



OPEN Spatiotemporal characteristics and influential factors of coupling coordination degree of urbanization and ecological environment in the Huaihe River ecological economic belt

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The rapid development of urbanization in recent years has led to significant economic and social progress, but it has also resulted in a series of eco-environmental challenges. This study, based on an evaluation model of urbanization and eco-environment for the Huaihe Ecological Economic Belt, conducts a comprehensive analysis of the coupling coordination degree between the two from 2005 to 2020, explores spatial aggregation characteristics, and reveals the reasons for the uneven development of urbanization and the eco-environment. The results are as follows: (1) Between 2005 and 2020, both the development level of urbanization and the coupling coordination degree between urbanization and the eco-environment steadily increased. (2) Global spatial autocorrelation analysis shows that in 2005, urbanization and coupling coordination exhibited a strong positive correlation, which weakened over time, while the eco-environment displayed a random spatial distribution. Local autocorrelation analysis reveals that in 2005, urbanization showed significant spatial clustering in Shandong and Jiangsu provinces, but this clustering became more spatially dispersed over time. (3) In 2005, spatial urbanization was the main factor contributing to the uneven level of urbanization in the Huaihe Ecological Economic Belt. By 2020, population urbanization had become a relatively weak factor in cities such as Taizhou, Yancheng, and Pingdingshan. Regarding the eco-environment, ecological pressure was a prominent issue between 2005 and 2015, but by 2020, ecological pressure had weakened, and the eco-environmental state became a new area of concern. To promote sustainable development in the Huaihe Ecological Economic Belt, it is essential to strengthen the development of central cities such as Bengbu and Huai'an, retain talent, increase the urbanization rate, and implement effective environmental protection policies. These measures will contribute to the region's long-term ecological and urban sustainability.

Keywords Huaihe ecological economic belt, Urbanization, Eco-environment, Coupling coordination, Spatial autocorrelation

As urbanization continues to advance, China has achieved historic economic milestones, with its Gross Domestic Product (GDP) surpassing 100 trillion yuan¹. The Huaihe River, as China's third-largest river, plays a crucial strategic role in the country's ecological civilization efforts and serves as a vital ecological safeguard for achieving balanced and high-quality economic development^{2,3}. However, in the early stages of the reform and opening-up policy, urban development primarily focused on economic growth while often neglecting ecological

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conservation. Many cities engaged in unchecked pollutant emissions and deforestation^{4–6} posing risks to regional ecological security and, to some extent, constraining the sustainable development of both the economy and society. Consequently, the coordinated development of urbanization and the ecological environment has become a critical pathway and core focus for China's modernization and sustainable development^{7,8}.

Against the backdrop of intensifying global climate change and ecological crises, the issue of coupling coordination between urbanization and ecological environmental protection has drawn increasing⁹. Developed countries recognized the impact of urbanization on the ecological environment early on and have conducted systematic policy and research explorations. For instance, the European Union introduced the Green Deal¹⁰, which prioritizes green economy and carbon neutrality as core objectives to drive the transformation toward sustainable development. Meanwhile, developing countries are also actively seeking pathways to balance urbanization with ecological conservation. In the context of rapid industrialization and urbanization, achieving harmony between environmental protection and economic growth has become a global challenge. China, for example, has underscored the importance of ecological civilization and green development^{11,12}. However, despite these efforts, there remains a lack of effective quantitative research on the coordination between urbanization and ecological environments. Therefore, investigating the coupling coordination between urbanization and ecological environment in the Huaihe Ecological Economic Belt is not only essential for guiding high-quality and differentiated development in this region but also serves as a valuable reference for sustainable development in similar regions worldwide.

Current research on urbanization and the ecological environment primarily focuses on the measurement of each aspect and their interrelationship. The mainstream measurement of urbanization is often based on the proportion of the non-agricultural population within the total population. However, this approach is overly simplistic, as urbanization also encompasses spatial expansion, socio-economic transformation, and other dimension^{13–15}. Consequently, various urbanization measurement methods have emerged, such as the Urban Expansion Intensity Index¹⁶ and the Urban Expansion Coefficient¹⁷. In terms of ecological environment assessment, key indicators include land surface temperature^{18–21}, urban land-use changes^{22,23}, and environmental pollution^{24,25}. However, given the complexity and diversity of urban ecological environments, a single-dimensional approach cannot fully capture their composition and impact. To address this, scholars have proposed integrated models such as the Remote Sensing Ecological Index (RSEI)^{26,27} and the Ecological Environmental Effects of Urban Expansion (EEUS)^{28,29}, which provide a more comprehensive evaluation of ecological conditions. Regarding the relationship between urbanization and the ecological environment, early theories, such as the Garden City Theory from the early 20th century^{30,31}, emphasized achieving harmony between urban development and ecological sustainability through proper planning. In the 21st century, the Organization for Economic Co-operation and Development (OECD) introduced decoupling theory to describe the intrinsic relationship between economic growth and resource consumption³². Some scholars have developed models to assess the impact of urban spatial expansion on regional physical geography, environmental factors, and natural disasters³³. Additionally, concepts such as the ecological footprint³⁴ and urban metabolism³⁵ have gained traction, reflecting global academic interest in the interplay between urbanization and ecological sustainability. Collectively, these theoretical advancements offer valuable insights into achieving sustainable urban development. However, research specifically examining the coupling coordination between urbanization and ecological environments remains relatively limited. Most existing studies focus on administrative units such as provinces and cities, with little attention given to ecological strongholds as a whole. From a research perspective, there is a noticeable gap in studies addressing regions that are both economically underdeveloped and ecologically fragile. Yet, in the process of urbanization, balancing urban expansion with ecological sustainability is of paramount importance. As a critical ecological security barrier in China, the Huaihe Ecological Economic Belt has experienced accelerated urbanization in recent years, accompanied by notable progress in economic performance and infrastructure development^{36,37}. However, this process has also led to environmental degradation and a reduction in available natural resources^{33,34}, posing significant challenges to the region's long-term sustainability. Therefore, there is an urgent need for an in-depth evaluation of the coordination between urbanization and ecological environments in the Huaihe Ecological Economic Belt to provide insights for achieving sustainable regional development.

In this regard, this study selects 29 cities and counties within the Huaihe Ecological Economic Belt in China as the fundamental research units. Urbanization is assessed through four primary dimensions: population urbanization, spatial urbanization, economic urbanization, and social urbanization, which serve as key indicators for evaluating regional urbanization levels. For ecological environment assessment, indicators are derived from the Pressure-State-Response (PSR) model, with their respective weights determined using the entropy weight method. The coupling coordination model is then employed to evaluate the interaction between urbanization and the ecological environment within the Huaihe Ecological Economic Belt. To enhance the clarity of the evaluation results, GIS technology is utilized for spatial visualization. Furthermore, the Moran's Index is applied to investigate potential spatial autocorrelation between the two systems and to identify underlying causes of developmental imbalances. This study provides a novel empirical basis for understanding the relationship between urbanization and the ecological environment. Additionally, it offers theoretical insights into achieving a coordinated approach to urbanization and ecological conservation, particularly for ecological strongholds in developing countries such as China and India.

