemic coordination across the basin, underpinned by dual strengths in both resilience and low-carbon development.



**Figure 4.** Spatial pattern

### 3.2. Spatial Correlation Analysis of the Coupling Coordination Degree in the Yellow River Basin

#### 3.2.1. Global Spatial Agglomeration Characteristics

Based on the Global Moran's I index, a spatial autocorrelation analysis was conducted on the coupling coordination degree between urban resilience and low-carbon development from 2016 to 2021, with the results presented in the table. During the study period, the Global Moran's I values passed the 5% significance level test in most years, indicating that, overall, the coupling coordination level between urban resilience and low-carbon development in the Yellow River Basin exhibits spatial agglomeration characteristics. As shown in the table, the Global Moran's I values are positive for all years, suggesting a clear positive spatial correlation in the coupling coordination degree between urban resilience and low-carbon development. From a temporal evolution perspective, the Global Moran's I index generally displays a trend of first increasing and then fluctuating downward. This indicates that over the study period, the spatial agglomeration effect of the coordination level between urban resilience and low-carbon development initially strengthened and subsequently weakened to some extent. The synergistic development relationship between neighboring areas has experienced certain fluctuations, reflecting the gradually emerging differences among cities in the process of coordinated resilience and low-carbon development, as well as a dynamic adjustment in the spatial dependency pattern across the region.

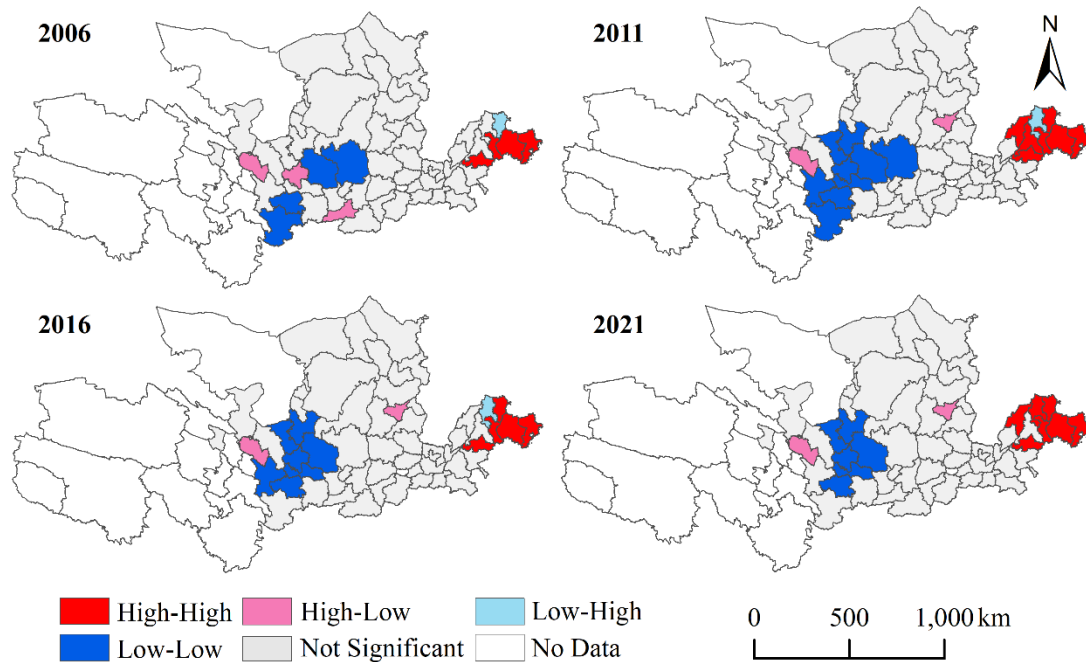
**Table 5.** The global Moran's I of coupling coordination degree between UR and LCD

Year	Moran's I	Z	P	Year	Moran's I	Z	P
2006	0.0291	2.2382	0.0252	2014	0.1979	4.1373	0.0000
2007	0.0408	2.8123	0.0049	2015	0.1404	3.0444	0.0023
2008	0.0427	2.4016	0.0163	2016	0.1359	2.9638	0.003
2009	0.1065	2.4052	0.0162	2017	0.1367	2.9744	0.0029
2010	0.1403	3.0505	0.0023	2018	0.1407	3.0676	0.0022
2011	0.1631	3.4858	0.0005	2019	0.1359	2.9854	0.0028
2012	0.1558	3.3464	0.0008	2020	0.1484	3.2324	0.0012
2013	0.1628	3.4871	0.0005	2021	0.1478	3.2208	0.0013

