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Coupling Coordination Between Urbanization and Ecological Environment in Henan Province and Its Influencing Factors

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ABSTRACT: Taking Henan Province as the research subject, this study constructs an evaluation index system for urbanization and ecological environment. Using the entropy method, coupling coordination degree model, and spatial center of gravity–ellipse model, the spatio-temporal evolution pattern of the coupling coordination between urbanization and ecological environment in Henan Province from 2011 to 2022 is quantitatively measured. The scissor difference model is employed to calculate the degree of discrepancy between the two systems. Additionally, the GTWR model is applied to analyze the influencing factors of their coupling. The results show that: 1) Both urbanization and ecological environment in Henan Province exhibited an upward trend, with significant spatio-temporal coupling characteristics. 2) The spatial center of gravity shifted only slightly during the study period, moving near the border of Xinzheng. 3) The coupling coordination degree showed a trend of "fluctuation–decline–rise" over the study period. 4) Macro-level government regulation, scientific and technological progress, and informatization exerted positive effects on the coupled system, whereas transportation construction-imposed pressure on the ecological environment, generating negative effects.

KEYWORDS: urbanization; ecological environment; coupling coordination; spatial center of gravity; scissor difference; influencing factors.

1 INTRODUCTION

Urbanization is an inevitable pathway for any country or region to achieve industrialization and modernization[1]. Since the 21st century, countries worldwide have embarked on urbanization initiatives. China's urbanization started relatively late and remained at a comparatively low level, with significant academic and policy attention emerging around 2009. In 2013, urbanization was highlighted as an independent key agenda item by the Central Committee of the Communist Party of China for the first time. In 2014, the National New-Type Urbanization Plan was officially released, piloting new-type urbanization in selected key cities. This new approach emphasizes a people-oriented transformation, encompassing shifts in industrial structure, environmental sustainability, and other dimensions. By 2017, urbanization had achieved phased outcomes, and as of 2020, China continues to vigorously advance urbanization development. As noted in the State Council Government Work Report, efforts should focus on strengthening new-type urbanization and deepening its progress. Data indicate that China's urbanization rate increased from 10.64% in 1949 to 17.92% in 1978. Following the reform and opening-up policy, urbanization accelerated significantly, with an average annual growth rate of approximately 1%. By 2016, the urbanization rate had reached 58.84%, and by 2022, it climbed to 65.22%. This rapid growth represents a remarkable achievement in the history of urbanization. However, the swift pace of urbanization has also exacerbated ecological and environmental degradation, including issues such as air and water pollution. Conversely, the state of the ecological environment directly constrains the progress of urbanization. Therefore, studying the coupling coordination between urbanization and the ecological environment has become a critical subject in contemporary societal development. Coupling coordination implies that urbanization must fully consider and protect the ecological environment, achieving a win-win scenario for urban development and ecological conservation through rational planning, scientific management, and effective policies. Only by establishing a harmonious relationship between urbanization and the ecological environment can sustainable urban development be realized, ensuring long-term societal prosperity and the healthy coexistence of ecosystems.

Research on the interaction and coupling between urbanization and the ecological environment has gained increasing attention from scholars in recent years, primarily focusing on two dimensions: content and regional scope.

In terms of content, studies have mainly addressed theoretical frameworks and future predictions. Theoretically, Fang et al. conducted theoretical analyses of this coupling, discussing its mechanisms[Error! Reference source not found.], fundamental principles[Error! Reference source not found.], and key evolutionary stages[4]. Regarding coupling predictions, Wu et al.[5] utilized a projection pursuit model to analyze the coupling coordination between urbanization and the ecological environment system. Liu et al.[6] employed a spatial Markov chain to study the coupling coordination degree between urbanization and the ecological environment. Muhadaisi Ariken et al.[7] examined the spatiotemporal patterns and influencing factors of the coupling between new-type urbanization and the ecological environment. In terms of regional scope, research has expanded progressively from the provincial level to urban agglomerations, river basins, and the national scale. Examples include studies on urban agglomerations[8,9], the Yellow River Basin[10,11], the Yangtze River Delta and the Yangtze River Basin[12,13], and nationwide analyses[14,15]. Internationally, the relationship between urbanization and the ecological environment has also attracted scholarly attention. Approaches such as the Environmental Kuznets Curve[16] and the Pressure-State-Response model[17] have been used to explore the coupling between the ecological environment and economic or high-quality development. Research regions internationally often focus on smaller units like districts or villages[18,19]. Overall, studies on the relationship between urbanization and the ecological environment, whether domestic or international, have predominantly concentrated on theoretical mechanisms, spatiotemporal distribution, and evolutionary characteristics. However, there remains a need for deeper exploration into the spatiotemporal evolution of coupling coordination and its driving influences.

Based on the above discussion, this paper takes municipal districts within Henan Province as the basic research units. It constructs an urbanization-ecological environment indicator system and framework, employing a coupling coordination model to analyze the spatio-temporal evolution characteristics between urbanization and ecological environment development in Henan Province. Subsequently, the spatial center-of-gravity model and the scissors difference model are applied to further explore the patterns and disparities in spatio-temporal evolution. Following this, the GTWR (Geographically and Temporally Weighted Regression) model is used to analyze the influence of indicators across different dimensions. The study aims to provide references and theoretical support for coordinating the relationship between urbanization and ecological environment construction in Henan Province.

2 OVERVIEW OF THE STUDY AREA

Henan Province (see Fig 1) is situated in central-eastern China, within the middle and lower reaches of the Yellow River. With a total area of 167,000 square kilometers, it is one of the most populous provinces in the country. In terms of resources, Henan lies at the junction of the coastal open regions and the central-western inland cities, serving as a major producer of agricultural products and a province rich in mineral resources. In 2022, Henan's GDP reached 6.1345 trillion yuan, ranking fifth in the nation, while its resident population stood at 98.72 million, placing it third nationwide. However, its urbanization rate was only 57.07%, significantly lower than that of other provinces. In recent years, Henan has been accelerating its urbanization process. Therefore, studying the coupled and coordinated relationship between urbanization and ecological environment development in Henan holds considerable significance, as it can provide theoretical support and reference for the provincial government.

