

Article

Spatio-Temporal Pattern of Coupling Coordination between Urban Development and Ecological Environment under the “Double Carbon” Goal: A Case Study in Anhui, China

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Abstract: Based on the “double carbon” goal, this paper constructs an evaluation index system for the coordinated development of the urban and ecological environments, using the entropy method and coupling coordination degree model to analyze the spatio-temporal differentiation characteristics of the degree of coupling coordination of urbanization and ecological environment in 16 cities in Anhui Province from 2010 to 2020 and uses ArcGIS software to draw the spatial distribution of the coupling coordination relationship between urbanization and ecological environment in these cities. The results show that in terms of time, the coupling and coordination relationship between urban development and the ecological environment in Anhui Province showed a continuous improvement from 2010 to 2020. The coupling degree showed a stable trend, and the coupling and coordination level changed from mild imbalance to a high-quality coordination stage. Spatially, the coupling and coordinated development of 16 cities in Anhui Province in 2020 involves three types: mild imbalance, imminent imbalance and reluctantly coordinated, indicating that there is still a gap between this cities. Therefore, it is proposed to improve the comprehensive level of the ecological environment system, promote the coordinated symbiosis between urban development and the ecological environment and reduce the developmental differences of cities within the region.

Keywords: urban development; ecological environment; coupling coordination



Citation: Qian, L.; Shen, M.; Yi, H. Spatio-Temporal Pattern of Coupling Coordination between Urban Development and Ecological Environment under the “Double Carbon” Goal: A Case Study in Anhui, China. *Sustainability* **2022**, *14*, 11277. <https://doi.org/10.3390/su141811277>

Academic Editor: Antonio Boggia

Received: 24 July 2022

Accepted: 1 September 2022

Published: 8 September 2022

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1. Introduction

From a qualitative perspective, urban development is a manifestation of steady economic growth and effective social progress, and from a quantitative perspective, it is a manifestation of population growth and spatial expansion. A good ecological environment provides conditional support for urban development, but with the continuous development of cities, the ecological environment is under increasing pressure. Anhui Province is an important part of the Yangtze River Delta and plays an important role in promoting the integrated development of the Yangtze River Delta. In recent years, Anhui Province has actively responded to the policy of “carbon peak and carbon neutrality” while accelerating urban construction. However, in the process of rapid development, it is still necessary to overcome the dilemma of ecological environmental protection and the gap between cities. Therefore, it is necessary to couple the coordination of urban development and the ecological environment in Anhui province. We utilized a time-dimension analysis of Anhui province to monitor urbanization and the ecological environment to determine problems of coordination. To analyze the gap between cities in Anhui province from a spatial dimension, it is helpful to grasp the general trend in Anhui province in relation to urbanization and the ecological environment. This will aid in further enhancing the position of Anhui Province in the integrated development strategy of the Yangtze River Delta and promote the acceleration of the integrated development of the Yangtze River Delta and provide expertise and experience for other regions in China and abroad.

The study of the relationship between urban development and the ecological environment in foreign lands can be divided into the following two stages. The first stage (late 19th century to 20th century) began with the “pastoral city” theory proposed by Howard (1898). In the early 20th century, on this basis, scholars put forward the “Wide-acre City Theory” (Wright, 1932) and the “Northam curve” (Northam, 1932), “stress-state-response” model (Rapport, 1979), sustainable development theory, circular economy theory (Pearce, 1990), environmental Kuznets curve (Grossman, 1995) [1] and other ideas and theories. In the second stage (since the 21st century), scholars began to pay attention to the coordinated developmental relationship between urbanization and the ecological environment. Research during this period mainly showed the following three characteristics: first, the research angle was more distinct. Olish (2006) analyzed the nature of coordinated development between urbanization and the ecological environment from the perspective of survival capacity and green cities [2]; Chikaraishi et al. (2015) studied the relationship between urbanization and carbon emissions from the perspective of the environment [3]. Second, the research content is more in-depth. Odum H.T et al. (2000) adopted the system dynamics and sensitivity model, took some regions and cities in the world as research objects for analysis and proposed the bidirectional impact mechanism of cities on environmental change in the process of development [4]. Harveson P M et al. (2006) analyzed the data of Florida in the past 30 years and believed that in the process of urbanization, the surge in population would have a certain impact on the survival and development of other biological populations [5]. Third, the research purpose is clearer. Beall (2010) proposed in *Urbanization and Development* that strengthening the construction of ecological civilization in the aspects of natural resource protection and industrial structure upgrading can greatly promote the sustainable development of cities [6]. F. Martellozzo et al. (2018) studied land loss in rural areas, and the expansion of urban areas in Italy over the past several decades, and the results showed that only with sufficient attention to environmental protection issues can urban development continue [7].