Materials and methods

Studying area

Huaihe Ecological Economic Belt is defined by the main stream of the Huaihe River, its primary tributaries and the area through which the downstream water system flows, including 24 cities and 4 counties, covering an area of 243,000 km², as shown in Fig. 1. It is located in the north-south climate transition zone of China, with rich and diverse biological species, precipitation seasonal changes and interannual changes, and low terrain,

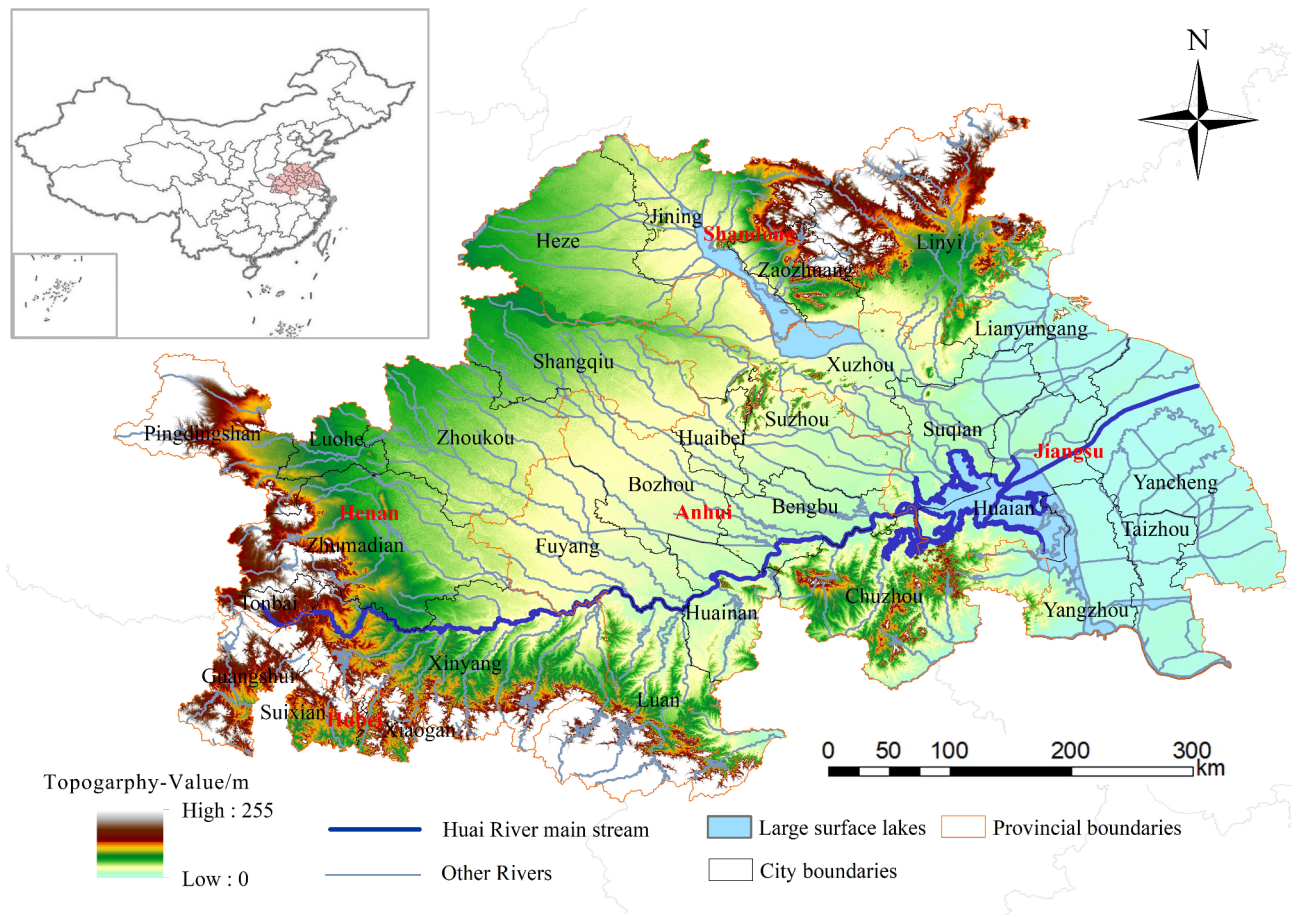


Fig. 1. Location and geographical overview of the study area (Source; ASTER-GDEM-V2 30 m, <https://search.earthdata.nasa.gov/search>, created with ArcGIS 10.6).

many tributaries, and complex surface water system³⁸. Meanwhile, Huaihe Ecological Economic Belt is located between the Yangtze River Basin and the Yellow River Basin, connecting the central-eastern part of China and the Yangtze River. The Huaihe River system is navigable up to 2300 km, but the socio-economic development of the region still has a certain gap compared to other watershed ecological strong-holds such as the lower reaches of the Yangtze River. The financial resources for eco-environment are less than other regions, at the same time, there are 43 fragile ecological zones³⁹. If the ecology of the Huaihe River Basin is destroyed, it will directly damage the environmental situation of the Huaihe River Basin and other watersheds as well as the nearby sea areas of China. Therefore, it is urgent to observe and evaluate the coupling coordination degree between the level of urbanization and eco-environment in the Huaihe Ecological Economic Belt, so as to provide a reference for governments to optimise the ecological pattern of the region or other watershed ecological strongholds in the world.

Data

In consideration of the availability and completeness of the data, the study has positioned the research period from 2005 to 2020, and the data of each indicator is mainly obtained from the statistical yearbooks of the city⁴⁰, provincial statistical yearbooks and Chinese statistical yearbooks in previous years. In order to obtain sufficient data, some of the data that cannot be found in the statistical yearbooks are obtained by searching the official website, the relevant statistical bulletin, annual reports of the related functional department or directly consulting the department.

Methods

Weight calculation method

In the evaluation system, the indicators are diverse and have a large numerical gap, so the entropy weighting method was used to determine the proportion of each indicator within the respective system⁴¹, which is based on the change of values to determine the weight. This way is objective.

Firstly, in order to avoid differences due to different units and magnitudes of the indicators, the extreme value method is used to standardise the indicators. Secondly, in order to make the comparison obvious, the study is carried out on a time series⁴². Different formulas were used for the treatment of positive and negative indicators, as shown below respectively.

$$V_{ij} = [r_{ij} - \min(r_{ij}) / \max(r_{ij}) - \min(r_{ij})] + 0.0001 \quad (1)$$

$$V_{ij} = [\max(r_{ij}) - r_{ij} / \max(r_{ij}) - \min(r_{ij})] + 0.0001 \quad (2)$$

where V_{ij} is the standardised value and r_{ij} is the original value of the indicator⁴³.

The standardised data is then normalised and the entropy value of the j th indicator is calculated using the formulae shown below.

$$P_{ij} = V_{ij} / \sum_{i=1}^m V_{ij} \quad (3)$$

$$e_j = -\frac{1}{\ln m} \times \sum_{i=1}^m P_{ij} \times \ln P_{ij} \quad (4)$$

where P_{ij} is the normalized indicator data after normalization, e_j is the entropy value of the indicator, and m is the data set, which is the number of data sets being four in this study⁴⁴.

The formula for calculating the weight of each indicator is:

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

Where W_j is the weight value of the j th indicator⁴⁵, while the V_{ij} value used in the calculation of the weight is the average value of the indicators within the Huaihe Ecological Economic Belt.

The development index can estimate the development of each system on its own, and the formula is shown below:

$$U(E) = \sum_{j=1}^n W_j \times V_{ij} \quad (6)$$

Where U and E represent the urbanization development index and eco-environment development index of the Huaihe Ecological Economic Belt respectively⁴⁶.

