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Original Research

Spatiotemporal Evolution of and Regional Disparities in Coupling Coordination between Economic Development Quality and Urban Ecological Resilience in the Yangtze River Economic Belt

Xuan Chen[1], Xudong Li[1]* Qunli Chen[2]

[1]School of Geography and Environmental Science, Guizhou Normal University, Guiyang 550025, China
[2]School of Ecological Engineering, Guizhou University of Engineering Science, Bijie 551700, China

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Abstract

Good economic progress and the coordinated development of urban ecological resilience are essential for achieving ecological protection and high-quality development. This study uses 2011-2021 panel data on 110 Yangtze River Economic Belt cities and employs an entropy-weighted technique for order of preference by similarity to an ideal solution, coupled coordination degree model, and kernel density estimation to determine spatiotemporal evolution characteristics of and regional differences in the coupled coordination relationship between economic development quality and urban ecological resilience. Results reveal (1) a close relationship between the two, whose degree of coupled coordination increases yearly, continuously narrowing the disparity in urban coordinated development. (2) The coupled coordination types change from imbalance and decline to the dominance of coordinated development, exhibiting a stepwise spatial pattern of "downstream>midstream>upstream." Spatial agglomeration is evident, forming a clustering characteristic predominantly led by high–high agglomeration areas downstream and low–low agglomeration areas upstream. (3) The most pronounced differences are observed upstream, and coupling coordination differs most prominently between the upstream and downstream regions. The study concluded that interregional disparities are the primary factors influencing the spatial differences in the coupling coordination level. The findings provide scientific theoretical support for future urban planning and national strategies.

Keywords: economic development quality, urban ecological resilience, coupling coordination, spatiotemporal evolution, regional disparities, Yangtze river economic belt

*e-mail: 21010090331@gznu.edu.cn
Tel.: +86-193-0651-8608 Fax: +1-111-111-112

Introduction

With the development of socialism with Chinese characteristics, the economic development model in China has transformed from quantity- to quality-oriented [1]. The previous high-speed growth economic model was characterized by a predominantly extensive production method, triggering various ecological issues such as environmental pollution and excessive resource exploitation. This decreased urban ecological carrying capacity, increased ecological risks, and significantly weakened urban ecological resilience. The contradiction between economic development and ecological sustainability has continued to increase. The "19th National Congress" report of the Communist Party of China emphasized that promoting the green transformation of economic and social development is crucial for achieving high-quality development. The core significance of such transformation lies in resolving the conflict between economic development and ecological sustainability and pursuing coordinated development of the economy and society with a high level of ecological sustainability. In the 14th Five-Year Plan and the Outline of the 2035 Vision, the concept of "resilient cities" was first introduced, with urban ecological resilience being a key indicator of urban resilience, attracting considerable attention. Presently, the Yangtze River Economic Belt serves as a crucial pillar for China's economic stability and development. Ecological protection and high-quality development in this region have been considered a significant national strategic priority, particularly in the "Outline of the Development Plan for the Yangtze River Economic Belt" (hereinafter referred to as the "Outline") issued by the National State Council in September 2016. Achieving a balance between economic development and ecological sustainability is essential for ensuring the high-quality development of the Yangtze River Economic Belt [2]. To this end, accurately understanding and promoting the coordinated development of the ecological environment and economy has become an important task of the Central Committee of the Communist Party of China and government organizations at all levels. Therefore, conducting a thorough analysis of the coupling coordination relationship between economic development quality and urban ecological resilience holds practical significance for narrowing the development disparity between the eastern, central, and western regions in the Yangtze River Economic Belt. This will further promote coordinated and sustainable development of the regional economy and ecology.

The relationship between economic development and the coordinated development of urban ecological environments has been studied extensively [3, 4]. Early foreign research explorations were initiated by the American scholar Boulding, who proposed the "Spaceship Earth" economic perspective, marking the beginning of scholarly attention toward the contradictory relationship between economy and ecology [5]. Based on the environmental Kuznets curve, Grossman confirmed an inverted U-shaped developmental relationship between economic development and ecological sustainability [6]. Owing to accelerated urbanization and increased demand for high-quality economic development, research on the interrelationship between the aforementioned two factors has gradually increased in recent years, with a focus on the coupling coordination level of both factors [7], theoretical mechanisms [8], laws of coordinated development [9], and influencing factors [10] at the provincial [11], municipal [12], and county [13] levels. The research regions encompass typical climatic zones [14], river basins [15], mountainous areas [16], urban agglomerations [17], and various other provinces [18]. With the flourishing development of geographic information technologies such as geographic information systems, spatial statistical analysis is widely applied in research. Scholars have employed models such as coupling coordination models [19, 20], vector autoregression models [21], spatial correlation models [22], and back propagation neural network models [23] to conduct in-depth investigations into the coupling coordination relationship between the two factors.

The significant research progress on the relationship between the economy and ecological sustainability has laid a solid foundation for collaborative and sustainable development research on the quality of economic development and urban ecological resilience. However, existing studies tend to focus on measuring the level of economic development using a single indicator, neglecting the quality of economic development. Few studies have explored the spatial and temporal evolution of, and regional differences between, the two from a geographical perspective.

Given the above analysis, the potential contributions of this study are as follows: (1) The study is not limited to the measurement of economic development quality and urban ecological resilience using a single indicator; instead, we construct evaluation indicator systems for both factors from three dimensions and comprehensively and scientifically explore their relational changes. (2) Using the entropy-weighted technique for order of preference by similarity to ideal solution (TOPSIS) and coupling coordination degree model, we quantitatively assess the coupling coordination relationship between economic development quality and urban ecological resilience, effectively avoiding biases caused by subjective weighting and significant dispersion of indicator values. (3) Using the Dagum Gini coefficient decomposition, we investigate differences in the coordinated development of the three regions in the Yangtze River Economic Belt from the perspective of regional disparities. This approach enables us to identify the sources of regional spatial differences and recommend strategies and policy suggestions to promote the sustainable development of the Yangtze River Economic Belt. These strategies include encouraging and supporting the development of urban green industries; formulating differentiated policies according to local conditions by leveraging the role of central cities; and adhering to the concept of integrated development, forming a pattern of complementary advantages and collaborative interactions among the upstream, midstream, and downstream sectors.

Experimental Procedures

Coupling Coordination Mechanism

As the central hubs of human activities, urban regions are intricately linked to the quality of economic development and the health of ecosystems. These two aspects are interdependent and mutually reinforcing. The enhancement of urban ecological resilience is significantly dependent on the quality of economic development in a region. Economic development quality emphasizes economic structure optimization and efficient resource utilization while maintaining stable economic growth. It involves the comprehensive development of society, economy, and ecology [24]. First, high-quality economic development is accompanied by industrial structure upgradation, which includes the transition of traditional industries to technology-intensive and environmentally friendly ones. Second, high-quality economic development imposes high ecological requirements on urban planning and construction. Urban planning requires the rational utilization of natural resources, promoting harmonious integration between cities and the ecological environment, and enhancing urban resistance to external impacts such as climate change. Finally, high-quality economic development emphasizes the sustainability of development. By improving residents' living standards and enhancing their healthcare and education levels, economic development stimulates greater resilience in the urban social system, reducing the impact of economic turbulence on the urban ecosystem.