Domestic research on the relationship between urban development and the ecological environment has been carried out mainly from the following two aspects. The first is the research of related theories. From the 1980s, scholars put forward the theory of “social-economic-natural composite ecosystem” (Ma Shijun et al., 1984) [8] and the concept of “urban ecological reservoir” (Wang Rusong et al., 1988) [9]. In the 21st century, domestic scholars began to pay more attention to the interrelationship between urbanization and the ecological environment. Fang Chuanglin (2006) revealed the coercive effect between the two systems, that is, an increase in urbanization levels has a certain constraint effect on the development of the ecological environment, the carrying capacity of the environment would in turn affect the development of urbanization, and the two systems are linked in their development [10]. Liu Haimeng et al. summarized the theoretical analysis framework of “Coupled Rubik’s Cube (CHNC)” from four aspects of space, time, appearance and organization, and further elaborated the coupling principle of urban development and ecological environmental protection [11]. Yang Liang et al. analyzed the coordination relationship and decoupling state between urbanization and ecological environment in Xingtai city by using decoupling theory [12]. Some scholars believe that urbanization has a negative impact on the ecological environment. For example, Du Leshan et al. (2017) suggest that excessive urban development would inhibit the ecological environment [13]. Ma Hongmei et al. (2020) argue that urbanization has a significant coercive effect on the ecological environment [14]. While some scholars believe that urbanization has a positive impact on the ecological environment, Wang Shaojian et al. (2015), for example, argue that an increase in the level of urbanization means an increase in the total economic volume, which makes the investment in environmental protection increase and can alleviate ecological pressure to a certain extent [15]. The second is about the empirical study of coupling coordination relationships. Firstly, regarding the construction of indicators, the four dimensions of population, economy, society and space are used to construct the urbanization indicator system. Yang Yang et al. (2020) believed that land use has an important influence

on urban development, so both added the land urbanization subsystem to the study of urbanization development [16]. To construct the urbanization and ecological environment index system, Mao Huiping et al. (2021) took from the four dimensions of population, economy, society and space and the three dimensions of ecological environment level, pressure and protection [17]. While level, pressure and governance (response) of the ecological environment are mostly used to construct the ecological environment index system, Guo Hongping (2019) added the green life subsystem to the study together with resource utilization, environmental governance, environmental quality, ecological protection and growth quality to form the ecological civilization construction evaluation indicator system [18]. Wang Lunyan et al. (2021) constructed the ecological environment system from ecological environmental state, pressure and governance [19]. Secondly, regarding model construction, most scholars used a coupling coordination model to study the relationship between urban development and the eco-environment [20,21]; while on this basis, the interaction coercion model (Ma Yan, 2020) [22], gray correlation degree model (Zhou Zhengzhu et al., 2020) [23], remote sensing (Zhao Jinlong et al., 2021) [24], relative development model (Guo Yukun et al., 2021) [25], SEM model (Gao Honggui et al., 2021) [26], and geodetector models (Guo Lina et al., 2022) [27] were used to conduct a comprehensive study. For example, Feng Yuxue et al. (2020) used the decoupling model and gray prediction model to analyze and predict the coupled coordination relationship of the Qinghai-Tibet Plateau [28]. Sun Bin et al. (2021) used the ARIMA-BP combination model to predict the coupling coordination of urban agglomerations in the Yellow River Basin [29]. Thirdly, regarding the research scale, the research area mainly includes national [30], urban agglomerations [31], regions [32], provinces [33] and other different regions. For example, He Qingyun (2020) et al. used the objective entropy weight method to calculate the index weights of the urbanization system and ecological environment system in the middle reaches of Yangtze River urban agglomeration and made a comprehensive evaluation of the development status of the system [34]. Guo Haonan (2021) analyzed Taiyuan city as the research object [35]; Yun Xiaopeng (2022) took the Yellow River basin as an example and mainly measured the coupling coordination and interaction relationship [36].