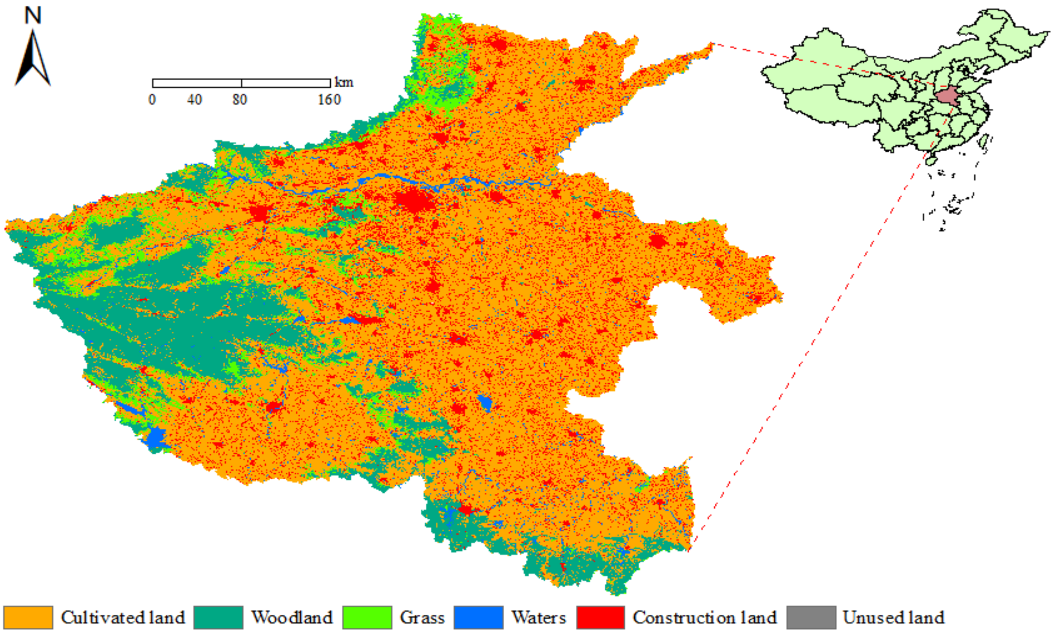

Fig1. Study Area

3 DATA AND METHODOLOGY

Building on prior research and contemporary definitions of urbanization, this paper constructs an evaluation index system for assessing the coupled coordination between urbanization and the ecological environment (see Tab 1). The urbanization system is evaluated based on four key dimensions: coordinated development, open development, shared development, and cultural and innovative development. Meanwhile, the ecological environment system is assessed using a framework that encompasses three aspects: environmental condition, resource utilization, and conservation efforts.

The data used in this study were primarily sourced from the Henan Statistical Yearbook (2011–2022), environmental statistical bulletins of various cities in Henan Province, and statistical bulletins on national economic and social development of the respective cities.

Tab 1. Evaluation Indicator System and Weights for the Coordinated Development of Urbanization and Ecological Environment Coupling

	Level 1 Indicator	Level 2 Indicator	Unit	Comprehensive Weight	Attribute
Urbanization Development System	Coordinated Development	Urbanization Rate	%	0.08922	+
		Proportion of Employment in Secondary and Tertiary Industries	%	0.09300	+
		Per Capita Disposable Income of Urban Residents	RMB	0.09218	+
		GDP per capita	RMB	0.09140	+
	Open Development	Total Retail Sales of Consumer Goods	10000 RMB	0.09280	+
		Proportion Of Tax Revenue	%	0.12268	+
	Shared Development	Number of Hospital Beds per 10,000 Population	Number	0.09182	+
		Urban Built-up Area per 10,000 Population	Km²	0.09953	+
		Water Supply Coverage Rate	%	0.09420	+
	Cultural Development	Proportion Of Education Expenditure	%	0.13318	+

Ecological Development	Ecological Status	Green Coverage Rate of Built-up Area	%	0.12995	+
		Per Capita Public Green Space Area	m²	0.14668	+
		Gas Coverage Rate	%	0.13190	+
Environment	Ecological Pressure	Per Capita Daily Water Consumption	L	0.16258	-
		Industrial Energy Consumption	Ton	0.16653	-
	Ecological Protection	Harmless Waste Treatment Rate	%	0.13794	+
		Wastewater Treatment Rate	%	0.12442	+

3.1 Entropy Method

The entropy method is an approach that objectively reflects the required information and determines indicator weights based on the degree of data dispersion of the indicators[20]. It can avoid the influence of subjective factors, as the information reflected is entirely determined by the data itself. The formulas are as follows:

(1) Normalization:

Positive indicator: $X_{ij} = \frac{x_{ij}-x_{min}}{x_{max}-x_{min}}$ (1)

Negative indicator: $X_{ij} = \frac{x_{max}-x_{ij}}{x_{max}-x_{min}}$ (2)

In this formula, x_{ij} (i=1,2,…m;j=1,2,…n) represents the data of the j-th indicator in the i-th year.