Furthermore, urban ecological resilience is a crucial pillar that supports high-quality economic development. Urban ecological resilience refers to a city's ability to rapidly adjust, adapt, and maintain stability despite ecological and environmental challenges and pressures [25]. With the expansion of urban regions and economic activities, urban ecosystems experience increasingly severe pressures. This underscores the significance of urban ecological resilience in ensuring sustainable urban development. First, enhancing urban ecological resilience improves urban attractiveness and competitiveness. Cities with a favorable ecological environment are more likely to attract talent and investments, thereby promoting high-quality economic development. Second, cities with a high level of ecological resilience typically emphasize technological innovation, driving the research and development of green technologies, fostering emerging industries, optimizing urban industrial structures, and subsequently elevating the quality of economic development. Finally, improving urban ecological resilience helps mitigate the risks associated with economic development. Natural disasters, environmental pollution, and other factors may severely impact urban economies; however, cities with robust ecological resilience can effectively withstand these risks. Thus, urban ecological resilience can better safeguard economic stability and sustainability.

Research Area Overview

The Yangtze River Economic Belt, which relies on the golden waterway of the Yangtze River, comprises three major regions in eastern, central, and western China. It is a key implementation area of China's three major development strategies. The belt covers approximately 2.0523 million square kilometers, accounting for 21.4% of the total land area of China. The region includes 11 provinces and municipalities (Shanghai, Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Yunnan, and Guizhou). Based on its natural geographical location and administrative divisions, the study area was classified into upstream, midstream, and downstream regions (Fig. 1). The region features a mild and humid climate, abundant natural and ecological resources, and a developed economy. As of 2022, the total economic output of the region reached 55.98 trillion yuan, accounting for 46.3% of the national total [26]. The Yangtze River Economic Belt is one of the regions in China with the strongest comprehensive strength and the most significant strategic role [27]. Owing to its unique strategic position, the region has become a crucial participant in China's "Belt and Road" initiative, fostering international cooperation and trade. The Yangtze River Economic Belt is evolving into an indispensable component of the global interconnected economy. However, because of prolonged industrialization and urbanization, the ecological carrying capacity in this region faces significant challenges, thus necessitating industrial transformation and upgradation to mitigate regional development imbalance.

Data Source

This study is based on the "Outline of the Development Plan for the Yangtze River Economic Belt" issued by the Central Committee of the Communist Party of China and the State Council. It focuses on prefecture-level cities within the Yangtze River Economic Belt. Considering the integrity and availability of data, the final number of research units was set at 110, and the study period spanned from 2011 to 2021. The relevant research data were primarily from the China Urban Statistical Yearbook (2012-2022) and the China Urban Construction Statistical Yearbook (2012-2022), as well as the statistical yearbooks of 110 cities in the Yangtze River Economic Belt and their National Economic and Social Development statistical bulletins. For years with

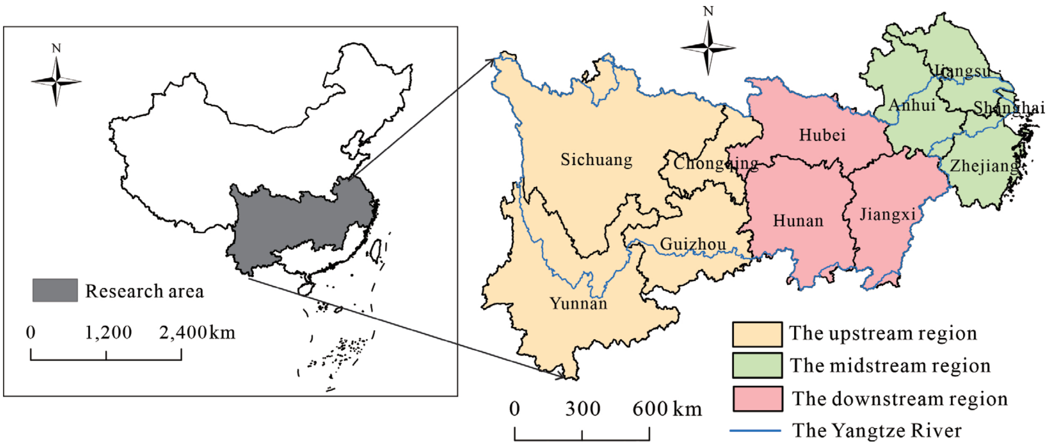

Fig. 1. Map of the study area.
Note: This map is based on the standard map with review number GS(2019)1822 (supervised by the Ministry of Natural Resources; the base map is unaltered).

missing indicators, the linear interpolation method was used for data completion.

Research Methodology

Construction of an Indicator System

Constructing an indicator system is crucial for assessing the coupling coordination between the quality of economic development and urban ecological resilience. The degree of coupling coordination between the two factors was established based on the measurement of both factors. In the context of the quality of economic development, based on the new development concept [28] and in accordance with existing research [29], the quality of economic development comprises three dimensions in this study: scale of economic development, optimization of economic structure, and sustainability of economic development. This enables the establishment of an indicator system for assessing economic development quality. In the context of urban ecological resilience systems, this study adopts a resilience perspective [30], and based on the principles of data availability and scientific rigor, it references the relevant research [31, 32]. The pressure-state-response model is introduced to construct an indicator system for urban ecological resilience (Table 1).

Entropy TOPSIS

In the literature, the methods for assessing indicator systems are mainly divided into subjective and objective weighting methods. The subjective weighting methods involve assigning specific numerical values or weights to indicators through expert evaluation or surveys, displaying a high degree of subjectivity [33]. The objective weighting methods include principal component analysis, correlation function, and entropy, which contribute to enhancing the objectivity and scientific rigor of indicator assessment [34]. Although the entropy method can overcome the shortcomings of the subjective weighting method, it can bias the indicator weights due to the significant variability in the values of a particular indicator. Therefore, the TOPSIS method is introduced for correction. The TOPSIS method assesses the relative distance between each measurement indicator and its optimal (or worst) solution, thus providing a basis for judgment. This approach aims to obtain a comprehensive evaluation index for corrected economic development quality and urban ecological resilience. It helps reduce interference from reference sequences on samples, thereby yielding accurate and reasonable evaluation results [35]. The specific steps are outlined below.

First, the original data matrix (X) is constructed.

$$X = (x_{ij})_{m \cdot n} (1 \le i \le m, 1 \le j \le n) \tag{1}$$

In the Equation, x_{ij} represents the original value of indicator *j* for city *i*, and *m* and *n* denote the total number of cities and indicators, respectively.

Next, the possible dimensional impact on the data is eliminated by standardizing the data to obtain standardized results (Z_{ij}).

$$\text{Positive indicator: } Z_{ij} = \frac{x_{ij} - x_{ij\min}}{x_{ij\max} - x_{ijmin}} \tag{2}$$

$$\text{Negative indicator: } Z_{ij} = \frac{x_{ij\max} - x_{ij}}{x_{ij\max} - x_{ijmin}} \tag{3}$$

Here, x_{ijmin} and x_{ijmax} are the minimum and maximum values of indicator *j* for city *i*, respectively.

The third step involves calculating the indicator weights (W_j) using the entropy method.

Table 1. Indicator system for economic development quality and urban ecological resilience.