Indicator system and weights

In order to accurately evaluate the coupling relationship between urbanization and the eco-environment in the Huaihe Ecological Economic Belt, 17 indicators were selected at the level of urbanization system and 13 indicators at the level of eco-environment system, based on the principles of scientificity and feasibility of indicator selection, with reference to existing studies and according to the characteristics of the Huaihe Ecological Economic Belt itself^{14,46–50}. The weight of each indicator in the respective system was also calculated by the entropy weighting method. The details are shown in Table 1.

Coupling coordination degree model

The coupling coordination degree model can reflect the degree of mutual influence and relationship between urbanization and eco-environmental system layers⁵¹. The larger the coupling coordination degree is, the better coupling between the various system layers is. The formula for calculating the degree of coupling coordination is shown below:

$$D = \sqrt{C \times T} \quad (7)$$

Where D is the coupling coordination between the two system layers; C is the coupling degree of the system layers (the larger the value of C is, the stronger the coupling between the two system layers is)⁴⁷;

T is the integrated coordination degree. the formulae for C and T are shown below:

$$C = \sqrt{(U \times E) / [(U + E) / 2]^2} \quad (8)$$

$$T = \alpha \times U + \beta \times E \quad (9)$$

Where U and E represent the comprehensive evaluation index of urbanization and eco-environment respectively; α and β are the relative importance between the two system layers. According to previous research results, α and β are both set at 0.5 in this paper, representing the equal importance, and the specific division standards are shown in Table 2^{8,49}.

Although the coupling coordination degree can reflect the level of coupling and coordination between urbanization and eco-environment, it is limited to reflect the relative development between the two, therefore, the article follows the relative development model to reflect the relative development of urbanization and eco-environment⁸. The model formula is shown in formula 10.

System layer	Rule layer	Basic-level index	Property	Weighting values
Index system for urbanization	Population urbanization	Population density in urban areas (person/km ²)	+	0.035
		Urban population (%)	+	0.066
		Share of employment of tertiary industry (%)	+	0.013
		natural growth rate of population (‰)	+	0.026
	Economic urbanization	GDP per capita (USD)	+	0.093
		Proportion of tertiary industry in GDP (%)	+	0.044
		GDP (USD)	+	0.085
		Engel coefficient of urban residents (%)	-	0.026
		urban per capita disposable income (USD)	+	0.055
	Spatial urbanization	Area of public green area (ha)	+	0.077
		Urban road area per capita (m ²)	+	0.044
		Urban built-up area (km ²)	+	0.070
	Social urbanization	Urban residential housing area per capita (m ²)	+	0.044
		Number of mobile phone subscriber devices per 1000 population	+	0.030
		Number of beds in medical institutions	+	0.073
		Number of vehicles operating on public buses (trams)	+	0.092
		Number of schools	+	0.126
Index system for eco-environment	Eco-environmental pressure	Total industrial wastewater discharge (t)	-	0.015
		Total industrial solid waste generation (t)	-	0.027
		Industrial SO ₂ emissions (t)	-	0.015
		Industrial dust emissions (t)	-	0.024
	Eco-environmental status	Greenery coverage in built-up areas (%)	+	0.100
		Area of landscaped areas in built-up areas (ha)	+	0.088
		Residential household water consumption (t)	-	0.013
		Actual forest land area at the end of the year (ha)	+	0.194
		Electricity consumption of the whole society (kWh)	-	0.028
	Eco-environmental response	Integrated utilization rate of industrial solid waste(%)	+	0.017
		Urban domestic sewage treatment rate (%)	+	0.022
		Industrial SO ₂ removal (t)	+	0.225
		Newly planted forest area (ha)	+	0.230

Table 1. Indicator system and weighting values of Huaihe ecological economic belt.

System layer	Rule layer	Relative development status
Highly coordinated	Advanced coordination (0.8 < D ≤ 1.0)	Eco-environment development lag (R > 1.1)
		Urbanization development lag (R < 0.9)
		Balanced development (0.9 < R < 1.1)
Transition period	Moderate coordination (0.6 < D ≤ 0.8)	Eco-environment development lag (R > 1.1)
		Urbanization development lag(R < 0.9)
		Balanced development (0.9 < R < 1.1)
	Low coordination (0.4 < D ≤ 0.6)	Eco-environment development lag (R > 1.1)
		Urbanization development lag (R < 0.9)
		Balanced development (0.9 < R < 1.1)
Uncoordinated	Moderate imbalance (0.2 < D ≤ 0.4)	Eco-environment development lag (R > 1.1)
		Urbanization development lag (R < 0.9)
		Balanced development (0.9 < R < 1.1)
	Severe imbalance (0 < D ≤ 0.2)	Eco-environment development lag (R > 1.1)
		Urbanization development lag (R < 0.9)
		Balanced development (0.9 < R < 1.1)

Table 2. Classification of coupling coordination levels.

$$R = U/E \tag{10}$$

where R is the relative development degree of urbanization and ecology.

Spatial autocorrelation

Spatial autocorrelation can be mainly divided into global autocorrelation and local autocorrelation. Firstly, global spatial autocorrelation analysis is mainly used to explore the degree of similarity of the spatially adjacent study units of the study object and whether the study units are correlated; while local spatial autocorrelation analysis can be used to verify whether there is clustering in space⁵². The Moran index is used in this study for the analysis, and the formulae are calculated as follows respectively.

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n w_{ij} (x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^n \sum_{j=1}^n w_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} \tag{11}$$

$$I_i = \frac{n (x_i - \bar{x}) \sum_{j=1}^n w_{ij} (x_j - \bar{x})}{\sum_{i=1}^n (x_i - \bar{x})^2} \tag{12}$$

where I is the global Moran index; I_i is the local Moran index; x_i is the measure of statistical unit i, i.e. the degree of coordination between urbanization and eco-environment coupling, and is the average of the measures; w_{ij} represents the spatial weight matrix.

When I>0 indicates that the coupling and coordination of urbanization and ecology in the study area shows spatial positive correlation, when I<0 indicates spatial negative correlation, and when I=0, spatial randomness. If I_i is positive, the statistical unit shows high or low spatial agglomeration around the unit, and if I_i is negative, it means that the statistical unit shows high or low spatial agglomeration around the unit.

Results
Comprehensive evaluation of urbanization and eco-environment

Level of urbanization development

During the period 2005–2020, the urbanization in the Huaihe Ecological Economic Zone advanced at a very fast pace, for example, the average urban population per city increased from 34.32 to 56.24%, the proportion of people employed in the tertiary sector per city rose from 31.78 to 44.48%, the average number of beds in medical institutions per city rose from 11,155 to 34,395, the total area of builtup urban areas in the region rose from 2107.81 to 5068.43 km², etc. This shows that the Huaihe Ecological Economic Belt has made a leap from low to high urbanization level during the study period.

The urbanization system layer is divided into four rule layers, of which the one with the greatest weighting values is social urbanization (0.313), followed by economic urbanization (0.292), population urbanization (0.222) and spatial urbanization (0.173), as shown in Table 3, overall, the Huaihe Ecological Economic Belt’s urbanization level rose from 0.088 to 0.888, a tenfold increase. Among these, economic urbanization increased the most, from 0.001 to 0.293, until it surpassed the other urbanisation aspects and became the one with the highest level of urbanisation, indicating that the Huaihe Ecological Economic Belt had a good economic development during the study period and had a good economic development environment. The main reason for this is that, as China’s urbanization progresses, the rural population is constantly changing to a urban population and the population is gathering in urban areas^[36], but as most of the cities in the Huaihe River Ecological and Economic Zone are less developed than the rest of China, the proportion of urban population in the study area is much lower than the proportion of urban population in China (63.9%).