In summary, there are many research achievements on urban development and ecological environment development in China and abroad. And this explanation of the harmonious relationship between urban development and the ecological environment is universal, which provides a solid theoretical basis and method reference for this paper. Foreign scholars take ecological environment factors into consideration in urbanization development, focusing on the relationship between urbanization, economic development and the ecological environment, while Chinese scholars started to study the coupling coordination relationship between urbanization and ecological environment late, mainly focusing on quantitative research. There are still many aspects to be improved. First, the indicator system of urban development and ecological environment is not perfect and lacks timeliness. The existing studies rarely combine the “double carbon” target to build an indicator system. Therefore, this paper combines the “double carbon” target to select indicators, such as energy consumption per unit GDP, to enrich the ecological environment indicator system. Second, the link mechanism and main influencing factors between urban development and ecological environment are relatively weak. Scholars’ studies mostly stay in the measurement of coupling coordination, without longitudinal comparison in the time dimension, horizontal comparison in the cross-section dimension and three-dimensional comparison in the space dimension. At the same time, urbanization as a dynamic measure of the process is relatively rare. Therefore, this paper analyzes the coupling coordination relationship between urban development and ecological environment in Anhui Province from two dimensions of time and space to promote the coordinated development of the two. Third, the research on provinces is less and lacks pertinence. Scholars mostly take some regions and urban agglomerations as the scale of research, and there are few studies on individual provinces. Therefore, this paper takes Anhui Province as the research object

and analyzes the evolution of characteristics of Anhui Province and the developmental differences among cities from the perspective of space and time, which is more targeted.

Therefore, this paper is based on the “two-carbon” goal, takes the statistical data of Anhui Province from 2010 to 2020 as an example and uses the coupling coordination degree model to analyze the coupling coordination change characteristics of urbanization and the ecological environment in Anhui Province from two aspects of time and space. The research contribution of this paper is to provide an operable theoretical basis and practical criteria for cities in China and abroad, narrow the regional urban gap and promote regional integration development. At the same time, this paper provides an overall idea and future direction for other cities in China and abroad to coordinate the relationship between urbanization and the ecological environment, and to a certain extent, it is conducive to the acceleration of the integration of the construction of China’s Yangtze River Delta, optimizing the regional economic development pattern and helping China to achieve the “double carbon” goal and the sustainable development of cities.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

Anhui province is a strategic area for national economic development. It is located in east China, close to the Yangtze River and Huai River, and belongs to the Yangtze River Delta with Shanghai, Jiangsu and Zhejiang. Anhui province has 16 prefecture-level cities, covering an area of 140,100 square kilometers, and the total population exceeds 60 million. In terms of urban development and ecological environment, Anhui province has actively responded to national policies, focusing on promoting economic development and improving the ecological environment. From 2010 to 2020, the urbanization rate of the permanent population has increased from 43.2% to 58.33%, the per capita GDP has increased from 21,923 yuan to 63,382.8 yuan, and the energy consumption per unit of GDP and the discharge of three industrial wastes have also decreased year by year.

2.2. Data Sources

This paper takes Anhui province as the basic unit to conduct a time series study from 2010 to 2020 and takes 16 prefecture-level cities as the basic unit to carry out spatial research in 2010, 2015 and 2020. Therefore, the data are from the *Anhui Statistical Yearbook*, the *Statistical Yearbook of prefecture-level cities* and the *Statistical Bulletin of social and economic development from 2010 to 2020*, and some missing data are filled by the means method.