Target Layer	Guideline Layer	Secondary Indicators	Indicator Layer	Properties
Economic Development Quality	Scale of Economic Development	Per capita fiscal revenue	Local public budget fiscal revenue/total population	+
		Per capita consumption	Retail sales of consumer goods/total population	+
		Per capita economic output	GDP/total population	+
	Economic Structure Optimization	Industrial structure	Added value of secondary industry/GDP	+
			Added value of tertiary industry/GDP	+
		Urban-rural structure	Urban population/total population	+
	Sustainable Economic Development	Innovation drives	Expenditure on science and education/local general budget	+
		Foreign trade openness	Actual use of foreign capital in the current year/gross domestic product	+
		Economic efficiency	Disposable income of urban and rural residents	+
		Economic vitality	Per capita GDP growth rate	+
		Capital productivity	GDP/Total Fixed Asset Investment	+
Urban Ecological Resilience	Pressure	Industrial wastewater discharge	Industrial wastewater discharge/GDP	-
		Air pollution	Industrial sulfur dioxide emissions/GDP	-
			Industrial particulate matter emissions/GDP	-
	State	Self-purification status	Green coverage rate in built-up areas	+
		Environmental conservation status	Park green space area per capita	+
	Response	Environmental remediation capacity	Harmless treatment rate of household waste	+
		Comprehensive use capacity	Comprehensive utilization rate of general industrial solid waste	+
		Wastewater treatment capacity	Centralized treatment rate of sewage treatment plants	+

$$e_j = -k\sum_{i=1}^{m}[(Y_{ij}/\sum_{i=1}^{m}Y_{ij})\cdot\ln(Y_{ij}/\sum_{i=1}^{m}Y_{ij})],\ k=\frac{1}{\ln m} \quad (4)$$

$$W_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (5)$$

Here, e_j is the information entropy, and Y_{ij} is the value of Z_{ij} after data translation to avoid zero values in entropy calculations.

The fourth step involves constructing the weighted matrix (*R*).

$$R=(r_{ij})_{m\cdot n}, r_{ij}=W_j\times Y_{ij} \quad (6)$$

The fifth step establishes the best (t_i^+) and worst solutions (t_i^-)

$$t_i^+=\max(r_{ij}), t_i^-=\min(r_{ij}), (1\le i\le m, 1\le j\le n) \quad (7)$$

In the sixth step, the Euclidean distance of each scenario is calculated for the ideal and anti-ideal solutions (T_i^+), (T_i^-).

$$T_i^+=\sqrt{\sum_{i=1}^{m}(t_j^+-r_{ij})^2}, T_i^-=\sqrt{\sum_{i=1}^{m}(t_j^--r_{ij})^2} \quad (8)$$

Finally, the comprehensive evaluation index *(U_{ij})* is calculated.

$$U_{ij}=\frac{T_i^-}{T_i^+-T_i} \quad (9)$$

In the Equation, U_{ij} represents the comprehensive evaluation index, ranging from 0 to 1. A higher value indicates a higher level of economic development quality and urban ecological resilience, whereas a lower value implies a lower level of development.

Coupling Coordination Degree

A coupling coordination degree is employed to assess the level of coordinated development between different regions, identify regions with imbalanced development, and promote coordination and integrated development between regions [36]. This model is introduced to reflect the overall level of coordinated development between the two systems, and the calculation Equation is as follows [37]:

$$D = \sqrt{C \times T}, T = \alpha U_1 + \beta U_2 \tag{10}$$

In the Equation, U_1 and U_2 are indicators of the quality of economic development and urban ecological resilience, respectively; T represents the comprehensive evaluation index of the two systems; D denotes the coupling coordination degree of the two systems; C represents the coupling degree of the two systems; and α and β are undetermined coefficients. Based on relevant research findings and practical results of this study, both factors are found to have an equal effect; hence, α and β are both assigned a value of 0.5. According to a previous study [38], the coupling coordination degree is classified into ten types with three levels based on magnitude (Table 2).

Table 2. Coupling coordination degree classification.

Coupling Coordination Range	Coupling Coordination Type	Level
0 ≤ D < 0.1	Extreme imbalance	Maladaptive decline type
0.1 ≤ D < 0.2	Severe imbalance	
0.2 ≤ D < 0.3	Moderate imbalance	
0.3 ≤ D < 0.4	Mild imbalance	
0.4 ≤ D < 0.5	On the verge of imbalance	Transition type
0.5 ≤ D < 0.6	Coordinate reluctantly	Coordinated development
0.6 ≤ D < 0.7	Basic coordination	
0.7 ≤ D < 0.8	Intermediate Coordination	
0.8 ≤ D < 0.9	Good coordination	
0.9 ≤ D < 1	High-quality coordination	

Kernel Density Estimation

Kernel density estimation is a nonparametric statistical method proposed by Rosenblatt [39]. It is employed to estimate the probability density function of continuous random variables. This method uses sample data to estimate the probability density function without relying on specific assumptions. This study introduces this method and draws the kernel density curve of the coupling coordination degree between economic development quality and urban ecological resilience in the Yangtze River Economic Belt. Then, the distribution dynamics and evolutionary characteristics of the coupling coordination level in this region are analyzed. The calculation Equation is as follows [40]:

$$G_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right) \tag{11}$$

Here, $G_{h(x)}$ represents the kernel density estimate; n is the number of cities in the study area; h is the bandwidth; x is the mean of the observed values; x_i represents independently and identically distributed observed values; and K is the kernel function. The Gaussian kernel function is selected in this study.

Spatial Autocorrelation Models

Spatial autocorrelation models can measure the spatial structure and clustering degree of attribute data for spatial units, which are divided into global and local autocorrelations. Global autocorrelation indicators reflect the degree of correlation of attribute values between regions and their spatial neighbors, probing the overall spatial patterns in the study area. Local autocorrelation indicators reveal the degree of correlation of attribute values between each spatial unit and its neighbors. The calculation Equation is as follows [41]:

Global Moran's index: $$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}(X_i - \bar{X})(X_j - \bar{X})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}} \tag{12}$$

Local Moran's index: $$I_i = \frac{(X_i - \bar{X})}{S^2} \sum_j C_{ij}(X_i - \bar{X}) \tag{13}$$

Here, n is the number of cities in the study area; X_i and X_j are the attribute values of regions i and j, respectively; and C_{ij} is the spatial weight matrix in the study area, representing the degree of influence between spatial units i and j. The range of I is between [−1, +1], and values greater than 0 indicate a positive spatial correlation between units. The closer I is to 1, the stronger the positive correlation between units. A value of 0 indicates no spatial correlation between units, whereas values less than 0 indicate a negative spatial correlation between units. The closer I is to −1, the stronger the negative correlation between units.