#### 3.2.2. Local Spatial Agglomeration Characteristics

Figure 5 illustrates the spatial agglomeration pattern of the coupling coordination degree among cities in the Yellow River Basin, which is predominantly characterized by "Low-Low" and "High-High" agglomerations, supplemented by heterogeneous types. The High-High agglomeration areas are concentrated in the Shandong Peninsula in the lower reaches of the Yellow River. Starting from Tai'an, Zibo, Weifang, and Qingdao in 2006, Dezhou and Jinan joined and formed contiguous clusters by 2011, and a stable synergistic highland had taken shape by 2021, demonstrating a virtuous cycle and demonstration potential. Low-Low agglomeration areas are widely distributed in the Shaanxi-Gansu-Ningxia region. In 2006, they were primarily concentrated in Gansu, and by 2011, they had expanded into contiguous cross-provincial depressions encompassing Dingxi, Tianshui, Guyuan, and Yan'an. Although Yan'an exited this category by 2021, the overall pattern remained persistent, indicating a low-level equilibrium trap. High-Low agglomeration areas are manifested as isolated polarization centered on provincial capitals: Lanzhou, Xi'an, and Guyuan in 2006, with Lanzhou and Taiyuan emerging as two growth poles after 2011, yet their radiation and driving effects remained insufficient while the siphonic effect was pronounced. Low-High agglomeration areas consisted of Dongying in 2006 and Binzhou in 2016; by 2021, Binzhou had successfully integrated into the High-High agglomeration area, leading to the disappearance of the Low-High type. This indicates that peripheral cities can achieve leapfrog development under the impetus of strongly synergistic regions.

Furthermore, the high proportion of cities with insignificant agglomeration suggests that regional spatial correlation remains loose and synergistic mechanisms are still weak.



**Figure 5.** LISA cluster graph of coupling coordination degree between UR and LCD

### 3.3. CCD Analysis of Influencing Factors

#### 3.3.1. Overall Impact Analysis

Based on the analysis results of the Geographic detector, the explanatory power (q-value) of each influencing factor on the coupling coordination degree between urban resilience and low-carbon development exhibited an overall fluctuating upward trend from 2006 to 2021. Specifically, the impact of X1 (Low-Carbon City Pilot) initially decreased and then increased, rising to 0.090 by 2021, though its overall influence remained relatively weak. X2 (GDP) continued to climb, reaching 0.917, consistently serving as a core high-impact factor. X3 (Fiscal Expenditure) increased steadily to 0.888, with its growth rate gradually slowing in the later period. X4 (Per Capita Park Green Area) rose initially before experiencing a slight decline, exerting a limited effect. X5 (Per Capita Domestic Water Consumption) increased steadily to 0.447, remaining at a medium-low level. X6 (Scientific and Technological Level) showed a fluctuating upward trend, impeded by transformation efficiency during the middle period. X7 (R&D Expenditure) rose to 0.907, demonstrating a prominent supportive role (Table 6).

**Table 6.** CCD influence factor coefficient results

Variable	2006	2011	2016	2021
X1	0.023	0.001	0.052	0.090
X2	0.707	0.816	0.859	0.917
X3	0.772	0.794	0.873	0.888
X4	0.244	0.267	0.289	0.284
X5	0.288	0.300	0.336	0.447
X6	0.236	0.597	0.517	0.593
X7	0.796	0.811	0.843	0.907

In terms of two-factor interaction detection, the interaction between any two factors is stronger than that of a single factor, with interaction types predominantly characterized by bi-factor enhancement

or non-linear enhancement. This indicates that the combined effect of multiple factors significantly strengthens the explanatory power for spatial differentiation. The explanatory power of two-factor interactions on the coupling coordination degree is generally stronger than that of single factors, demonstrating a synergistic enhancement effect. In 2006, the strongest interaction combination was Gross Domestic Product (GDP) and Per Capita Daily Domestic Water Consumption, with a q-value of 0.962, reflecting the close linkage between water resources and economic activities during the stage of extensive economic expansion. By 2011, the strongest combination shifted to GDP and Scientific and Technological Level, with a q-value of 0.972, highlighting the mutual reinforcement between economic strength and technological innovation. In 2016, it became Scientific and Technological Level and Intramural R&D Expenditure, with a q-value of 0.970, underscoring the prominent synergistic effect of green innovation factors. In 2021, the strongest combination was General Public Budget Expenditure and Per Capita Park Green Area, with a q-value of 0.992, signifying a peak integration of fiscal investment and ecological resilience (Figure 6).