The comprehensive urbanization index of the Huaihe Ecological Economic Belt is divided into eight levels, as shown in Fig. 2. In terms of the spatial and temporal evolution of the urbanisation level in the study area, the urbanisation level in the study area in 2005 was generally high in the west and low in the east, and as time progressed, the cities with lower development levels developed rapidly, and the spatial pattern of cities became low in the west and high in the east. The spatial pattern of cities changed to low in the west and high in the east. The fastest growing urbanisation levels are in cities such as Yangzhou in Jiangsu Province and Zaozhuang and Jining in Shandong Province, with most cities rising from below 0.125 to above 0.875. By 2020, most of the areas with low urbanisation levels are located in Henan Province, including cities such as Xinyang and Zhoukou.

Level of eco-environment development

The weighting value of the three ecological rule layers are, from highest to lowest, ecological condition (0.375), ecological protection (0.345) and ecological stress (0.280). During the study period, the comprehensive eco-

YEARS	Population urbanization	Economic urbanization	Spatial urbanization	Social urbanization	Urbanization comprehensive assessment index
2005	0.018	0.001	0.001	0.069	0.088
2010	0.074	0.045	0.053	0.110	0.281
2015	0.155	0.170	0.113	0.144	0.581
2020	0.170	0.293	0.173	0.252	0.888

Table 3. Level of urbanization development in the Huaihe ecological economic belt.

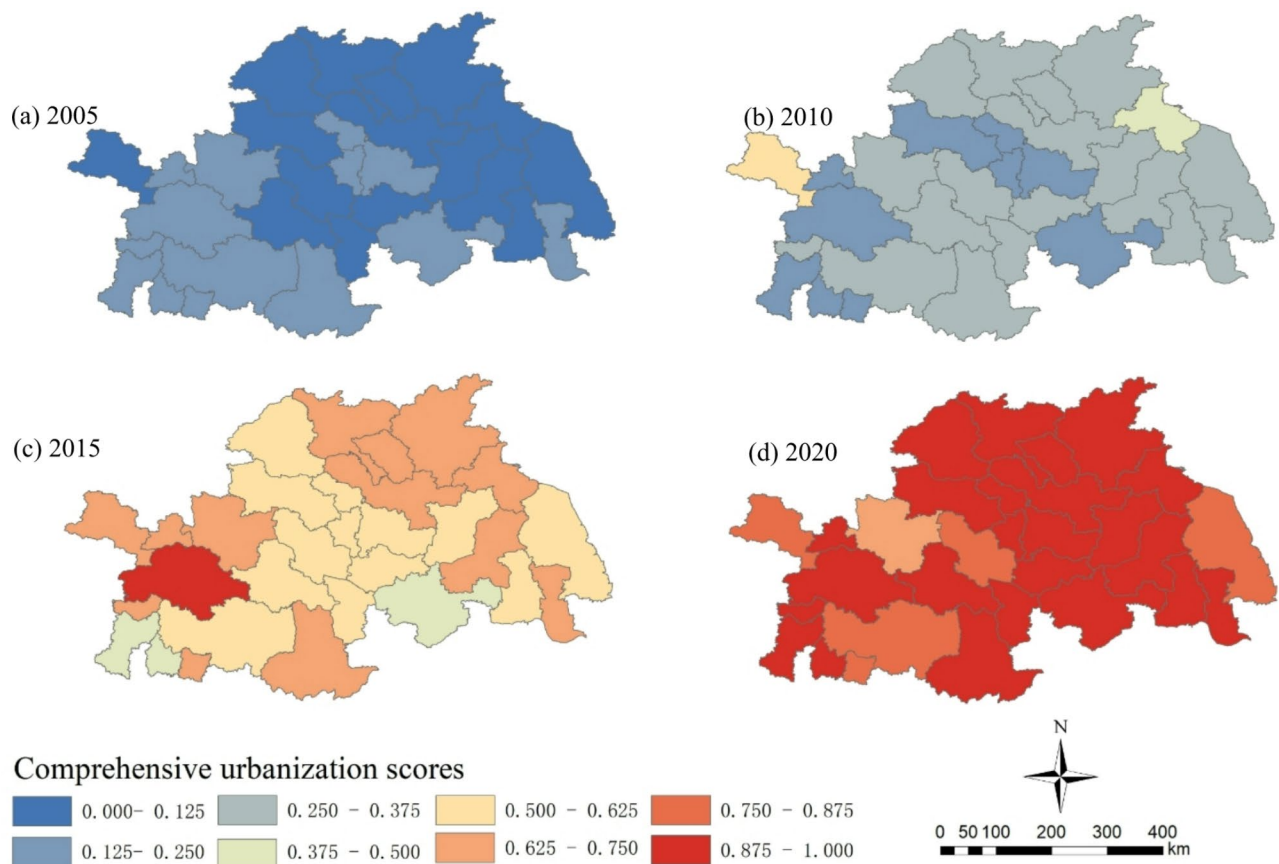


Fig. 2. urbanization development level of Huaihe ecological economic belt.

environment scores rose from 0.247 to 0.882, which means that the level of eco-environmental development in the Huaihe Ecological Economic Belt has been improving year by year. At the same time some of the indicators in the rule layer also underwent a dynamic change process, for example, the eco-environmental pressure value increased from 0.063 to 0.279 with some ups and downs in between, which indicates that that eco-environment pressures in the study area were higher in the early and decreased much lower in 2020. This is because China promulgated the *Measures on Administrative Penalties for Environmental Protection in 2010* and amended the *Law of the People's Republic of China on the Prevention and Control of Water Pollution* in 2008 and 2017, respectively, which led to a reduction in total industrial wastewater discharge in the study area from 1.6 billion tons to 1.2 billion tons, a 15 fold reduction in total industrial solid waste generation and a reduction in industrial dust emissions from 630,000 tons to 180,000 tons.

As for the eco-environmental status, although the negative effects caused by the average electricity consumption and household water consumption in the region are increasing, the positive effects such as the green coverage of built-up areas, the area of landscaped gardens and the area of actual forest land are also rising year by year, but the former is not growing as fast as the latter, finally making the eco-environmental state of the Huaihe Ecological Economic Belt better year by year. In terms of eco-environmental protection, indicators representing pollutant reduction such as industrial sulphur dioxide removal, urban sewage treatment rate and the value of the average area afforested in all years is rising, representing the good implementation of eco-environmental protection measures in place within the Huaihe Ecological Economic Belt (Table 4).