Dagum Gini Coefficient and Its Decomposition

The Dagum Gini coefficient method proposed by Dagum [42] can effectively measure regional disparities. Compared with traditional Gini coefficients, coefficients of variation, and Theil indices, the Dagum method provides a more accurate reflection of differences within and between regions. Additionally, it can precisely measure the contribution of regional disparities to overall differential changes [43]. The overall Gini coefficient is decomposed into three parts: the contribution of intraregional differences (G_w), the net contribution of interregional differences (G_{nb}), and the contribution of overdensity (G_t). This study adopts this method to calculate the spatial differences in the coupling coordination levels between the upstream, midstream, and downstream regions of the Yangtze River. The calculation Equation is as follows [44]:

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji} - y_{hr}|}{2n^2\delta} = G_w + G_{nb} + G_t \tag{14}$$

Here, G represents the overall Gini coefficient; k is the number of divided regions; n is the number of cities in the study area; n_j and n_h represent the number of cities in regions j and h, respectively; δ is the average coupling coordination degree of economic development quality and urban ecological resilience in the Yangtze River Economic Belt; j and h denote the defined regions; i and r denote cities within the defined regions; and y_{ji} and y_{hr} represent the coupling coordination levels of city i in region j and city r in region h, respectively.

$$G_{jj} = \frac{\frac{1}{2\delta}\sum_{i=1}^{n_j}|\sum_{r=1}^{n_j}|y_{ji} - y_{hr}|}{n_j^2} \tag{15}$$

$$G_{jh} = \sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\frac{|y_{ji} - y_{hr}|}{n_j n_h(\delta_j + \delta_h)} \tag{16}$$

Here, G_{jj} represents the Gini coefficient within a region; G_{jh} represents the Gini coefficient between regions; δ_j and δ_h are the average levels of coupling coordination in regions j and h, respectively; and $|y_{ji}-y_{hr}|$ denotes the absolute difference in coupling coordination levels between city i in region j and city r in region h.

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{17}$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{k=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)\ D_{jh} \tag{18}$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)\ (1- D_{jh}) \tag{19}$$

Here, G_w represents the contribution of within-region differences; G_{nb} represents the net value contribution of between-region differences; G_t represents the contribution of supervariable density; p_j denotes the proportion of the number of cities in region j to the total number of cities; s_j represents the proportion of the degree of coupling coordination in region j to the total degree of coupling coordination of all cities in the sample; and D_{jh} denotes the relative influence of the coupling coordination level between regions j and h.

$$D_{jh} = \frac{d_{jh} - p_{jh}}{d_{jh} + p_{jh}} \tag{20}$$

$$d_{jh} = \int_0^{\infty} dF_j(y)\int_0^{y}(y-x)dF_h(x) \tag{21}$$

$$p_{jh} = \int_0^{\infty} dF_h(y)\int_0^{y}(y-x)dF_j(x) \tag{22}$$

Here, d_{jh} represents the total impact of the coupling coordination level between regions j and h; p_{jh} denotes the supervariation first moment between regions j and h; and F is the cumulative density function of the degree of regional coupling coordination.

Results

Temporal Characteristics of the Coupling Coordination Relationship between Economic Development Quality and Urban Ecological Resilience

Temporal Evolution Characteristics

According to the results of the coupling coordination model (Fig. 2), the coupling coordination degree of the Yangtze River Economic Belt shows an upward trend from 2011 (0.439) to 2021 (0.561). This trend indirectly reflects the close connection between the quality of regional economic development and urban ecological resilience. Improved economic development quality enhances urban ecological resilience, and the level of urban ecological resilience is a reflection of the quality of economic development; the higher the urban ecological resilience, the higher the economic development. However, due to the extensive area covered by this study and the comprehensive influence of natural endowment and policies, significant differences are observed in the coupling coordination degrees of the upper, middle, and lower regions of the Yangtze River Economic Belt. In descending order, the coupling coordination degree is lowest upstream, significantly lower than the overall

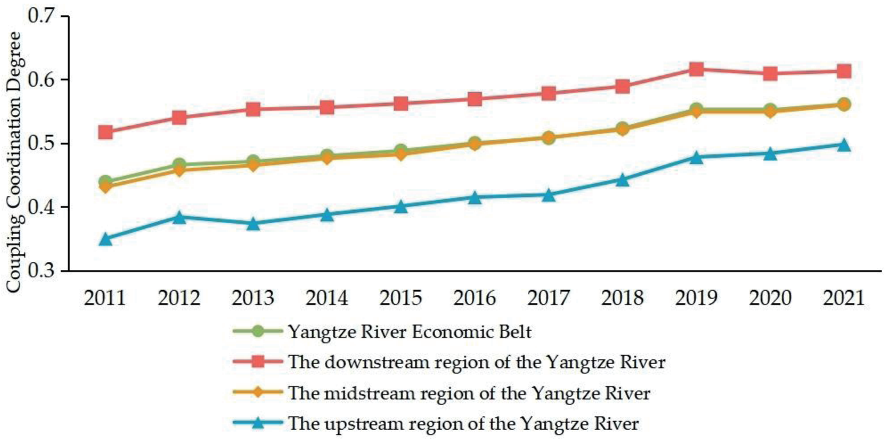

Fig. 2. Time-varying coupling coordination degree.

level, and highest downstream, significantly higher than the overall level; further, the middle region's coupling coordination degree is almost consistent with the overall level. This indicates spatial heterogeneity in the coupling coordination degree of economic development quality and urban ecological resilience in the Yangtze River Economic Belt.

Dynamic Evolution Characteristics

To further understand the dynamic evolution of the coupled and coordinated relationship between economic development quality and urban ecological resilience, the kernel density estimation method was employed to generate kernel density plots for the coupling coordination levels. As depicted in Fig. 3, the dynamic evolution of the coupling coordination level in the Yangtze River Economic Belt from 2011 to 2021 exhibits two characteristics. In terms of spatial distribution, the center of the kernel density curve shows a rightward trend, indicating that the coupling coordination between economic development quality and urban ecological resilience has gradually strengthened with the development of the socioeconomy and increased attention to the ecological environment. In terms of the distribution pattern, the shape of the main peak changes from flat and wide to sharp and narrow, and the peak value gradually increases. The transition from double peaks to a single peak indicates a tendency toward diminishing absolute differences in the coupling coordination level of the Yangtze River Economic Belt, displaying dynamic convergence characteristics. Overall, the coordinated role between the economic development quality and urban ecological resilience in the Yangtze River Economic Belt continues to strengthen. The development disparities between various cities are narrowing, indicating that the comprehensive promotion of high-quality development in China highlights its ecologically oriented core position and gradually enhances the coordination between economic development and ecological sustainability.

Spatial Characteristics of High-quality Development of the Yangtze River Economic Belt and Coupling Coordination with Urban Ecological Resilience

Spatial Evolution Characteristics

As depicted in Fig. 4, spatial differences are observed in the coupling coordination types of economic development quality and urban ecological resilience in the Yangtze River Economic Belt at the urban scale from 2011 to 2021, as described below:

First, in 2011, most cities in the Yangtze River Economic Belt were in a state of imbalanced decline. Of them, one city (0.91%), Chenzhou, located in the southern part of the middle reaches, experienced severe imbalance. There were 40 (36.36%) cities with moderate and mild imbalance, mainly distributed in the southwestern part of the upper reaches. Further, 32 (29.09%) cities were on the verge of imbalance, concentrated in the western and northern parts of the middle reaches. Cities with reluctantly coordinated and basic coordination types totaled 37 (33.64%), forming clusters in the lower reaches with sporadic distribution in the northeastern part of the upper reaches and the southeastern part of the middle reaches.

Second, in 2014, transition and coordinated development types became dominant in the transformation of urban coupling coordination. Of them, 32.73% of the cities were classified under the transition type, mainly concentrated in the northern part of the middle and upper reaches. Five cities, namely, Suqian, Jinhua, Taizhou, Zhangjiajie, and Guiyang, rose to the category of barely coordinated development, accounting for 26.36% of this type of city. Shanghai and Chongqing transitioned to intermediate coordination cities. The proportion of cities in the disordered decline type was 25.45%, a decrease of 10.91% compared to 2011; these cities were mainly concentrated in the western part of the upper and middle reaches.