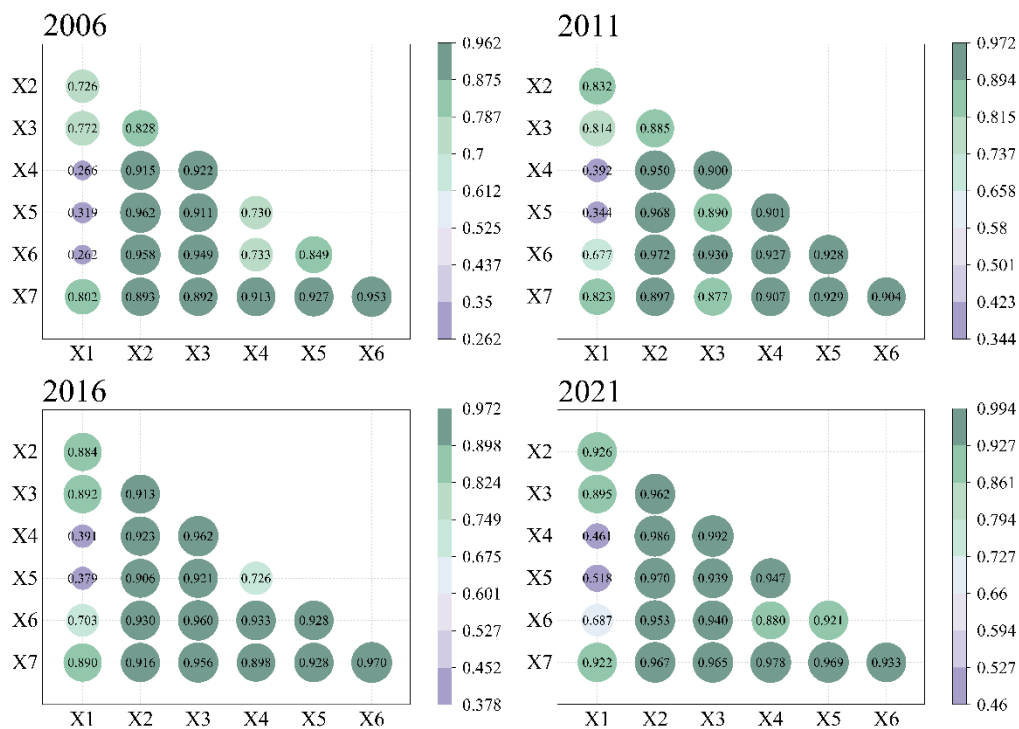


Figure 6. Interactive detection results of CCD influence factor

### 3.4. Spatial Effect Analysis of Factors Influencing The Coupling Coordination Degree in the Yellow River Basin

The study finds significant disparities in the influence of various factors on the coupling coordination between urban resilience and low-carbon development in the Yellow River Basin. X1 (the "Low-Carbon City" pilot policy) significantly improves the local coupling coordination degree only at the 1% level, while exhibiting no significant spillover effect on neighboring areas, reflecting its localized focus and limited spatial radiation. X2 (Gross Domestic Product) shows a significantly positive direct effect at the 1% level, yet its indirect and total effects are significantly negative. This indicates that although economic growth strengthens local synergy, it markedly suppresses surrounding areas by siphoning talent, capital, and other factors, underscoring the imbalance in regional development. X3 (General Public Budget Expenditure) has a significantly positive direct effect, while both its indirect and total effects are insignificant, suggesting that fiscal support primarily acts locally and the cross-regional transmission mechanism remains underdeveloped. All three effects—direct, indirect, and total—of X4 (Per Capita Park Green Area) and X5 (Per Capita Daily Domestic Water Consumption) are significantly negative at the 1% level. This suggests that suboptimal green space layout and low

water-use efficiency not only burden the local area but also generate negative spatial spillovers on neighboring regions through spatial competition. X6 (Scientific and Technological Level) has a significantly positive direct effect, but its indirect effect is insignificant, indicating that technological dividends are effectively localized while cross-regional diffusion is insufficient. X7 (Intramural R&D Expenditure) exhibits an insignificant direct effect, whereas its indirect and total effects are significantly negative. This reflects that a high concentration of R&D investment strengthens core cities' ability to absorb innovation resources, thereby weakening the support conditions in peripheral areas. Overall, the local impacts and spatial spillover directions of these factors differ, and coordinated development requires attention to both direct promotion and the regulation of negative spillover effects.