In 2005–2020, the comprehensive eco-environment scores of the Huaihe River Ecological and Economic Zone showed a fluctuating upward trend in its spatial distribution, indicating that the level of eco-environment in the Huaihe River Ecological and Economic Zone improved during the study period, with a large overall increase. In terms of spatial distribution, the distribution of the various levels of eco-environment indicators is rather scattered, but according to the distribution of each province it can be roughly seen that in 2005, Jiangsu Province had a better eco-environment than the other provinces, but by 2020, none city of Jiangsu Province had an eco-environment score greater than 0.84. In addition, from Fig. 3, we can learn that although many cities in the Huaihe Ecological and Economic Zone tend to have a good ecological environment, including Fuyang, Huainan, Xinyang and Zaozhuang etc., there are also some areas that show fluctuating changes in eco-environment level, such as Xuzhou, Heze and Zhoukou, with changes in the eco-environment development scores of 0.477–0.318–0.414–0.638, 0.377–0.485–0.411–0.705 and 0.295–0.634–0.600–0.592 respectively

Years	Eco-environmental pressure	Eco-environmental status	Eco-environmental response	Eco-environmental comprehensive assessment index
2005	0.063	0.142	0.043	0.247
2010	0.130	0.169	0.106	0.405
2015	0.097	0.199	0.247	0.543
2020	0.279	0.258	0.345	0.882

Table 4. Level of eco-environmental development in the Huaihe ecological economic belt.

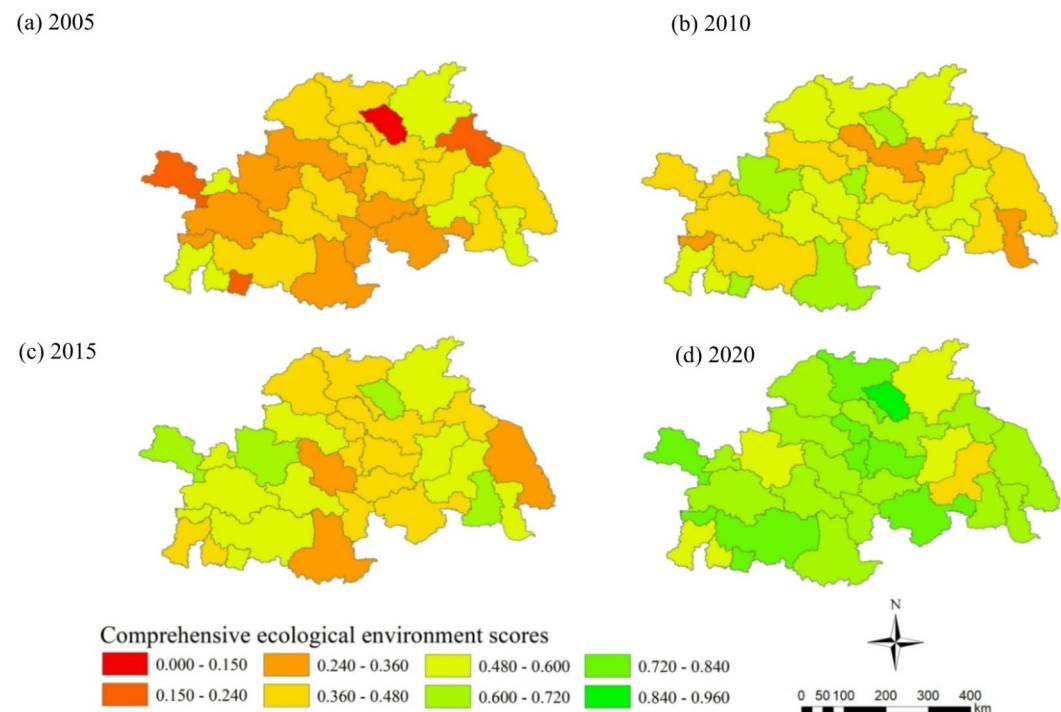


Fig. 3. Eco-environment development level of Huaihe ecological economic belt.

Coupling coordination

Stages of development of the coupling coordination degree between urbanization and eco-environment

From 2005 to 2020, the coupling coordination degree between urbanization and eco-environment in the Huaihe Ecological Economic Belt showed an increasing trend (Table 5), with the C value rising from 0.36 to 0.94, the T value rising from 0.16 to 0.99, the coupling coordination value rising from 0.25 to 0.91, D values as a whole change from moderate imbalance to advanced coordination, while the relative development of the two system layers in the study area changed from 0.36 to 1.00, signifying that the study area has changed from urbanization lag to balanced development. From the comparison of the five provinces included in the study area, the coupling coordination of Jiangsu, Henan, Anhui, Shandong and Hubei provinces increased from 0.33, 0.28, 0.28, 0.20 and 0.29 to 0.82, 0.89, 0.87, 0.86 and 0.87 respectively, which shows that the development stage of each province changes from severe imbalance or moderate imbalance to advanced coordination, with Jiangsu Province showing the least change and the lowest coupling coordination, and Shandong Province showing the most increase in coupling coordination.

When comparing all cities horizontally and vertically, it can be found that in 2005, cities with a high coupling coordination do not have a higher degree of coupling coordination than other cities at a later stage of development, but generally have a lower degree of coupling coordination, such as Taizhou and Guangshui. In contrast, some cities with a low coupling coordination in 2005, will have a higher degree of coupling and coordination than other cities by 2020, such as Zaozhuang and Heze. The reasons for this can be summarised as that In 2005, cities with a high degree of coupling and coordination had a high level of urbanisation and a small difference in value with their own level of ecological development, but as time progressed, these cities urbanised too quickly compared to other cities, resulting in a complete excess of ecological development, so that by 2020 the degree of coupling and coordination had decreased, such as Huaibei's urbanization development index of 0.18, 0.25, 0.58, 0.89 and the eco-environment development index 0.30, 0.41, 0.47, 0.75.

	Region	2005	2010	2015	2020
Jiangsu Province	Lianyungang	0.069	0.530	0.628	0.868
	Huaian	0.325	0.543	0.652	0.743
	Yancheng	0.355	0.481	0.563	0.818
	Suqian	0.356	0.513	0.629	0.771
	Xuzhou	0.353	0.433	0.625	0.830
	Yangzhou	0.283	0.455	0.702	0.842
	Taizhou	0.402	0.381	0.663	0.817
Anhui Province	Bengbu	0.266	0.485	0.591	0.813
	Huainan	0.345	0.430	0.623	0.864
	Fuyang	0.353	0.500	0.661	0.824
	Luan	0.297	0.554	0.578	0.840
	Bozhou	0.343	0.490	0.499	0.840
	Suzhou	0.339	0.430	0.583	0.857
	Huabei	0.402	0.464	0.564	0.851
	Chuzhou	0.315	0.443	0.566	0.872
Shandong Province	Zaozhuang	0.167	0.551	0.744	0.920
	Jining	0.259	0.559	0.647	0.856
	Linyi	0.189	0.551	0.688	0.799
	Heze	0.154	0.521	0.586	0.851
Henan Province	Xinyang	0.376	0.488	0.682	0.852
	Zhumadian	0.320	0.405	0.771	0.812
	Zhoukou	0.338	0.571	0.693	0.758
	Luohe	0.376	0.409	0.672	0.819
	Shangqiu	0.264	0.417	0.660	0.827
	Pingdingshan	0.264	0.571	0.699	0.883
	Tonbai	0.339	0.404	0.655	0.881
Hubei Province	Suixian	0.463	0.454	0.549	0.804
	Guangshui	0.463	0.454	0.549	0.804
	Xiaogan	0.238	0.449	0.670	0.878
	Entire study area	0.246	0.444	0.649	0.912

Table 5. Trends in coupling coordination by city in level of Huaihe ecological economic belt.