3. Research Methods

3.1. Construction of Urban Development and Ecological Environment Index System

According to relevant research documents [2,5,6,8,36], and based on the principles of science, objectivity and availability, the urban development system is divided into four first-class indicators: population development, economic development, social development and spatial development. The construction of an urban development-related indicator system refers to the following documents: the study on urban development by Tang Yiqun [37], the construction of population development indicators by Xu Xuexue [38], the construction of economic development indicators by Wang Xing [39], the construction of social development indicators by Wang Qingxue [40,41], and the construction of spatial development indicators defined by LV Youjin [30]. On this basis, according to the actual situation of urban development in Anhui Province, 15 indicators, such as the natural growth rate of the resident population and the per capita road area, are selected to form the urban development indicator system.

According to relevant research documents [3,4,9,10], the ecological environment system is divided into three first-class indicators: ecological environment level, ecological environment protection and ecological environment pressure. For the construction of an eco-environment-related indicator system, refer to the following documents: learn from the research of Weng Yijing [31] on the ecological environment, learn from the definition of

Wang Lunyan [19] on the ecological environment level and protection indicators, and learn from the definition of Mao Huiping [17] on the ecological environment pressure indicators. On this basis, combined with the “double carbon” target and the actual situation of the ecological environment development in Anhui Province, 11 indicators, such as the green coverage rate of the built-up area and the total industrial sulfur dioxide emission per capita, are selected to form the ecological environment indicator system (see Table 1).

Table 1. The index system of coupling coordination degree of urban development and ecological environment.

Target System	Primary Index	Secondary Indicators	Indicator Weight	Indicator Nature
Urban development	Population development (0.193)	Urbanization rate of permanent population	0.064	+
		Natural growth rate of permanent population	0.059	−
		Proportion of employment in the tertiary industry	0.070	+
	Economic development (0.268)	GDP per capita	0.066	+
		Proportion of output value of secondary and tertiary industries in GDP	0.068	+
		Total fixed asset investment	0.088	+
		Total imports and exports as a percentage of GDP	0.046	+
	Social development (0.378)	Per capita disposable income of urban households	0.065	+
		Per capita living area of urban residents	0.093	+
		Number of university students per 10,000 population	0.043	+
		Number of doctors per 10000 population	0.086	+
		The total retail sales of social consumer goods	0.091	+
	Spatial development (0.161)	Road area per capita	0.048	+
		Built-up area	0.062	+
		Urban population density	0.050	+
Ecological environment	Ecological environment level (0.294)	Total water resources per capita	0.093	+
		Per capita park green space	0.062	+
		Greening coverage rate of built-up area	0.055	+
		Percentage of days with air quality at or better than Grade II	0.084	+
	Ecological environment protection (0.169)	Centralized treatment rate of sewage treatment plant	0.042	+
		Comprehensive utilization rate of industrial solid waste	0.093	+
		Harmless treatment rate of domestic waste	0.034	+
	Ecological environment pressure (0.537)	Total industrial wastewater discharge per capita	0.182	−
		Per capita industrial sulfur dioxide emissions	0.149	−
		Per capita production of industrial solid waste	0.045	−
		Per capita electricity consumption	0.061	−
		Energy consumption per unit of GDP	0.100	−

Note: “+” indicates a positive indicator, and the greater the index value, the better the effect. “−” indicates a negative indicator. The larger the index value, the worse the effect.