**Table 7.** Results of spatial effect decomposition

Variable	Direct	Indirect	Total
X1	0.018***	-0.016	0.002
X2	0.039***	-0.305***	-0.266***
X3	0.036***	0.029	0.065
X4	-0.009***	-0.104***	-0.112***
X5	-0.008***	-0.194***	-0.202***
X6	0.825***	-0.697	0.128
X7	0.001	-0.066***	-0.066***

\*\*\* p<0.01, \*\* p<0.05, \* p<0.1

## 4. DISCUSSION

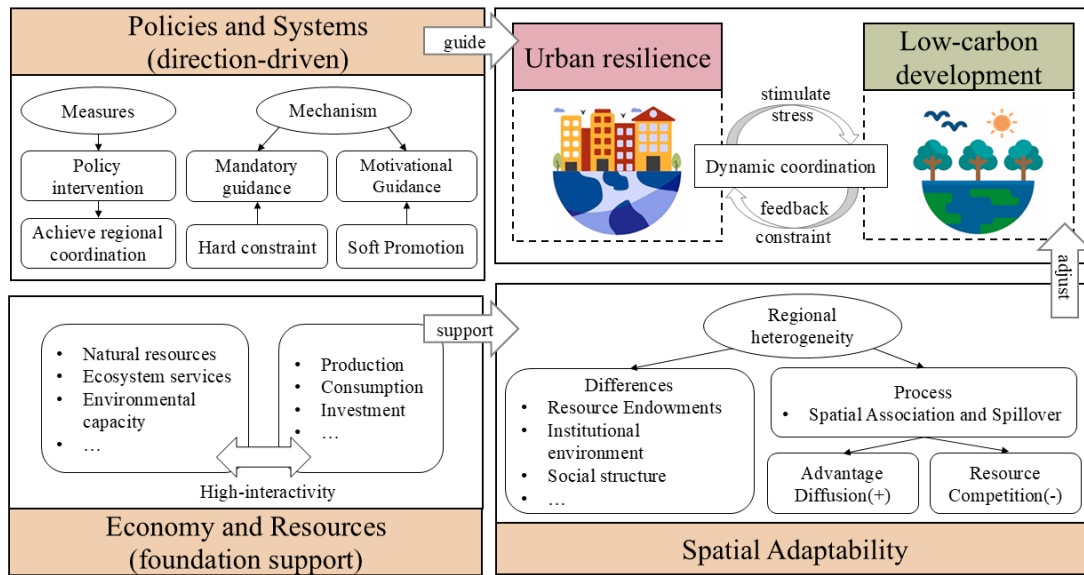
### 4.1. Spatial Differentiation Characteristics of the Coupling Coordination

The coupling coordination across the upper, middle, and lower reaches of the basin has improved to varying degrees, yet the spatial pattern consistently follows the order: lower reaches > middle reaches > upper reaches. This finding aligns with the conclusions of Guo et al. (2023): owing to higher levels of urbanization and stronger economic foundations, the lower reaches can integrate resources more effectively, thereby facilitating the synergistic development of low-carbon technologies and resilient infrastructure. The middle reaches, dominated by loess landscapes and subjected to severe soil erosion, may experience compromised ecological resilience, which in turn hinders overall coordinated development. The upper reaches suffer from ecosystem degradation and weak soil and water conservation capacity, leading to lagging ecological resilience that impedes socioeconomic progress. This spatial pattern is consistent with the findings of Zhou et al. (2025); however, the upper reaches persistently prioritize economic resilience while ecological resilience remains relatively lagging. This suggests that less-developed regions continue to find it difficult to break away from the conventional development path of "economic growth first," a phenomenon possibly linked to inadequate ecological compensation mechanisms or insufficient momentum for green transition. Such regional heterogeneity is consistent with the findings of Peng et al. (2025). Related studies have indicated that the same driving factor can produce divergent effects across different regions, a conclusion that resonates strongly with our own observations (Chen et al., 2026). In the Yellow River Basin, Gross Domestic Product (GDP) exerts a significantly positive impact on cities in the middle and lower reaches but a negative one on the upper reaches—a phenomenon that profoundly reveals how the upper, middle, and lower reaches are situated at different development stages and are confronted with distinct trade-offs between growth and transformation. The literature has employed the Spatial Durbin Model to reveal spatial spillovers and resource competition among regions (Wang et al., 2024). This finding corresponds with our own research: we observed negative spatial spillovers from green space areas on neighboring cities in the upper and middle reaches, and from water resources in the lower