(2) The weight of the i-th city under the j-th indicator:

$$P_{ij} = \frac{1+X_{ij}}{\Sigma_{i=1}^{m}(1+X_{ij})} \quad (3)$$

(3) The entropy value of the j-th indicator:

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

(4) Calculate the coefficient of variation for indicator j:

$$g_j = 1 - e_j \quad (5)$$

(5) Calculate the weights:

$$W_{1j} = \frac{g_j}{\Sigma_{j=1}^{n} g_j} \quad (6)$$

3.2 Coupled Coordination Model

This paper employs a Coupling Coordination Degree Model to investigate the coupling coordination relationship between urbanization and the ecological environment. Since the results calculated using the traditional coupling formula generally indicate a high level of coupling, which does not align with reality, a modified coupling coordination model is adopted for this study. Assuming that $\max U_i$ is U_2, the calculation formula is as follows:

$$C = \sqrt{\left[1-\sqrt{(U_2-U_1)^2}\right] \times \frac{U_1}{U_2}} = \sqrt{1-(U_2-U_1) \times \frac{U_1}{U_2}}$$

(7)

$$T = \alpha_1 U_1 + \alpha_2 U_2, \alpha_1 + \alpha_2 = 1 \quad (8)$$

$$D = \sqrt{C \times T} \quad (9)$$

In the formula, C represents the coupling degree, reflecting the interaction between the urbanization and ecological environment systems. The closer the value of C is to 1, the higher the coupling degree. T denotes the coordination degree, characterizing the contribution of the two systems to coupling coordination. α_1 and α_2 are coefficients, with $\alpha_1 = \alpha_2 = 0.5$. D stands for the coupling coordination degree, which comprehensively reflects the development levels of urbanization and the ecological environment. The closer D is to 1, the higher the coordination degree. This paper classifies the coupling coordination degree into five categories (Tab 2):

Tab.2. Coupling Coordination Classification Table

Coupling Coordination Type	Coupling Coordination Degree
Declining Imbalance	0≤D<0.3
Low-Level Coordination	0.3≤D<0.4
Primary Coordination	0.4≤D<0.5
Positive Coordination	0.5≤D<0.8
Advanced Coordination	0.8≤D<1

3.3 Center of Gravity Shift Analysis

This study employs the Center of Gravity Shift Model to analyze the spatio-temporal variation patterns between urbanization and the ecological environment. While reflecting the coordination between the two systems, this approach also reveals the positional trends between them over time. The formula is as follows:

$$(X,Y)=\left(\frac{\Sigma_{i=1}^{n}E\times x_i}{\Sigma_{i=1}^{n}},\frac{\Sigma_{i=1}^{n}E\times y_i}{\Sigma_{i=1}^{n}}\right) \quad (10)$$

In the formula, E represents the coupling coordination degree between the two systems,x_i, y_i denote the longitude and latitude coordinates of the city, and (X,Y) represent the coordinates of the center of mass. The subscript I corresponds to the years 2011, 2013, 2015, 2017, 2019, 2021, and 2022, respectively.

3.4 Scissors Difference Model

The Scissors Difference Model can be used to analyze the variation disparities between systems. In this study, the model is applied to examine the difference in change rates between the urbanization and ecological environment systems[21]. The formula is as follows:

$$f'(x)=\frac{dx}{dt} \quad (11)$$

$$f'(y)=\frac{dy}{dt} \quad (12)$$

$$\theta=arctan\left|\frac{f'(x)-f'(y)}{1+f'(x)\times f'(y)}\right| \quad (13)$$

$f'(x)$ and $f'(x)$represent the change trends in year t. A larger angle θ indicates a more significant change trend.

3.5 GTWR Combined Model

Given the complex relationship between urbanization and the ecological environment, statistical models often overlook the spatial heterogeneity and non-stationarity between the two systems. The Spatio-temporal Geographically Weighted Regression model is a modified local linear regression model that extends the general linear regression model by incorporating a temporal dimension, effectively addressing issues of regional correlation. The formula is as follows:

$$Y_i=\beta_0(u_i,v_i,t_i)+\Sigma_k\beta_k(u_i,v_i,t_i)X_{ik}+\varepsilon_i \quad (14)$$

In the formula, (u_i,v_i,t_i) represent the spatiotemporal coordinates of the study element i, $\beta_k(u_i,v_i,t_i)$ denotes the k-th regression coefficient for the i-th study element, and $\varepsilon_i$is the random error term. The calculation formula for $\beta_k(u_i,v_i,t_i)$ is as follows:

$$\hat{\beta}(u_i,v_i,t_i)=\left[X^TW(u_{i,}v_{i,}t_i)X\right]^{-1}X^TW(u_{i,}v_i,t_i)Y$$

(15)

$$W(u_{i,}v_{i,}t_i)=diag(a_{i1},a_{i2,\cdots,}a_{in}) \quad , \quad a_{ij}=\exp\left(-d_{ij}{}^{ST^2}/h^{ST^2}\right) \quad (16)$$

In the formula,d_{ij} represents the spatiotemporal distance between cities, and h is determined using cross-validation to minimize the sum of squared errors, i.e.: $h=\sum_i(y_i-\hat{y}_{\neq 1}(h))^2$, $d_{ij}{}^{ST}=\sqrt{\lambda[(u_i-u_j)^2+(v_i-v_j)^2]+\mu(t_i-t_j)^2}$.

This study further investigates the impact of urbanization on the ecological environment in Henan Province from 2011 to 2022 under spatiotemporal conditions using the Spatio-temporal Geographically Weighted Regression model. Influencing factors of urbanization across different dimensions are treated as independent variables in the Geographically Weighted Regression model, while changes in ecological environment development serve as the dependent variable.