Third, from 2014 to 2018, the State Council issued policies such as the "Guiding Opinions on Promoting

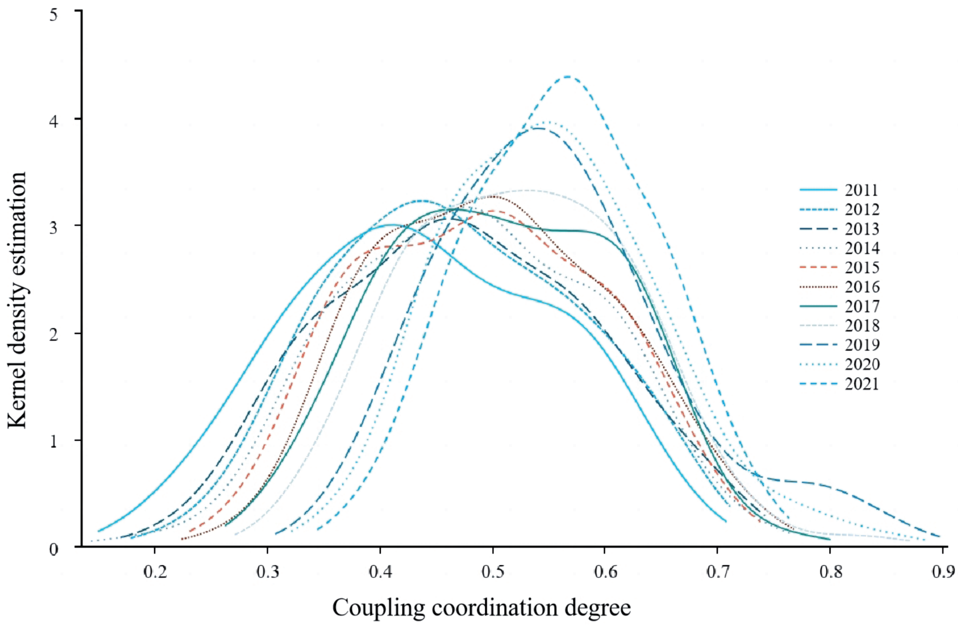

Fig. 3. Kernel density estimation of the coupling coordination degree.

the Development of the Yangtze River Economic Belt by Relying on the Golden Waterway" and the Outline, outlining the development pattern of the Yangtze River Economic Belt as one with "one axis, two wings, three poles, and multiple points." The quality of economic development and urban ecological resilience has improved to varying degrees. The coupling coordination levels between the two have continuously increased, gradually entering a stage of coordinated development. In 2018, the proportion of mildly imbalanced cities was only 9.10%, scattered mainly in the upstream southwest. Cities on the verge of imbalance accounted for 34.55% of the total, whereas barely coordinated and primarily coordinated cities accounted for 52.73%. Shanghai, Suzhou, and Chengdu were classified as intermediate coordinated cities, and Chongqing was considered a well-coordinated city.

Finally, from 2018 to 2021, with the establishment of a more effective mechanism for regional coordinated development in the Yangtze River Economic Belt, the degree of coupling coordination between economic development quality and urban ecological resilience continued to improve. In 2021, cities in the Yangtze River Economic Belt primarily exhibited a coordinated development pattern. Of them, 70.91% of cities were barely coordinated and primarily coordinated, predominantly distributed in the middle and lower reaches. Cities in the upper reaches, such as Zhaotong and Lincang, belonged to the mildly imbalanced category. Cities on the verge of imbalance accounted for 24.54% of the total, mainly distributed in the southwestern part of the upper reaches and the northern part of the middle reaches. Shanghai, Wuhan, and Chengdu belonged to the intermediate coordination category. Overall, in terms of the economic development quality and coupling coordination of urban ecological resilience in the Yangtze River Economic Belt, the predominant shift was from the imbalanced and declining type to the coordinated development type. The hierarchical spatial pattern of "lower reaches>middle reaches>upper reaches" did not undergo any significant change.

Spatial Agglomeration Characteristics

To determine the spatial agglomeration characteristics of the coupling coordination level between economic development quality and urban ecological resilience in the Yangtze River Economic Belt, the global Moran's I value of the coupling coordination degree in the study period was calculated using spatial autocorrelation methods. Table 3 indicates that the global Moran's I values corresponding to the coupling coordination levels in the study area for each year are all greater than 5.975 and pass the significance test at the 0.001 level. This indicates significant spatial agglomeration in the coupling coordination levels of economic development quality and urban ecological resilience in the Yangtze River Economic Belt. Thus, cities with higher coupling coordination levels tend to be relatively concentrated, and those with lower coupling coordination levels also exhibit a relative concentration. From 2011 to 2021, the global Moran's I value of the coupling coordination degree in the study area decreased from 0.493 to 0.446. This indicates a certain degree of spatial agglomeration in the coupling coordination between cities in the Yangtze River Economic Belt. However, this agglomeration tendency is weakening, implying that cities with high and low coupling coordination tend to be spatially adjacent.

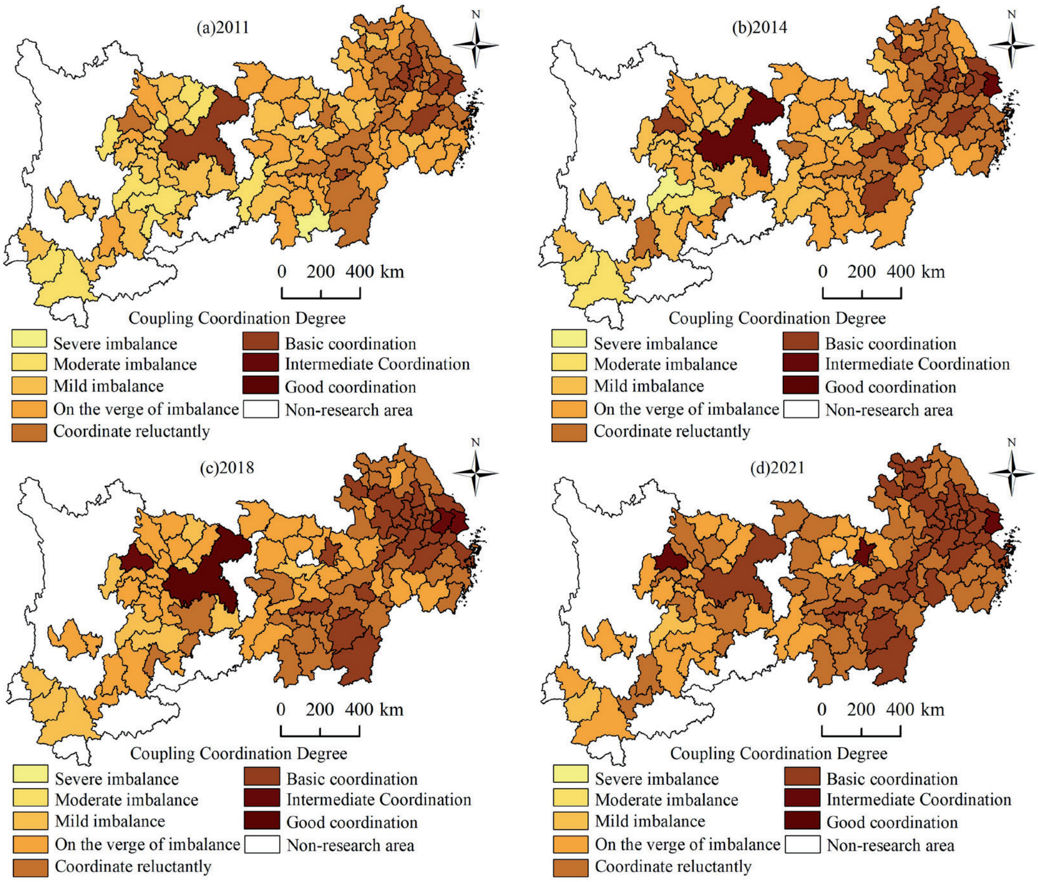

Fig. 4. Spatial evolution of the coupling coordination degree.