3.2. Entropy Value Method to Determine Indicator Weight

3.2.1. Data Standardization

Since each indicator unit is different, it is necessary to standardize each indicator. The standardization formula of positive indicators is Equation (1), and that of negative indicators is Equation (2).

$$X_{ij} = \frac{x_{ij} - \min(x_{1j,2j,\dots,nj})}{\max(x_{1j,2j,\dots,nj}) - \min(x_{1j,2j,\dots,nj})} \quad i = 1, 2, \dots, n, j = 1, 2, \dots, m \quad (1)$$

$$X_{ij} = \frac{\max(x_{1j,2j,\dots,nj}) - x_{ij}}{\max(x_{1j,2j,\dots,nj}) - \min(x_{1j,2j,\dots,nj})} \quad (2)$$

In the above formula: $i = 1, 2, 3, \dots, n$, $j = 1, 2, 3, \dots, m$; X_{ij} is the total index value of Anhui province in terms of the time dimension and is the index value of 16 cities in terms of space dimension; X_{ij} is the standardized value.

3.2.2. Determine the Weight of Each Indicator

First, to quantify each indicator, the calculation formula is displayed in Equation (3).

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad i = 1, 2, 3 \dots n, j = 1, 2, 3 \dots m \quad (3)$$

Next, to calculate the information entropy of each index item, where n is the year from the time dimension and the city from the space dimension, the calculation formula of information entropy is displayed in Equation (4).

$$e_j = -k \sum_{i=1}^n p_{ij} \ln(p_{ij}) \quad (k = 1/\ln(n), k > 0, e_j \geq 0) \quad (4)$$

Finally, to calculate the weight of each index and the calculation formula is displayed in Equation (5).

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

According to the above formula, we get the index weights in Table 1 from the time dimension.

3.3. Construction of the Coupling Coordination Degree Model

3.3.1. Coupling Model

The coupling degree model can reflect the degree of mutual influence between two or more systems. A high degree of coupling indicates that these systems have a positive influence and promote each other; otherwise, it is a negative influence and the systems inhibit each other. In this paper, we use the coupling degree model to effectively reflect the degree of mutual influence between urban development and the ecological environment.

First, we calculated the development index of urban development and the ecological environment by Equation (6).

$$U_c = \sum_{j=1}^m (W_j^* X_{ij}) \quad (c = 1, 2, 3) \quad (6)$$

Secondly, we used Formula (7) to measure the coupling degree of these two systems.

$$C = \sqrt{\frac{U_1 U_2}{\left[\frac{U_1 + U_2}{2}\right]^2}} \quad (7)$$

In the above formula: C is the coupling degree, and its value is in the interval $[0, 1]$. U_1 and U_2 are the comprehensive development indexes of urban development and ecological environment, respectively. According to the coupling degree of the two, we get four coupling levels as shown in Table 2.

Table 2. Coupling degree classification type.

Coupling Degree	Coupling Degree
$0.8 \leq C < 1.0$	High level coupling
$0.5 \leq C < 0.8$	Running-in horizontal coupling
$0.3 \leq C < 0.5$	Antagonistic horizontal coupling
$0 \leq C < 0.3$	Low level coupling

3.3.2. Coupling Coordination Degree Model

The coupling degree can reflect the coupling status between urban development and the ecological environment but cannot measure the coupling coordination level between the two, so this paper introduces the coupling coordination degree model. The degree of coordinated development is a quantitative index to measure the coordination relationship of each system, which can better clarify the degree of coordinated development between the two systems. The calculation formulas are (8) and (9).

$$T = \alpha U_1 + \beta U_2 \quad (8)$$

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

In the formula: D is the coupling coordination degree; T is the comprehensive coordination index; α and β are undetermined coefficients, considering that urban development and ecological development are equally important, so $\alpha = \beta = 1/2$. According to the degree of coupling coordination of urban development and the ecological environment, we get ten coupling coordination levels, as shown in Table 3.

Table 3. Classification of coupling coordination degree.