4 RESULTS AND ANALYSIS

4.1 Spatiotemporal Analysis of Urbanization and Ecological Environment Development

4.1.1 Spatiotemporal Analysis of Urbanization

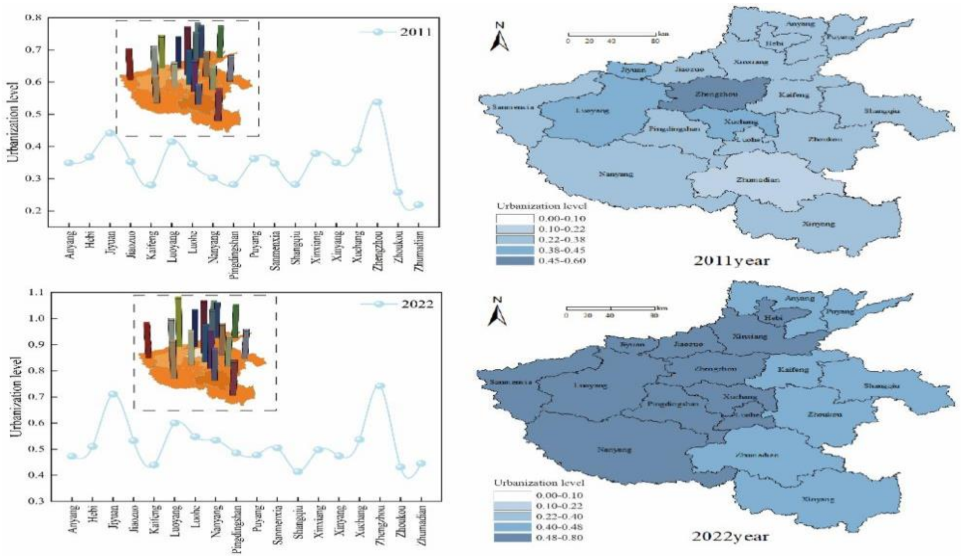

Fig 2. Urbanization Level

From 2011 to 2022, the overall urbanization level in the province showed an upward trend, rising from 0.348 in 2011 to 0.52 in 2022. Spatially, the changes were more complex, evolving from an initial pattern of "higher in the center and lower in the periphery" to a "stepped distribution with higher levels in the west and lower levels in the east" (Fig 2). High levels of urbanization were primarily concentrated in the Yellow River Basin region. As the driving force of Henan's development and located in the middle and lower reaches of the Yellow River, this region—represented by cities such as Zhengzhou and Jiyuan—took the lead in achieving economic growth and higher urbanization, subsequently radiating its influence northward from Zhengzhou. During this period, spatial disparities across the province also began to shift, forming two high-level urban clusters: the "Zhengzhou-Jiyuan Yellow River Basin Zone" and the "Anyang-Hebi Metropolitan Area." This demonstrates the significant radiating and driving effect of the Zhengzhou economic metropolitan area. In contrast, cities like Shangqiu and Zhoukou developed more gradually, while Zhumadian—the only city initially at a relatively low level—also progressed to a moderate level.

4.1.2 Spatiotemporal Analysis of Ecological Environment Level

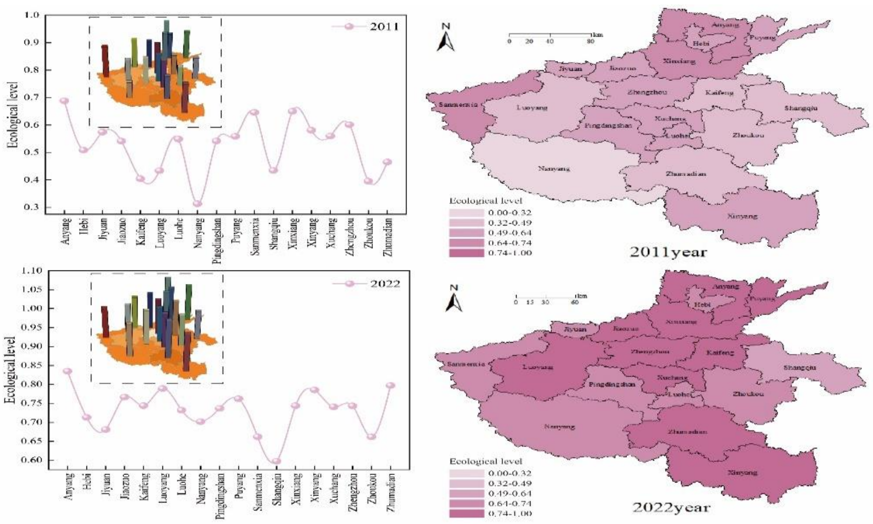

Fig.3. Ecological Environment Level

From 2011 to 2022 (see Fig 3), the ecological environment development level in the province advanced rapidly, rising from 0.524 in 2011 to 0.73 in 2022. Spatially, it exhibited a "higher in the west, lower in the east" distribution pattern. During 2011–2015, Most cities in the province were at a moderate level with relatively weak ecological conditions, largely due to the extensive mining of coal resources in Henan during this period. From 2019 to 2022, the ecological environment in the province gradually improved, with the majority of cities reaching a relatively high level (above 0.64). Development began to radiate in a circular pattern centered on Zhengzhou, and nearly all cities achieved high-level ecological development, forming two zones of extremely high ecological level (above 0.74)—one north of the Yellow River and one south of it. Sanmenxia and Nanyang, located in the Qinling mountain region, lagged in development. Shangqiu experienced a slight decline.