Table 3. Global Moran's I value of the coupling coordination level.

Year	Moran's I	*Z*-value	*P*-value	Year	Moran's I	*Z*-value	*P*-value
2011	0.493	7.828	0.001	2017	0.467	7.189	0.001
2012	0.441	7.188	0.001	2018	0.460	7.131	0.001
2013	0.371	5.975	0.001	2019	0.466	7.147	0.001
2014	0.442	6.865	0.001	2020	0.432	6.774	0.001
2015	0.498	7.873	0.001	2021	0.446	6.927	0.001
2016	0.453	7.074	0.001				

Using the local spatial autocorrelation model, we computed the local Moran's I values for the coupling coordination level between the quality of economic development and urban ecological resilience and categorized them into four spatial agglomeration types: high–high, high–low, low–high, and low–low. As depicted in Fig. 5, discernible spatial variations are found in the agglomeration patterns of the coupling coordination level. High–high agglomeration areas are mainly concentrated in the downstream Yangtze River Delta region, gradually forming a high–high agglomeration spatial pattern centered on Shanghai in 2021. The cities in this region rely on resource endowments to establish a rational industrial structure in order to drive social and economic green transformation. This enhances urban ecological resilience and promotes high-quality economic development. Consequently, a virtuous interaction emerges between high-quality economic development and urban ecological resilience.

Moreover, these cities stimulate the development of surrounding cities, showing certain spatial spillover effects. Chongqing, Kunming, Chengdu, and other new first-tier cities belong to a high–low agglomeration cluster. These cities exhibit prominent features with regard to their economy and green development, and the coupling coordination level between the two aspects is relatively high. However, their radiating effects on surrounding cities are insufficient. Thus,

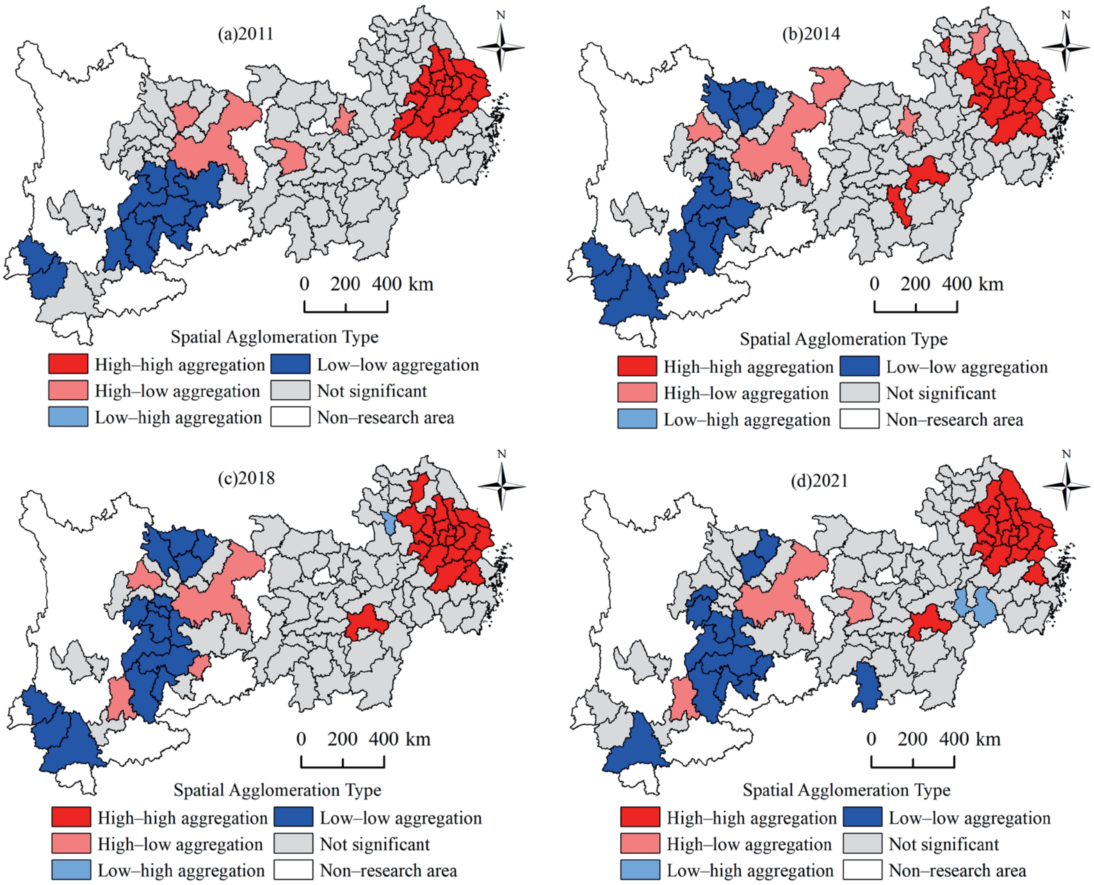

Fig. 5. Spatial agglomeration of coupling coordination levels.

these cities form a high–low developmental disparity with surrounding cities. In the low–high agglomeration category, only Huainan in 2018 and Shangrao in 2021 fit this agglomeration type. Huainan, which is located in the hinterland of the Yangtze River Delta, and Shangrao, which is adjacent to Zhejiang, exhibit a relatively high level of coordinated development with surrounding cities. However, no significant spillover effect is observed in these regions; to some extent, their development is constrained by the surrounding cities, resulting in a low–high spatial pattern. Low–low agglomeration areas are primarily located in relatively remote regions such as Bijie, Zunyi, and Zhaotong. These regions exhibit significant disparities in economic development quality and urban ecological resilience compared with more developed downstream regions. The low technological level of industrial development in these areas makes it challenging to attract innovative talent, thereby hindering robust support for green development [45]. Moreover, the relatively slow economic development influenced by various factors underscores the need to enhance regional coordinated development. Therefore, it is crucial to identify ways to strengthen the coordinated development of different types of cities, ensure efficient circulation of factors, and facilitate the appropriate allocation of resources. Maximizing the region's advantages is essential for simultaneously improving its quality of economic development and level of urban ecological resilience.

Spatial Difference Characteristics

The Dagum Gini coefficient decomposition is employed to measure the spatial difference characteristics of the coupling coordination between economic development quality and urban ecological resilience.