reaches, indicating insufficient regional synergy. Some scholars posit that economic development levels and technological innovation significantly influence the coordination of urban systems, which is largely consistent with our findings (Peng et al., 2025). In this study, the Low-Carbon City Pilot Policy demonstrates significant positive effects and spatial spillover impacts on adjacent areas, echoing existing research that emphasizes the crucial role of policy intervention in advancing sustainable development (Zhou et al., 2025).

## 4.2. Driving Mechanisms of Low-Carbon Resilience

Overall, although the Yellow River Basin has laid a foundation for the synergistic advancement of the dual carbon goals and resilient urban development, the extent of improvement in overall coordination remains constrained by regional heterogeneity and developmental imbalances. Building low-carbon and resilient cities has emerged as a critical pathway toward achieving carbon neutrality and enhancing climate adaptation capacity, while also providing empirically valuable insights for global climate governance. The relationship between urban resilience and low-carbon development exhibits dynamically coordinated evolutionary characteristics. On one hand, urban resilience—through its capacity to absorb and dissipate disturbances and pressures—furnishes the essential stability foundation and development space required for low-carbon transition. On the other hand, low-carbon development—via structural emission reductions and systematic optimization—generates positive feedback and imposes path constraints on the enhancement of urban resilience. The two processes progressively achieve co-evolution through their interaction, and the degree of their coupling coordination is subject to the combined influence of multiple driving mechanisms. At the level of driving mechanisms, policy and institutions play a directional guiding role and serve as key intervention instruments for achieving their coupling coordination. Their operational pathways primarily manifest as a dual logic of mandatory guidance and incentive-based guidance: the former establishes development baselines through hard constraints such as regulations and standards, whereas the latter stimulates the vitality of actors through soft instruments like fiscal subsidies and green finance, thereby fostering the formation of regional collaborative governance frameworks. The economy and resources constitute the foundational support system. Economic activities encompass processes of production, consumption, and investment, while resource allocation involves natural resource endowments, ecological service functions, and environmental capacity thresholds. These two dimensions exhibit a strong interactive relationship, mutually constraining yet reinforcing each other, and represent core variables in determining the sustainability of urban systems. Spatial regulatory forces are manifested as differentiated response mechanisms induced by spatial heterogeneity. The uneven spatial distribution of resource endowments, institutional environments, and social structures shapes the diversity of coupling pathways between urban resilience and low-carbon development. Their functional processes primarily manifest as spatial correlation and spillover effects: the diffusion of advantageous factors contributes to synergistic gains, whereas resource competition may precipitate developmental imbalances that require adjustment through spatial governance. Green innovation constitutes the core impetus driving systemic transition. It not only fulfills the functions of technological breakthroughs and model reconfiguration but also facilitates the transformation from external policy constraints into endogenous developmental momentum, propelling cities toward adaptive evolutionary trajectories under the dual imperatives of resilience and low-carbon development (Figure 7).



**Figure 7.** Mechanism

### 4.3. Policy

(1) Implement differentiated spatial economic policies. For the lower reaches, leverage their "win-win" advantages characterized by positive total effects to deepen urban agglomeration integration and establish regional collaborative innovation and industrial cooperation networks. For the middle and upper reaches, special attention must be paid to the potential "siphonic effects" or negative spillovers associated with GDP growth. Policy design in these areas should emphasize "shared growth" by utilizing mechanisms such as enclave economies and benefit-sharing arrangements to ensure that the developmental achievements of central cities benefit the surrounding regions.