4.2 Spatiotemporal Analysis of Urbanization and Ecological Environment Coupling

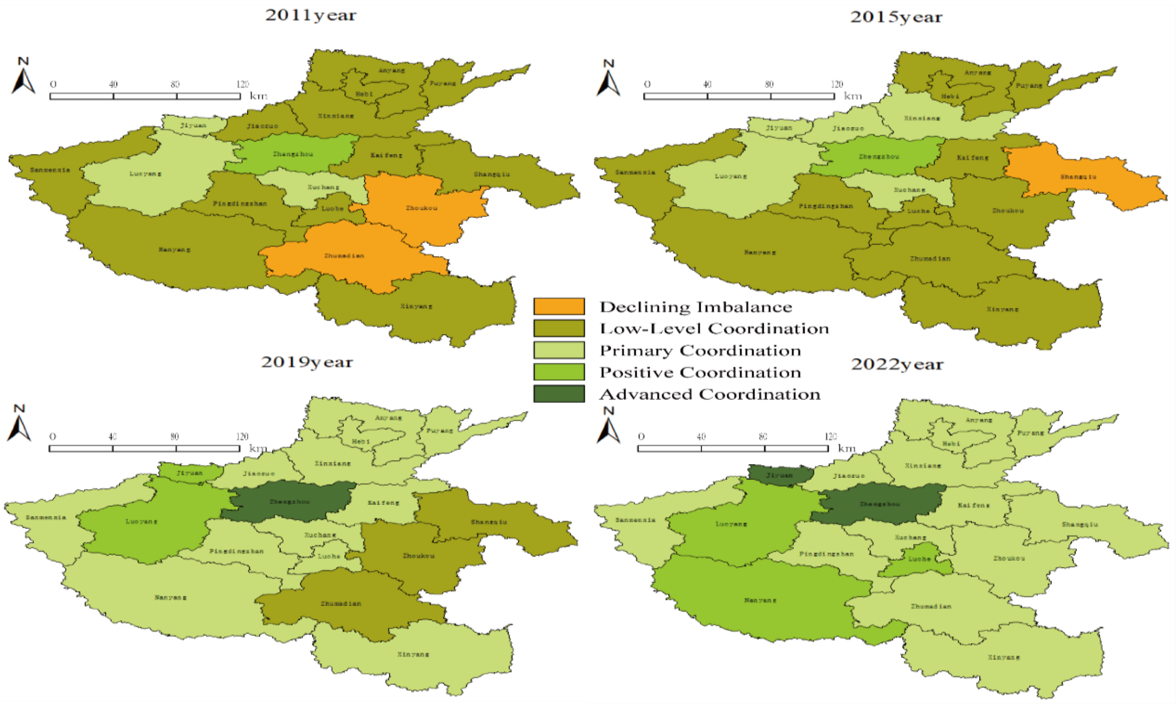

Fig.3. Coupling Development Level

From a temporal perspective (see Fig 3), the coupled and coordinated development of urbanization and the ecological environment in cities across Henan Province generally showed an upward trend from 2011 to 2022. Spatially, the provincial pattern shifted from being "centered on Zhengzhou and declining toward the periphery" to a "dual-core pattern radiating outward with declining levels." In 2011, all 16 cities in the province had achieved a high level or above (above 0.5) of coupling coordination, with only Zhoukou and Zhumadian at a moderate level. High-quality coupling coordination (above 0.6) was mainly distributed in cities within the Yellow River Basin region. By 2015, the coupling coordination between urbanization and the ecological environment in the province had gradually improved, though the pace of development remained relatively slow. The relatively high-level coupling coordination areas continued to radiate outward from Zhengzhou, while Shangqiu experienced a slight decline. Zhoukou and Zhumadian progressed to a moderately high level, revealing pronounced spatial ladder differences. By 2019, the province had developed rapidly, with all cities achieving a coupling coordination level above 0.5. Except for Shangqiu, Zhoukou, and Zhumadian, all other cities reached levels above 0.6, while Luoyang and Jiyuan exceeded 0.7, and Zhengzhou advanced to an extremely high level (above 0.8). In 2022, the province further accelerated its development, with all cities attaining levels above 0.6. Jiyuan progressed to an extremely high level, spatially forming a trend centered around the dual cores of Zhengzhou and Jiyuan, with other areas gradually declining in level. Thus, the spatial and temporal disparities in Henan Province are primarily attributed to the radiating influence of the Yellow River Basin and the strong support and development policies implemented by the national and local governments in recent years, particularly for Jiyuan.