Intraregional Differences

As depicted in Fig. 6, the overall Gini coefficient of the coupling coordination between economic development quality and urban ecological resilience in the Yangtze River Economic Belt from 2011 to 2021 experienced a decreasing trend, dropping from 0.147 in 2011 to 0.081 in 2021, indicating a gradual reduction in the overall regional imbalance. This reduction is attributable to the implementation of the development strategy of the Yangtze River Economic Belt, which follows the principles of regional coordinated development, promoting the coordination and high-quality development of the upper, middle, and lower reaches of the region. Considering the evolution of differences in the three major regions, the greatest

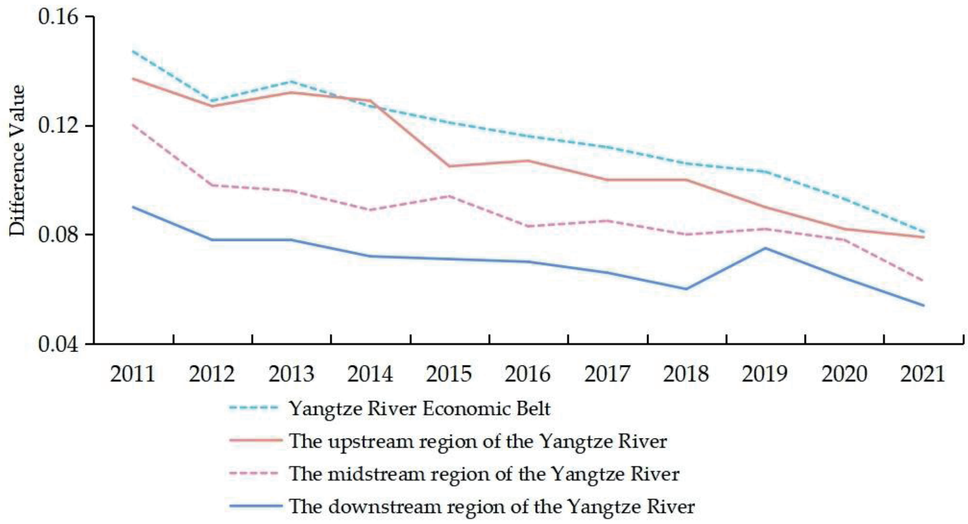

Fig. 6. Overall and regional disparities in the level of coupling coordination.

disparities are observed in the upstream region, followed by the midstream region; the downstream region exhibits the smallest differences. This trend indicates that the imbalance in the coupling coordination level is most severe upstream and the spatial imbalance is weakest downstream. This could be attributable to the presence of certain “polarization phenomena” in the upstream region. Representative provincial capitals such as Chongqing, Kunming, and Chengdu exert a siphon effect on surrounding cities, resulting in relatively large differences in coupling coordination levels in the upstream region. In contrast, the downstream region experiences a strong driving force from urban centers, resulting in higher levels of overall economic development and a more favorable ecological environment and contributing to smaller internal disparities in the region. In terms of temporal evolution, the coefficient of variation in the three major regions has experienced varying degrees of decline, indicating that internal coupling coordinated development in the upper, middle, and lower reaches of the Yangtze River has achieved certain results.

Regional Disparities

As depicted in Fig. 7, the largest difference exists between the upstream and downstream regions, with a mean value of 0.172. The difference between the upstream and midstream regions has a mean value of 0.129, whereas that between the midstream and downstream regions is the smallest and has a mean value of 0.099. This trend implies that regional differences in the quality of economic development and coupled coordination level of urban ecological resilience in the Yangtze River Economic Belt are mainly attributable to the disparity between the upstream and downstream regions. The significantly small difference between the midstream and downstream regions indicates a relatively close coupled coordination level between these regions, while a certain disparity remains between the midstream and upstream regions. From the perspective of temporal evolution, the overall differences between the three major regions display a decreasing trend. Moreover, the development disparities between different regions exhibit similar characteristics over time. The Gini coefficients between downstream and upstream regions, as well as between midstream and upstream regions, show a slight decline in 2012, followed by a brief increase. However, from 2013 to 2021, they demonstrate a consistent annual decline. Therefore, it is essential to accurately formulate and implement specific measures based on the developmental advantages of different regions to enhance the level of coordinated development of the three regions.

Sources and Contributions of Regional Disparities

As presented in Table 4 and Fig. 8, the contribution rate of interregional differences is the highest, with a mean value of 58.214%. The mean contribution rate of intraregional differences is 24.837%, whereas that of supervariable density is the lowest, with a mean value of 16.949%. This indicates that the spatial differences in the coupling coordination level of the Yangtze River Economic Belt are primarily attributable to interregional differences, followed by intraregional differences and supervariable density. From the perspective of temporal evolution, the contribution rate of interregional differences first increases and then decreases, whereas that of intraregional differences remains relatively stable at approximately 24%. Conversely, the contribution rate of supervariable density exhibits a more complex fluctuation pattern, displaying a W-shaped trend. Overall, regional disparities remain the primary factor influencing the differences in coupling coordination levels in the Yangtze River Economic Belt, and the issue

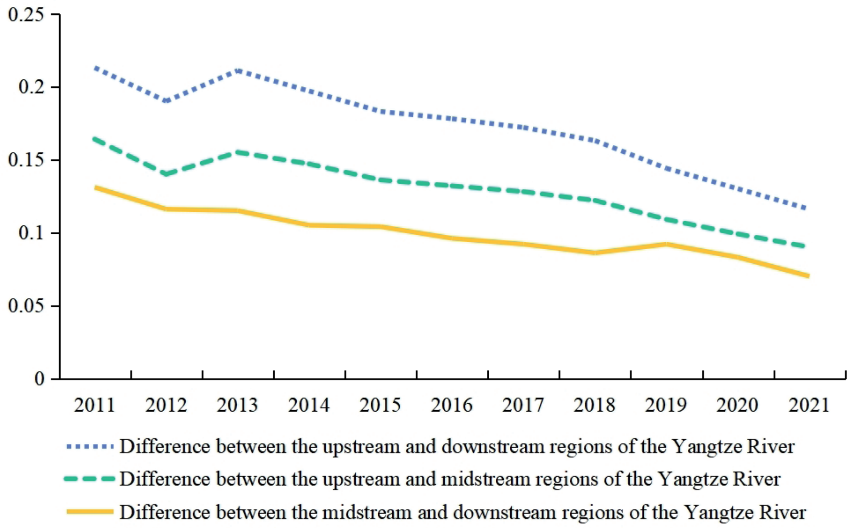

Fig. 7. Regional disparities in the coupling coordination level.

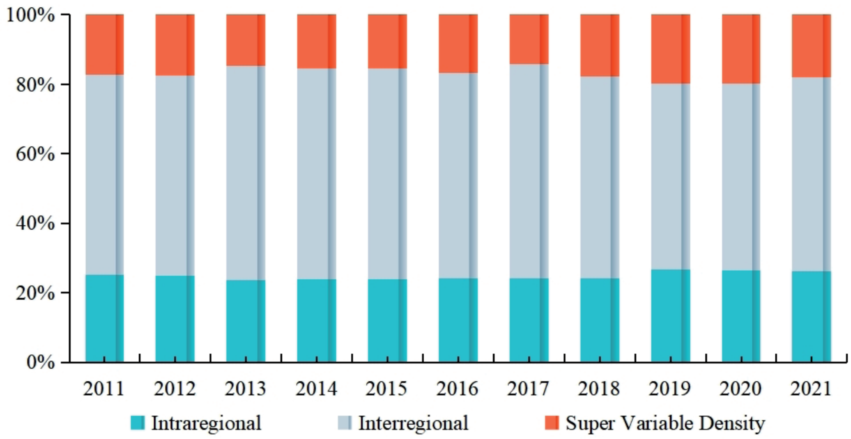

Fig. 8. Contribution rate of the coupling coordination level in regional disparities.

of overlapping samples has a relatively minor impact. In the future, to achieve high-quality coordinated development in the Yangtze River Economic Belt, greater attention should be paid to interregional differences.