Coupling Coordination Degree (D)	Coordination Level	Coupling Coordination Degree (D)	Coordination Level
0.0–0.09	Extreme disorder	0.5–0.59	Reluctantly coordination
0.1–0.19	Serious disorder	0.6–0.69	Primary coordination
0.2–0.29	Moderate disorder	0.7–0.79	Intermediate coordination
0.3–0.39	Mild disorder	0.8–0.89	Good coordination
0.4–0.49	Verge of disorder	0.9–1.00	High quality coordination

4. Results and Analysis

4.1. Time Series Analysis of Coupling between Urban Development and Ecological Environment in Anhui Province

4.1.1. Evolution of Urban Development Level

As can be seen from Figure 1, the comprehensive index of urban development in Anhui Province from 2010 to 2020 presented a trend of steady rise. From each level of indicators, the growth of population development level is relatively slow. Economic development showed a fluctuating, upward trend, continuing to grow from 2010 to 2014, and then showed a trend of fluctuation from 2015 to 2020, reaching its highest point in 2020. Social development showed the fastest growth rate, which indicates that the quality of people's life is gradually improving during this period, and the relevant measures to ensure people's quality of life in Anhui Province can be effectively implemented. As for the spatial development level, which includes the continuous expansion of urban built-up area and per capita road area, it showed a slow growth trend, which is basically consistent with the trend of population development.

4.1.2. Evolution of Ecological Environment Level

As can be seen from Figure 2, the comprehensive index of ecological environment development in Anhui Province from 2010 to 2020 showed a fluctuating development trend on the whole, with a slight decline in 2011 and 2013, and a sharp decline in 2019, but an overall upward development. From each level of indicators, the level of ecological environment and ecological environment protection showed a rising trend of fluctuation. The level curve of the ecological environment is higher than the curve of ecological environment protection, indicating that the investment in ecological environment protection in

Anhui province was not sufficient, but the quality of the ecological environment had been improved to some extent. The curve of the ecological environment pressure is basically consistent with the ecological environment composite index. In 2016, the ecological environment pressure increased sharply with an increase in per capita industrial solid waste and per capita electricity consumption, while the growth rate of the ecological environment composite index also accelerated, indicating that the ecological environment pressure had a great impact on the development of the ecological environment.

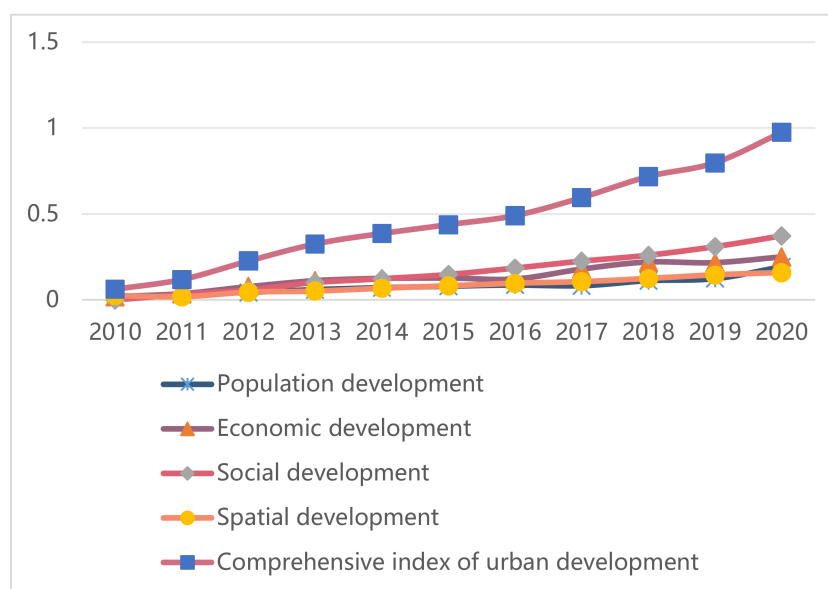


Figure 1. Urban development index of Anhui province from 2010 to 2020.