Spatial and temporal evolution patterns of the coupling coordination between urban-ization and eco-environment
From the spatial distribution of the coupling coordination between urbanization and the eco-environment in the study area in Fig. 4, the distribution pattern of the coupling coordination degree is mainly related to the province where each city is located, for example, the coupling coordination degree of the eight cities in central Anhui Province do not differ significantly.

In the timeline, the cities in the Huaihe Ecological Economic Belt have mainly gone through the urbanization development stage and the transition stage. In 2005 and 2010, the stage of the cities are mainly urbanization lagging, but urbanization is also growing, and by 2015, the point in time with the most various types of coupling and coordination and belonged to the transition stage, and by 2020, as the cities' urbanization development level has exceeded the eco-environment development level, so a new pattern is formed: the eco-environment development level lags behind the level of urbanization, which shows that, as urbanisation continues, the level of urbanisation in the Huaihe Ecological and Economic Zone is increasing rapidly, while the level of ecological development, although also increasing with the various policies proposed, is not as fast as urbanisation development.

Spatial autocorrelation analysis

Global autocorrelation

This study is based on the spatial correlation analysis of the neighbourhood spatial weight matrix, with the help of Arcgis, using the global Moran's index to reflect whether the urbanization development level, ecological development level and the coupling coordination degree are spatially correlated respectively, and the results are shown in Table 3; Fig. 4. The values of the urbanization development level and the coupling coordination have been greater than 0, but From 2005 to 2020, the Moran's index of the urbanisation development level and the coupling coordination declined each year, from 0.355 to 0.170 to 0.140 and -0.116 respectively, representing a positive trend in the correlation between urbanisation development level and spatial correlation, but the correlation has also been weakening, while the spatial correlation of the coupling coordination has changed from a positive to a negative one.

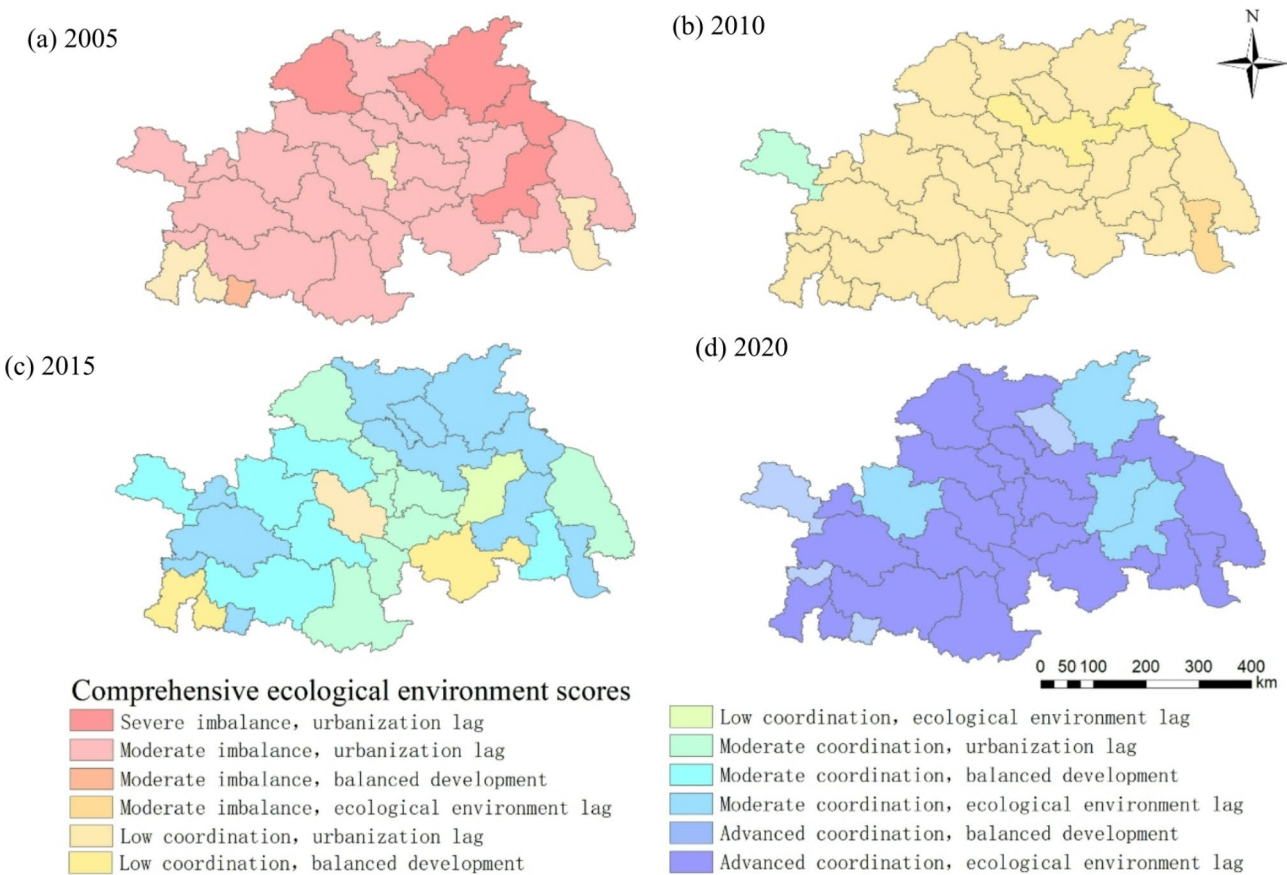


Fig. 4. Coupling coordination of urbanization and eco-environment in Huaihe ecological economic belt.

Years	Urbanization			Eco-environment			Coupling coordination		
	Moran's I	Z	p	Moran's I	Z	p	Moran's I	Z	p
2005	0.355	3.33	0.001	-0.22	-1.53	0.1	0.17	2.08	0.03
2010	0.246	2.37	0.01	0.05	0.76	0.4	0.124	1.32	0.1
2015	0.191	1.9	0.05	0.074	0.91	0.3	0.04	0.62	0.53
2020	0.14	1.5	0.1	-0.148	-0.977	0.32	-0.116	-0.7	0.48

Table 6. Global autocorrelation of urbanization, eco-environment, and coupling coordination.

As can be seen in Table 6, the distribution and variation of the Moran's index of the eco-environment is irregular and always lies between randomness, indicating that the level of the eco-environment in the Huaihe Ecological Economic Belt is characterised by a random distribution.