(2) Technological investment, economic growth, and low-carbon city pilot policies constitute the core driving forces, and their interaction yields significant enhancement effects. To further unlock policy dividends, efforts should focus on strengthening policy synergy by deeply integrating low-carbon city pilot policies with major regional development strategies—such as the transition from old to new growth drivers—and coupling them with dedicated science and technology funds and green financial instruments. This approach aims to construct a policy portfolio characterized by "pilot policy guidance, technological R&D support, and industrial investment follow-through," thereby consolidating and amplifying policy outcomes. Concurrently, the enabling role of technological innovation must be emphasized. It is recommended to establish a Joint Fund for Green Technology Innovation in the Yellow River Basin, with a focus on supporting key technologies—including smart energy systems and ecological restoration techniques—that can synergistically enhance both system resilience and low-carbon performance. Furthermore, the development model for green patents should shift from mere quantitative growth toward quality enhancement and efficient transformation, thereby substantively increasing their contribution and explanatory power in green development. On the other hand, it is crucial to actively steer the green investment orientation of household wealth. Given the growing influence of urban and rural residents' savings, innovative green financial products should be developed to channel savings—through green bonds and Environmental, Social, and Governance (ESG) investments—into local resilient infrastructure and low-carbon industrial projects. Such measures not only help prevent capital outflow but also effectively convert existing social wealth stock into new momentum for regional green development.

#### 4.4. Limitations and Future Research Directions

This study has several limitations. Due to data availability constraints, certain cities and regions could not be incorporated into the evaluation framework. Consequently, the selection of scientific and comprehensive indicators and measurement methods for systematically assessing the overall situation of the Yellow River Basin constitutes a critical direction for future research. Additionally, the data employed in this study exhibit certain temporal limitations, as they do not fully capture the most recent developmental dynamics. Future work will require further data updates to enhance the timeliness and practical reference value of the research.

### 5. CONCLUSION

(1) From 2006 to 2021, the coupling coordination degree of low-carbon development and urban resilience in the Yellow River Basin steadily improved, transitioning overall from "barely coordinated" to "primary coordination." In the early part of the study period, over eighty percent of cities in the basin exhibited low coordination levels, concentrated primarily in the middle and upper reaches. By 2021, only a quarter of cities remained at the barely coordinated level, while a few had attained high-quality coordination. Coordination levels increased across the upper, middle, and lower reaches, yet the spatial pattern consistently maintained a gradient hierarchy of "lower reaches > middle reaches > upper reaches."

(2) The spatial agglomeration characteristics of the coordination degree are pronounced. The "Low-Low" agglomeration type is concentrated in the upper reaches, particularly in Ningxia and Gansu, where the majority of cities still require substantial improvement. In contrast, the "High-High" type is clustered in the lower reaches within Shandong Province. Transitional types are exceedingly rare, appearing only in isolated provincial capitals, indicating that interregional synergistic development and radiation-driven effects remain insufficient.

(3) Regarding influencing factors, the intensity of single-factor effects exhibits significant disparities. GDP and R&D expenditure persistently rose to high levels, reaching 0.917 and 0.907 respectively by 2021, thereby constituting the core drivers of synergistic development. Fiscal expenditure steadily increased to 0.888, demonstrating a pronounced supportive role. The impact of the Low-Carbon City Pilot Policy initially declined before rebounding, though its overall influence remained relatively weak. The effects of per capita park green area and per capita domestic water consumption were limited and declined in the later period. The scientific and technological level exhibited a fluctuating upward trend, constrained by transformation efficiency. The explanatory power of two-factor interactions is universally stronger than that of single factors, with key interaction combinations evolving across developmental stages: shifting from an economy-water resource linkage to mutual reinforcement between economy and technology, and further transitioning toward green innovation synergy and fiscal-ecological integration. Notably, the interaction between fiscal expenditure and park green area achieved an explanatory power of 0.992 in 2021. Decomposition of spatial effects further reveals that while economic growth and R&D investment strengthen local synergy, they generate significant negative spillover effects on neighboring areas through siphonic mechanisms. Factors such as the low-carbon pilot policy and scientific and technological level exhibit insufficient cross-regional diffusion. The negative spatial competition effects arising from green space allocation and water-use efficiency are particularly prominent.

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## AUTHORS' CONTRIBUTIONS

Ying An: Supervision, Validation, Writing – review & editing. Jing Bai: Conceptualization, Formal analysis, Writing – original draft, Funding acquisition, Methodology, Writing-original draft, Writing-review & editing. Xi Wang: Data curation, Validation, Investigation, Visualization.

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