Discussion

Research Significance

Considering the country's three major development strategies and global efforts to build a community with a shared future for humanity, the quality of economic development in the Yangtze River Economic Belt must be promoted and urban ecological resilience must be enhanced. Based on the administrative unit scale of prefecture-level cities, this study investigates the economic development quality and urban ecological resilience level of the Yangtze River Economic Belt. It constructs an economic development quality indicator system considering three dimensions – the scale of economic development, optimization of economic structure, and sustainability of economic development – building an urban ecological resilience index system from three dimensions: pressure, state, and response. On this basis, this study reveals the spatiotemporal pattern evolution and regional differentiation characteristics of the coupling coordination relationships between economic development quality and urban ecological resilience. The study aims to seek a balance between regional economic and ecological aspects, which has profound practical significance and provides critical research directions for future theoretical exploration.

From a practical perspective, an in-depth exploration of the interrelationships between the economy and urban ecosystems can help cities identify and implement sustainable resource utilization methods to prevent excessive resource consumption, enhance resource utilization efficiency, and facilitate high-quality

Table 4. Sources and contributions of regional disparities in coupling coordination levels.

Year	Regional Intradifferences		Regional Interdifferences		Super Variable Density	
	Difference	Contribution Rate (%)	Difference	Contribution Rate (%)	Difference	Contribution Rate (%)
2011	0.037	25.199	0.085	57.514	0.025	17.287
2012	0.032	24.922	0.074	57.483	0.023	17.594
2013	0.032	23.713	0.084	61.703	0.020	14.584
2014	0.03	23.860	0.078	60.808	0.020	15.332
2015	0.029	23.968	0.073	60.609	0.019	15.423
2016	0.028	24.133	0.068	59.043	0.019	16.823
2017	0.027	24.036	0.069	61.723	0.016	14.241
2018	0.026	24.157	0.062	58.163	0.019	17.680
2019	0.027	26.656	0.055	53.636	0.020	19.708
2020	0.025	26.418	0.050	53.880	0.018	19.702
2021	0.021	26.143	0.045	55.794	0.015	18.063
Mean	0.029	24.837	0.068	58.214	0.019	16.949

economic development. Next, an understanding of the differences in the coordinated economic development quality and urban ecological resilience in various regions can facilitate the rational planning of cities and industrial structures of different types. This approach aims to reduce the environmental burden and promote the sustainable development of cities. Finally, researching the coordinated development of the economy and ecology can improve the ability of cities and countries to respond to economic crises and environmental changes, thereby mitigating their impacts.

From a theoretical perspective, studying the relationship between economic development quality and urban ecological resilience can enable the establishment of a comprehensive theoretical framework. By enhancing our understanding of the interaction between the economy and ecology, we can further refine the theory of sustainable development. This research organically integrates economic, social, and ecological factors to provide theoretical support for achieving sustainable development. Moreover, the research findings enable the government to develop targeted economic and urban planning policies that align with actual needs, facilitating a strategic shift from traditional growth models to high-quality and strategic development of ecological civilization. Overall, investigating the coupled and coordinated relationship between economic development quality and urban ecological resilience contributes to the promotion of sustainable economic and social development and provides scientific theoretical support for future urban planning and national strategies.

Recommendations for Policymakers

To promote the coordinated development of economic quality and urban ecological resilience of the Yangtze River Economic Belt and leverage the role of pilot demonstration zones, the following suggestions are proposed.

First, the development of urban green industries, such as clean energy, energy conservation, environmental protection, and circular economy, should be encouraged and provided policy support by incentivizing businesses to transform into green and low-carbon industries. This approach can drive economic structural upgrading and achieve sustainable economic development. The protection and restoration of the ecological environment should be emphasized to enhance the resilience of urban ecosystems and achieve balanced development of the economy and ecology.

Second, policies should be tailored to local conditions in order to fully leverage the role of central cities. Significant regional disparities exist in the coordinated development level between economic development quality and urban ecological resilience, with considerable disparity between relatively underdeveloped and advanced cities. Therefore, it is essential to flexibly formulate and modify local economic development plans and environmental governance strategies according to the specific resources and environmental characteristics of each city. Targeted supportive policies should be implemented to facilitate the development of underdeveloped cities. Cities along the Yangtze River Economic Belt should rely on the golden waterway, leveraging the radiating and driving roles of central cities such as Shanghai, Wuhan, and

Chongqing. The spillover effects of these central cities can promote the development of surrounding cities, reduce intercity disparities, and drive overall coordinated regional development.

Finally, the integrated development approach must be adopted, and a pattern of complementary advantages and collaborative interactions should be fostered between the upper, middle, and lower reaches. Although coordinated development differences in the overall, upper, middle, and lower reaches of the Yangtze River Economic Belt have somewhat decreased in recent years, a certain degree of imbalance persists. Regional disparities remain a primary factor influencing collaborative development. The Yangtze River Economic Belt spans the three major regions of eastern, central, and western China, with significant disparities in development conditions, including resources, environment, economy, and industrial foundations. To promote the coordinated development of the Yangtze River Economic Belt, it is essential to develop strategies for each region, coordinate economic planning with resource and environmental carrying capacity, overcome market barriers caused by administrative bottlenecks, facilitate the free flow of factors between regions, effectively enhance economic vitality, mitigate ecological challenges, and promote mutually beneficial development in the region, thereby fostering a virtuous development cycle for the entire area.

Conclusions

This study utilizes various methods – entropy value-TOPSIS, coupling coordination degree model, kernel density estimation, spatial autocorrelation, and Dagum Gini coefficient decomposition – to investigate the spatiotemporal changes and regional differences in the coupling coordination relationship between economic development quality and urban ecological resilience in the Yangtze River Economic Belt from 2011 to 2021. The findings are as follows:

First, in terms of temporal changes, a close relationship is found between economic development quality and urban ecological resilience, with both factors interacting and influencing each other. The overall coupling coordination degree shows an increasing trend each year. The downstream region exhibits a significantly higher level of coupling coordination than other regions. Regarding dynamic evolution, the level of coordinated development is elevated, and the disparities in coordinated development between various cities continue to decrease.

Second, from the perspective of spatial evolution, the coupling coordination types of economic development quality and urban ecological resilience transition from a predominantly imbalanced and declining type to a predominantly coordinated development type. The spatial basic pattern of lower development level downstream and higher development level upstream does not undergo significant changes. Based on global spatial autocorrelation analysis, it is evident that the coupling coordination levels exhibit notable spatial agglomeration, which tends to weaken gradually. Local spatial autocorrelation analysis reveals the formation of a spatial pattern characterized by high–high agglomeration areas downstream and low–low agglomeration areas upstream.

Finally, from the perspective of regional disparities, the imbalances in the three major regions gradually decrease. However, regional coordinated development continues to exhibit differences, with the most pronounced disparities observed in the upstream region. Regarding interregional differences, the coupling coordination level experienced the highest variation between the upstream and downstream regions and the smallest difference between the midstream and downstream regions. Analysis of regional disparities and their contribution rates indicates that interregional differences are the primary factors influencing spatial variations in the coupling coordination level of the Yangtze River Economic Belt.

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Conflict of Interest

The authors declare no conflict of interest.

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