Local autocorrelation

The local autocorrelation is calculated from the local clustering proposed by Anselin and is called the local Moran's index. This study presents a local autocorrelation analysis of urbanisation, eco-environment, and coupling coordination, as shown in Fig. 4. In 2005, the higher urbanization levels were mainly clustered in Shandong and Jiangsu. With the development of time, the urbanization development level of Shandong Province has been higher than that of Jiangsu Province in 2005 than the part of the development in the study period, so that the High-High Cluster gradually shifted towards Shandong Province, this is because Shandong Province is developing faster than Jiangsu Province, and although the actual level of urbanisation may not be as high as in the cities of Jiangsu Province, the degree of change from 2005 to 2020 is higher than in the cities of Jiangsu Province. In terms of eco-environment level, the change is less regular, but from Fig. 5, we can see that Pingdingshan originally belonged to the Low-Low Cluster, and as the eco-environment of Pingdingshan developed at a higher and higher level, it experienced the High-High Cluster and High-Low Cluster, with the three stages representing its eco-environment going through (1) low level stage, (2) high level and higher level in the surrounding area, (3) Higher level but the slower development of the surrounding area cannot keep up with the development of

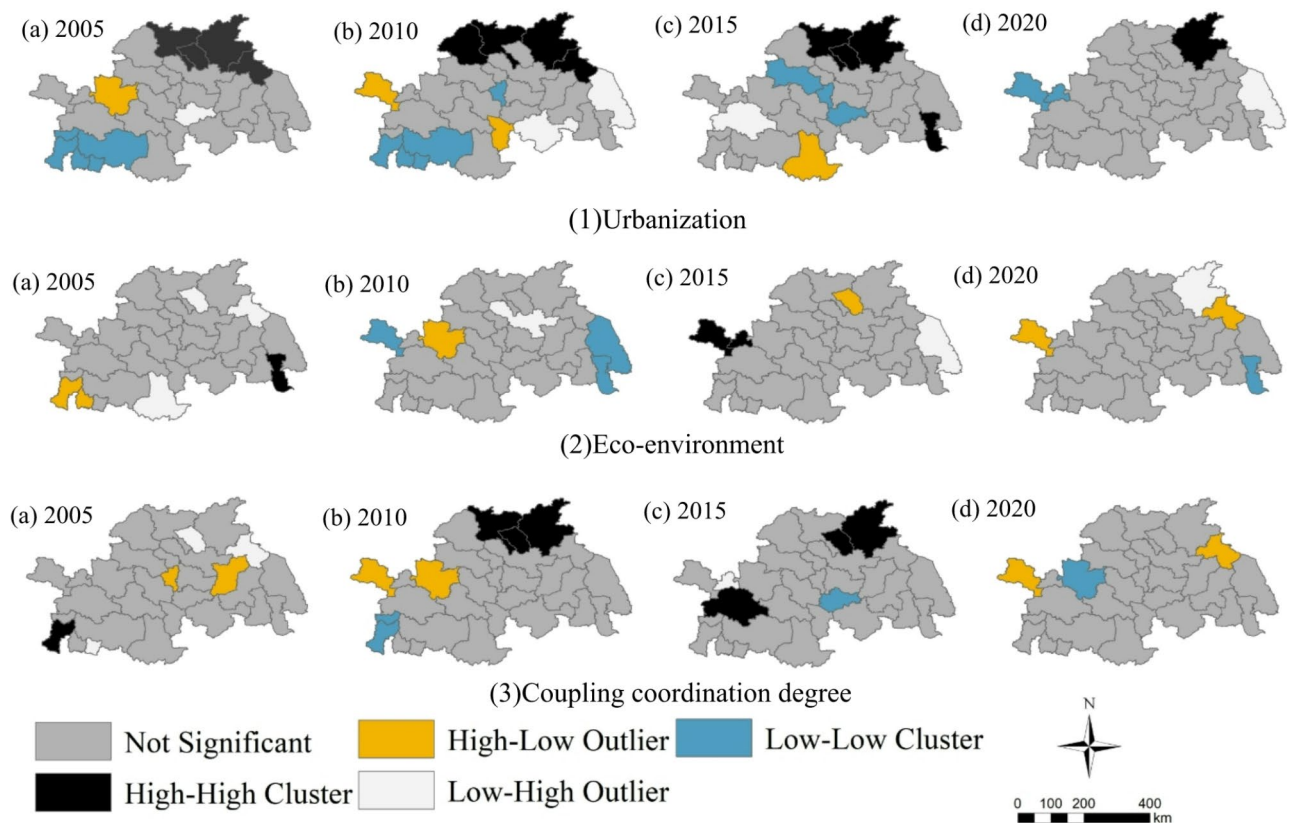


Fig. 5. Local autocorrelation distribution of urbanization, eco-environment and coupling coordination.

Pingdingshan, resulting in a High-Low Cluster situation in Pingdingshan. In terms of coupling coordination, the high coupling coordination areas were mainly clustered in Shandong Province in 2010 and 2015, and then gradually dispersed with no regularity as time progressed.

Discussion and suggestions

The Huaihe Ecological Economic Belt contains many rivers and lakes with ample surface water, but it also causes the high landscape ecological risk of the research area and it is difficult to recover from natural or manmade disasters on its own. If the eco-environment is damaged, it will not only directly affect⁵³ the Huai River eco-economic zone, but also the Yangtze River basin and other nearby countries in China's waters⁵⁴. With the advancement of urbanization, the impact of humans on the ecology of the region is increasing. The study found that within the past 15 years, the Huaihe Ecological Economic Belt has seen an overall acceleration in urbanization and an increase in the level of eco-environmental development, with a trend of increasing coupling and coordination between the two year by year, and although some results have been achieved, some problems still exist and recommendations are made based on these problems.

Problems faced by the Huaihe ecological economic belt in terms of urbanization

By comparing the scores obtained by each city on the four rule layers of urbanization, the lowest score is considered to be the aspects where the city is lagging behind in terms of urbanization, as shown in Fig. 6. In 2005, most cities in the Huaihe Ecological Economic Belt were relatively weak in spatial urbanization, including indicators such as built-up area and urban road area per capita, which were relatively low. In 2015, population urbanization becomes relatively weak, and finally by 2020, population urbanization become a relative deficiency for most cities. The finding that spatial urbanization has gradually become more urbanized than population urbanization symbolizes that this may result in a certain degree of serious waste of land resources is consistent with the findings of other scholars^{8,14,49}.

The reason for this is that as time goes on, economic urbanization development gets better and better, and the regional average GDP per capita, tertiary sector share and disposable income per capita become 5.6 times, 1.5 times and 3.58 times higher respectively, but in 2010, the development situation was not sufficient compared to other aspects, so this led to economic urbanization becoming a weak points for many cities in 2010, at the same time, the urbanisation of the population in these cities was progressing steadily until 2010. However, as time progresses, the Many cities have experienced declining or even negative natural population growth rates, slow growth or declining population density in urban areas, making urbanisation imbalanced, reflecting the fact that within the Huaihe Ecological Economic Belt, due to its ecological importance, but local economic development

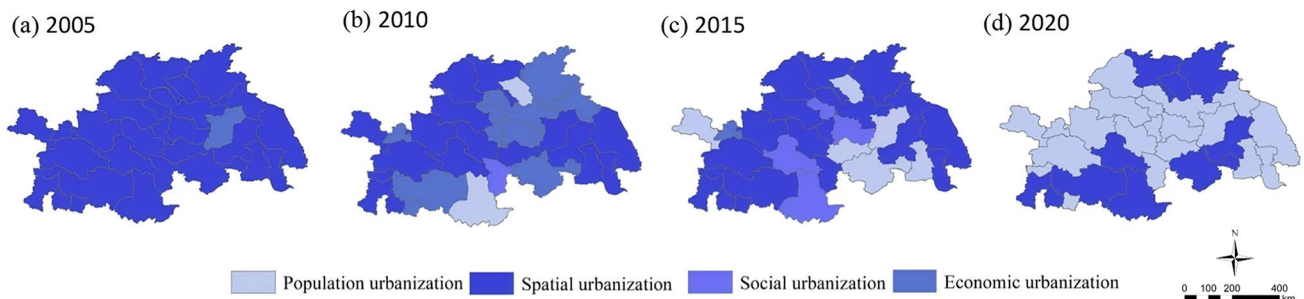


Fig. 6. Local autocorrelation distribution of urbanization, eco-environment and coupling coordination.