4.3 Center of Gravity Model Analysis

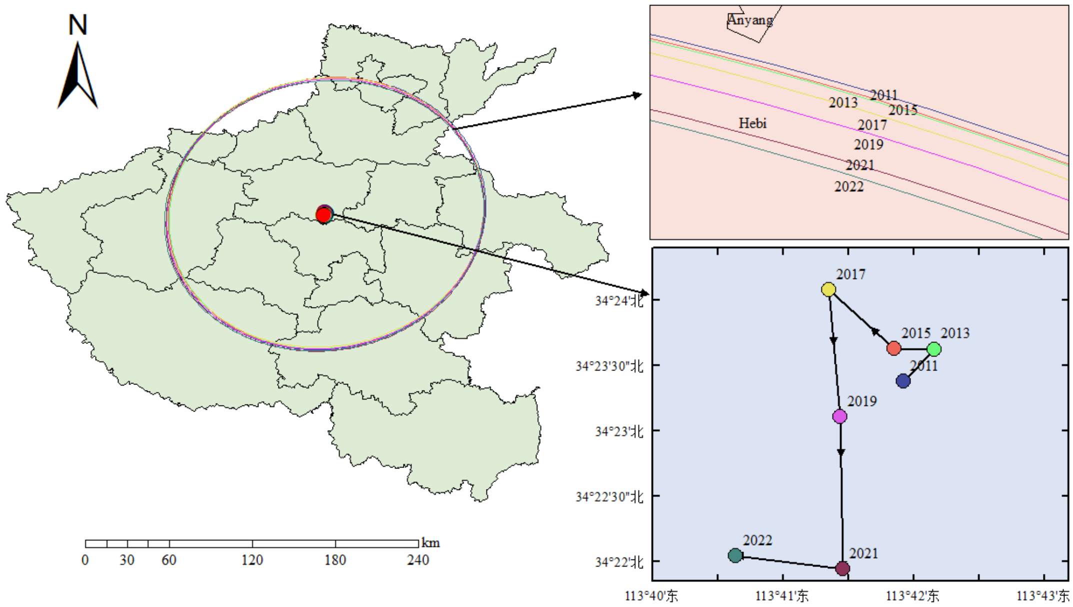

Fig.5. Trajectory Migration Map

In the study, the center of gravity shift model was used to analyze the spatial and temporal patterns of the center distribution and evolutionary trends in the coupling coordination between urbanization and the ecological environment. The results are shown in Figure 4. The findings indicate that the center of gravity for the coupling coordination between urbanization and the ecological environment is generally located in the southern part of Zhengzhou, shifting within the area of Xinzheng City. The longitude and latitude variations are approximately between 113°40.5′E and 113°42.25′E, and 34°22′N and 34°24′N, indicating a relatively stable position. In 2013, the center of gravity shifted briefly to the northeast, then moved back westward, and began shifting northwestward. Starting in 2017, it began moving southward, with the most significant shift occurring by 2021. This period also saw the fastest growth in the degree of coupling coordination. Overall, the center of gravity has been shifting toward the western region, suggesting that in recent years, the development speed of coupling coordination levels in the western part of Henan Province has been higher than that in the eastern part. This aligns with the earlier finding that the coupling coordination level evolved from a ladder-like differential distribution centered around Zhengzhou to a trend of higher levels in the west and lower levels in the east. However, the overall range and magnitude of change are relatively small, remaining concentrated in the Xinzheng City area.

4.4 Scissors differential analysis

To fully demonstrate the disparities in the coupled and coordinated development between urbanization and the ecological environment, the scissors differential method was further employed to analyze the evolutionary process between the two (see Tab 3).

Tab 3. Scissors Differential Results

Time	Urbanization Development Rate	Ecological Development Rate	Scissors Differential
2012	0.052001	0.024081	0.027878
2013	0.061845	0.037068	0.024715
2014	-0.004	0.039215	0.043195
2015	-0.01815	0.021325	0.03947
2016	0.034897	0.067328	0.032344
2017	0.096475	0.056606	0.039632
2018	0.069598	0.025004	0.044487

2019	0.041161	0.007005	0.034133
2020	0.021645	0.020847	0.000798
2021	0.059897	-0.01304	0.072865
2022	-0.00048	0.056298	0.056719

From the perspective of the development rates of the two systems, both urbanization and ecological environment development show an overall upward trend. First, looking at the ecological environment, it experienced rapid development during 2012–2015 and 2016–2017, followed by a declining trend from 2020 to 2021, before rebounding in 2022. In contrast, the development of urbanization has been more complex and variable. During 2012–2013 and 2015–2019, urbanization in Henan Province exhibited relatively fast growth rates. Although there were fluctuations in 2018, the overall pace remained substantial. Growth slowed from 2019 to 2020, but picked up again in 2021.

From the perspective of the scissors differential, the overall trend shows a pattern of "fluctuation–decline–rise." From 2012 to 2017, the fluctuation was relatively minor with no extreme deviations, indicating a relatively stable match between the two systems during this period. Although fluctuations occurred after 2014, the differential generally remained within a moderate range of 0.03–0.045, suggesting that the tension between urbanization and the carrying capacity of the ecological environment was gradually emerging but had not yet intensified. In 2019, an extreme minimum value appeared, approaching a state of near-zero scissors differential. This can be attributed to policies implemented around that time, such as pollution reduction, ecological restoration, and stricter control over disorderly urban expansion. In 2020, the scissors differential surged sharply, indicating that the contradiction between urbanization and the ecological environment had fully erupted, with the development gap between the two reaching its peak. This may be related to the "economic recovery first" policy orientation following the pandemic in 2020, which temporarily prioritized economic revival over ecological protection, causing the ecological environment to lag behind the pace of urbanization. In 2021, the value decreased slightly but remained significantly higher than the average level of 0.035 observed between 2012 and 2018. This indicates that while the tension had somewhat eased, it remained at a high level and had not yet returned to a moderate and coordinated range.

4.5 Analysis of Influencing Factors

To investigate the factors that may influence the coupling level between urbanization and the ecological environment in Henan Province, this study employs the Geographically and Temporally Weighted Regression (GTWR) model for further analysis. In the process of urbanization, the improvement of transportation infrastructure is a key factor driving urban expansion and economic development. Additionally, favorable transportation conditions rely on advancements in science and technology and the widespread application of internet-based solutions, enabling intelligent traffic management and promoting green travel. At the same time, government policy support can help strike a balance between urban expansion and ecological protection, fostering the development of green technologies and the preservation of the ecological environment.

The widespread adoption of internet technologies and the innovation in science and technology have not only propelled the construction of smart cities but also provided data support and technological means for ecological management during urbanization, contributing to reducing the negative impacts of urbanization on the ecological environment. Overall, the synergistic effects among transportation, technology, government policies, internet integration, and the ecological environment will directly influence the trajectory of urbanization and the sustainability of the ecological environment. Therefore, this study takes the coupling relationship as the explanatory variable, selecting transportation conditions[20], government support[21], science and technology[22], and internet integration[23] as the influencing factors.

Tab 4. Variable Description

Influencing Factors	Description
Transportation Status	Road Route Mileage
Government Support	General Public Budget Expenditure

Science and Technology	Science and Technology Account For General Public Budget Expenditure
Informatization	International Internet Users

This study conducted an analysis of influencing factors selection using the GTWR model[24]. The model calculations indicate that the study passed relevant significance tests, with an R^2 value of 0.971627, demonstrating that the model possesses high precision and accuracy and can serve as a theoretical reference.

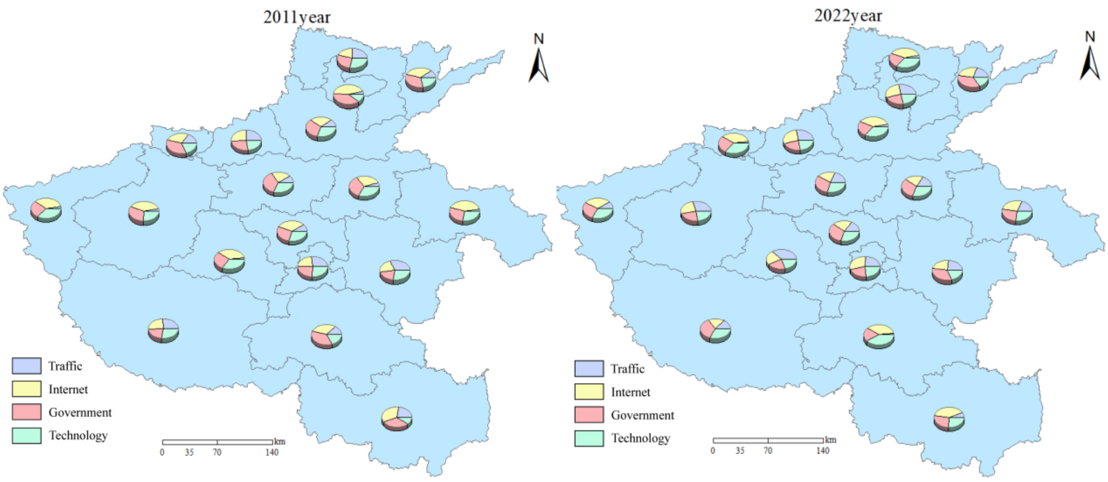

Fig 6. Influencing Factors

The impact of transportation on coupling coordination exhibits significant regional variations. Visual analysis shows that in the initial stage, high-quality areas were primarily located in southern and northern Henan, whereas by the later stage, a horizontal clustering pattern of high-value areas had emerged. Convenient transportation facilitates the flow of capital, information, resources, and other factors, providing favorable external conditions and maximizing the spillover effects of urban development. However, as transportation infrastructure continues to expand, it may lead to environmental degradation in the ecologically sensitive southern Henan region, thereby generating negative impacts[25]. This explains the adverse effects observed in southern Henan.

The impact of informatization on coupling coordination exhibits a positive exponential trend. As shown in Fig 6, the pattern of informatization has shifted from being irregular to regionally clustered, displaying a certain "concave" distribution—higher in the peripheral areas and lower in the central region. The increase in internet users accelerates information dissemination and promotes the upgrading of the industrial structure. However, the impact has slightly weakened in some cities, which may be attributed to technological lag and imbalances in regional informatization development.

Government support plays a significant and positive role in promoting coupling coordination. In the early stage, low-value areas were primarily concentrated in western Henan. In the later stage, the level of support improved significantly across the province, with western and central Henan gradually advancing toward high-value regions. Clear regional disparities exist within the province, with the impact being most direct in western Henan. Appropriate government intervention can provide sound technical and managerial expertise, thereby mitigating negative external factors, accelerating the pace of urbanization and ecological construction, and enhancing coupling coordination.

Science and technology have a fluctuating impact on the system. In 2011, high-quality areas were mainly located in northern Henan, and by 2022, they gradually spread to the central and western regions. Technological advancement can mitigate the impact of traditional models, stimulate innovation, and establish a well-structured[26] innovation ecosystem with a sustainable talent supply. However, due to the siphon effect, resources and talent from northern Henan may, to some extent, flow into the central regions of the province.

5 RESULTS AND DISCUSSION

5.1 Discussion

In 2022, the coupling coordination degree between urbanization and the ecological environment in Henan Province showed significant improvement compared to 2011. All cities have entered the stage of "positive coordination," indicating an overall enhancement in ecological protection within the study area, along with effective urban development planning and notable economic benefits. However, except for Zhengzhou and Jiyuan, which are relatively at a high level of coupling, development across other regions remains uneven, with substantial room for progress. To achieve long-term sustainable development of the urban ecological system in Henan Province, efforts should be made in the following four areas. First, efforts should be directed toward promoting the transformation and upgrading of the urban economic structure to ensure the rational development and utilization of resources, especially in traditional coal-based cities and industrial cities. Second, the government should increase fiscal expenditure on ecological and environmental protection, formulate corresponding policies, strictly control over-exploitation of resources, enhance ecological standards, and strengthen conservation efforts. Third, regional cooperation should be strengthened to reinforce the core radiating function of the Zhengzhou metropolitan area, forming a spatial pattern characterized by "central leadership, regional synergy, and inter-provincial collaboration." This includes promoting industrial and ecological coordination and improving infrastructure and resource mobility. Fourth, development potential should be explored by leveraging cultural history and resource endowments to build culturally renowned cities. Cities such as Luoyang and Kaifeng should harness the historical city effect to enhance their development potential.

5.2 Results

This study constructed evaluation indices for urbanization and ecological environment development to elucidate the coupling coordination mechanisms between urban and ecological systems in Henan Province. Using the entropy method and the coupling coordination model, this research quantitatively analyzed the spatiotemporal evolution of the coordinated development between urbanization and the ecological environment at the municipal scale in Henan Province from 2011 to 2022. It also conducted trajectory and differential analyses to identify the main influencing factors. The main conclusions of this study are as follows:

(1) Based on the relationship between the ecological and urban systems, coupling coordination is divided into five stages: declining imbalance, low-level coordination, primary coordination, positive coordination, and advanced coordination. Following the principles of index construction, an indicator system for urbanization and the ecological environment was established. Ten urbanization evaluation indicators were selected based on the requirements for urban development in the new era, and seven evaluation indicators were chosen based on three aspects: ecological pressure, ecological state, and ecological protection.