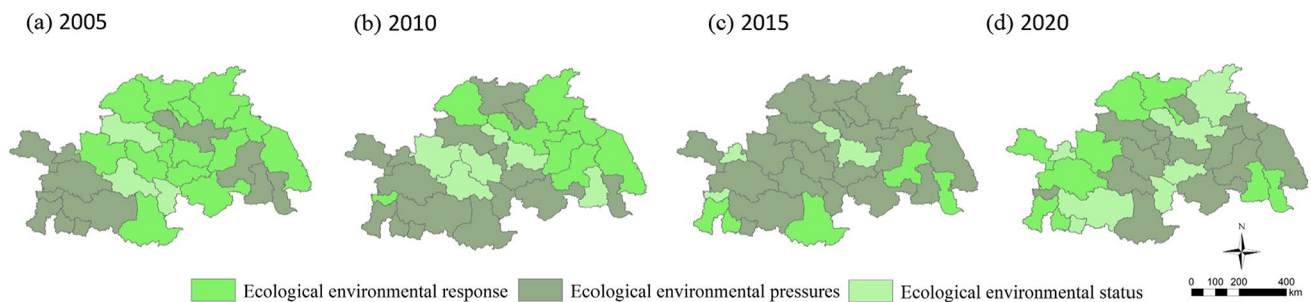


Fig. 7. Each city in the Huaihe River ecological economic belt is relatively weak in urbanization.

is not as good as other cities in China, leading to serious regional population loss and thus a situation where local population urbanisation is lagging behind other aspects of development in the context of China's rising total population⁵⁵. Compared to the better developed river basins of the Yangtze⁵⁶, Pearl River⁵⁷ and Yellow River⁵⁸, the Huai River is less developed in terms of urbanization, while there is a huge difference in the spatial distribution of the urbanization of the population.

Problems faced by the Huaihe ecological economic belt in terms of eco-environment

The three aspects in which each city is lagging behind in terms of eco-environment response, pressure and status are shown in Fig. 7, where a low ecological pressure score represents high ecological pressure. As can be seen from the overview of the evolving trends, in 2005, the deficiencies in the development of the eco-environment in many cities such as Lu'an and Bozhou again were mainly reflected in the ecological response, and with the development of time, excessive ecological pressure on the eco-environment became the main ecological problem in each region⁵⁸, while *The National Environmental Protection 12th Five-Year Plan* promulgated during the study period, the revision of the Environmental Protection Law, the inclusion of ecological construction in the Constitution and a series of other laws and regulations have improved the basic system of ecological protection in China and added many ecological protection measures, resulting in a relatively high ecological response score and a reduction in ecological pressure by 2020⁵⁹.

In detail, Linyi, for example, has gone through three stages: inadequate ecological response - excessive ecological pressure - inadequate ecological status. There are two possible reasons for this: (i) the regional policy has been in place for too short a time, and it takes longer for the policy to respond to ecological status, so the provisional status score is not as good as the pressure and response scores. (ii) China's central government has issued many requirements to cities for environmental protection, which have been fulfilled by various local governments, but superficially and without taking into account the actual situation of each city, resulting in an imbalance between pressure, response and status. In comparison with additional studies with other regions, it was found that many regions within China, such as Jiangxi Province⁶⁰ and Shaanxi Province⁴⁹, have shown a higher development of urbanisation than eco-logical environment in recent years, suggesting that there is room for improvement in many regions within China.

Suggestions

- (1) Accelerating the urbanization process and improve the level of population urbanization and spatial urbanization. The urbanization level of the Huaihe Ecological Economic Belt is still a long way from the Chinese average. In its future development, it should improve the urban public green areas, road areas, built-up areas and other infrastructure, while most importantly optimising the industrial layout, improving the regional economic strength and enhancing the attraction of talents to stay in the local population and also be able to attract part of the foreign population, in order to get rid of the current lagging behind the Chinese. The Huaihe Ecological Economic Belt will be able to develop with high quality.

- (2) Protecting the regional eco-environment and achieving sustainable development The government should not only set emission standards for various pollutants, but also control the actual situation of emission in each place, so as to avoid any enterprises or manufacturers from stealing water and polluting gases, and to reduce the pressure on the eco-environment, and also actively develop and encourage the use of new energy sources, improve the efficiency of resource use, and reasonably develop new land for construction.
- (3) Strengthening the construction of central cities and drive regional development. There is a huge gap between the central cities of the Huaihe River basin (such as Bengbu and Huai'an) and the central cities of the Yangtze River basin (such as Shanghai and Nanjing). The development of the central cities of the Huaihe River should be accelerated to drive the development of the surrounding areas, forming a spatial pattern of coupled and coordinated degrees of aggregation, so that other cities can actively dovetail with the centre to produce advantageous industries and accelerate integrated development.

Conclusions

This study takes the Huaihe Ecological Economic Belt as an example, on the basis of a comprehensive evaluation index system for the coupling and coordination degree of urbanization and eco-environment in the ecological stronghold area and analyses the direct coupling and coordination relationship between urbanization and eco-environment in the whole ecological stronghold, as well as uses GIS technology to visualise the measurement results and make a comprehensive comparison. Then the study also uses the spatial autocorrelation technique to view the spatial correlation between urbanization, eco-environment and coupling and coordination degree. correlation. The aspects and reasons for the uneven development of the cities in the study area are discussed. The conclusions are as follows.

- (1) The level of urbanization development in many cities within the Huaihe Ecological Economic Belt is low. The level of urbanization within the study area is somewhat less than the average, but it is also growing steadily, with the urbanization development index rising from 0.088 to 0.888, and there is significant variability across cities in the composite index and the four criterion layers of population, space, society and economy, with the spatial autocorrelation of urbanization levels decreasing year by year. In 2020, the imbalances of many cities is mainly reflected in spatial urbanization and demographic urbanization.
- (2) The ecological and environmental conditions in the study area get better and better year by year. The ecological development index has increased from 0.247 to 0.882, in which the main reason is that the ecological response is doing better and the ecological pressure is decreasing year by year, and the ecological state is also improving but not changing much. At the same time, ecological and environmental pressure and condition did not change much before 2015, but ecological and environmental response largely increased, representing the region implemented more protection policies during this period.
- (3) The degree of coupling coordination between urbanization and eco-environment in the Huaihe Ecological Economic Belt shows a continuous growth. The value of the coupling coordination degree rose from 0.25 to 0.91, indicating that the two coupling development trends of urbanization and eco-environment in the Huaihe Ecological Economic Belt, which promote each other, have taken initial shape. The regional government has seen the first results in economic development, spatial planning and ecological protection. The coupling coordination degree shows a weak autocorrelation in spatial distribution, and the distribution of high and low coupling areas is more random.

Data availability

The datasets generated and analysed during the current study are not publicly available due policies and confidentiality agreements adhered to in our laboratory but are available from the corresponding author on reasonable request.

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C.O.: Conceptualization, Methodology, Formal analysis, Investigation, Visualization. X.Y.: Methodology, Formal analysis, investigation and processed the experimental data. Y.C.: Conceptualization, Methodology, Formal analysis, Data curation and Writing-original draft. X.Z.: Conceptualization, Methodology, Formal analysis, Data curation. H.L., L.K. and Y.C.: Conceptualization, Investigation, Methodology, Data curation, Supervision.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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