(2) This study employed the entropy method and a coupling coordination model to quantitatively analyze the spatiotemporal evolution of the coupling coordination between urbanization and the ecological environment in Henan Province. The results show that the overall coupling coordination level in Henan Province has exhibited an upward trend. Radiating outward from Zhengzhou as the center, the focus shows a tendency to shift westward, though this shift is not pronounced.

(3) Compared to transportation infrastructure, macro-level policies, science and technology, and the internet have a more significant impact on the coupled and coordinated development of the study area. The advancement of these latter factors has notably enhanced the level of coupling coordination. In light of the urban development and ecological requirements of the study area, efforts should be intensified in research and development, the integration of digital technologies should be promoted, and technological innovation should be strengthened.

REFERENCES

1. Guo, Y., et al., Space–time indicators in interdependent urban–environmental systems: A study on the Huai River Basin in China. Habitat International, 2015. 45: p. 135-146.
2. Huang, J. C., and C. L. Fang. "Analysis of coupling mechanism and rules between urbanization and eco-environment." Geographical Research, 2003.
3. Fang C L, Yang Y M. Basic laws of the interactive coupling system of urbanization and ecological environment[J]. Arid Land Geography, 2006.
4. Qiao B, C. L. Fang. The dynamic coupling model of the harmonious development between urbanization and eco-environment and its application in arid area[J]. Journal of Ecology, 2005.
5. Wu, X. and Y. Zhang, Coupling analysis of ecological environment evaluation and urbanization using projection pursuit model in Xi'an, China. Ecological Indicators, 2023. 156: p. 111078.
6. Liu, N., et al., Examining the coordination between urbanization and eco-environment using coupling and spatial analyses: A case study in China. Ecological

Indicators, 2018. 93: p. 1163-1175.

7. Ariken, M., F. Zhang, and N. weng Chan, Coupling coordination analysis and spatio-temporal heterogeneity between urbanization and eco-environment along the Silk Road Economic Belt in China. Ecological Indicators, 2021. 121: p. 107014.
8. Lei, X., et al., Coupling coordination analysis of urbanization and ecological environment in Chengdu-Chongqing urban agglomeration. Ecological Indicators, 2024. 161: p. 111969.
9. Lei, Y., et al., Investigation on the complex relationship between urbanization and eco-efficiency in urban agglomeration of China: The case study of Chengdu-Chongqing urban agglomeration. Ecological Indicators, 2024. 159: p. 111704.
10. Yang, M., et al., Spatiotemporal exploration of ecosystem service, urbanization, and their interactive coercing relationship in the Yellow River Basin over the past 40 years. Science of The Total Environment, 2023. 858: p. 159757.
11. Ma, M. and J. Tang, Nonlinear impact and spatial effect of tourism urbanization on human settlement environment: Evidence from the Yellow River Basin, China. Journal of Cleaner Production, 2023. 428: p. 139432.
12. Li, R., et al., Multiscale assessment of the spatiotemporal coupling relationship between urbanization and ecosystem service value along an urban–rural gradient: A case study of the Yangtze River Delta urban agglomeration, China. Ecological Indicators, 2024. 160: p. 111864.
13. Yang, Z., et al., A new model based on coupling coordination analysis incorporates the development rate for urbanization and ecosystem services assessment: A case of the Yangtze River Delta. Ecological Indicators, 2024. 159: p. 111596.
14. Zheng, Z., et al., Exploration of eco-environment and urbanization changes in coastal zones: A case study in China over the past 20 years. Ecological Indicators, 2020. 119: p. 106847.
15. Cai, J., et al., Coupling and coordinated development of new urbanization and agro-ecological environment in China. Science of The Total Environment, 2021. 776: p. 145837.
16. Wang, Y., et al., A disaggregated analysis of the environmental Kuznets curve for industrial CO2 emissions in China. Applied Energy, 2017. 190: p. 172-180.
17. Levrel, H., et al., OECD pressure–state–response indicators for managing biodiversity: a realistic perspective for a French biosphere reserve. Biodiversity and Conservation, 2009. 18: p. 1719-1732.
18. Hein, L., et al., Temporal scales, ecosystem dynamics, stakeholders and the valuation of ecosystems services. Ecosystem Services, 2016. 21: p. 109-119.
19. Sherrouse, B.C., J.M. Clement, and D.J. Semmens, A GIS application for assessing, mapping, and quantifying the social values of ecosystem services. Applied geography, 2011. 31(2): p. 748-760.
20. Tang, R., Digital economy and total factor productivity of tourism enterprises in China: the perspective of market competition theory. Current Issues in Tourism, 2024. 27(1): p. 76-91.
21. Wang, W., et al., Energy internet, digital economy, and green economic growth: Evidence from China. Innovation and Green Development, 1 (2), 100011. 2022.
22. Zhang, Y., et al., Spatiotemporal differentiation and driving mechanism of coupling coordination between new-type urbanization and ecological environment in China. Sustainability, 2022. 14(18): p. 11780.
23. Song, Y., et al., Research on the Coupling Coordination and Driving Mechanisms of New-Type Urbanization and the Ecological Environment in China's Yangtze River Delta. Sustainability, 2024. 16(13): p. 5308.
24. Cheng, J., S. Dai, and X. Ye, Spatiotemporal heterogeneity of industrial pollution in China. China Economic Review, 2016. 40: p. 179-191.
25. Mejjad, N., A. Rossi, and A.B. Pavel, The coastal tourism industry in the Mediterranean: A critical review of the socio-economic and environmental pressures & impacts. Tourism Management Perspectives, 2022. 44: p. 101007.
26. ur Rehman, S., et al., Open innovation big data analytics and its influence on sustainable tourism development: A multi-dimensional assessment of economic, policy, and behavioral factors. Journal of Open Innovation: Technology, Market, and Complexity, 2024. 10(2): p. 100254.