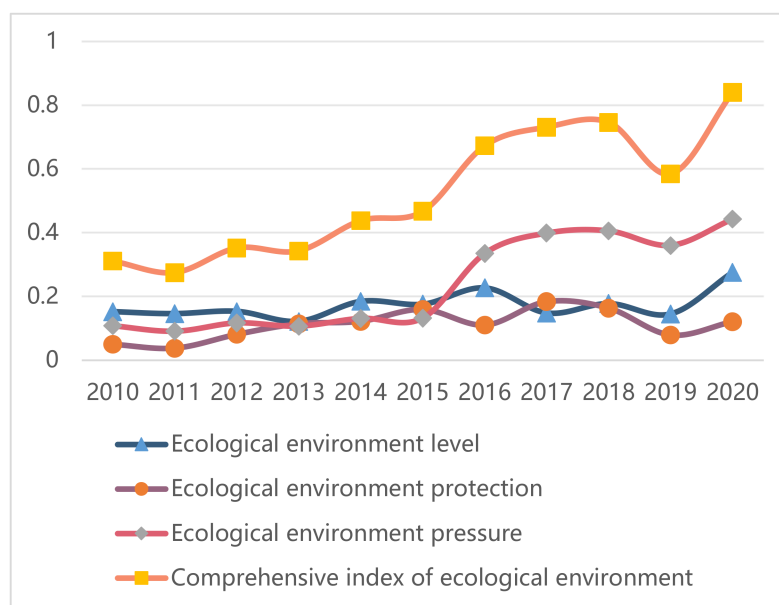


Figure 2. Ecological environment index of Anhui province from 2010 to 2020.

4.1.3. Horizontal Evolution of Coupling Degree and Coupling Coordination Degree

It can be seen from Figure 3 that the coupling status of urban development and the ecological environment in Anhui Province from 2010 to 2020 is at a high level of coupling stage after 2010, indicating that the relationship between these two systems was very close and mutually beneficial. From the perspective of coordination degree,

the coupling coordination between these two systems shows an overall positive trend and has completed the transformation from mild disorder to high-quality coordination, indicating that Anhui province had attached great importance to both urban development and ecological protection, which greatly promoted economic development and ecological environment improvement.

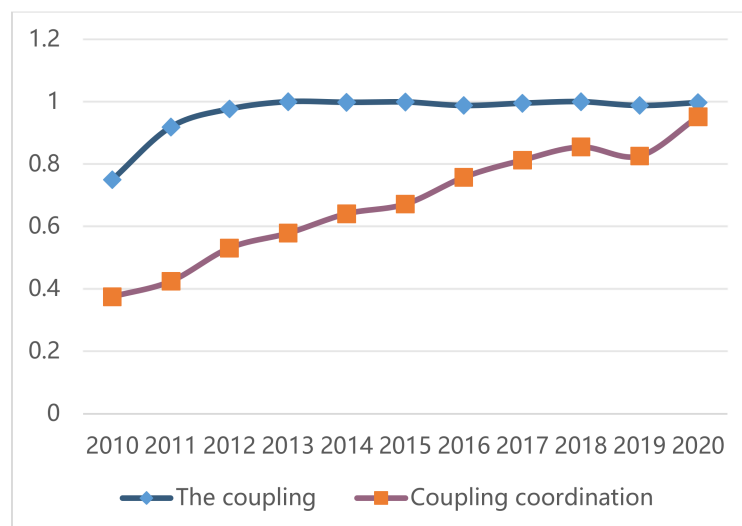


Figure 3. Coupling degree and coupling coordination degree of urban development and ecological environment in Anhui province from 2010 to 2020.

4.2. Spatial Difference of Coupling Coordination Degree between Urban Development and Ecological Environment in Anhui Province

In order to deeply explore the coupling coordination level of urban development and ecological environment in Anhui Province, we have further analyzed the spatial differences in the degree of coupling coordination of urban development and ecological environment in Anhui Province. The final years 2010, 2015 and 2020 are of the “Eleventh Five-Year Plan”, “Twelfth Five-Year Plan” and “Thirteenth Five-Year Plan”, respectively, which can effectively reflect the coupling condition between urban development and the ecological environment in 16 prefecture-level cities in Anhui Province. Therefore, we selected these three-time nodes to measure the degree of coupling coordination of urban development and ecological environment in 16 prefecture-level cities in Anhui Province. According to the measurement results (as shown in Table 4), we mainly classified the coupling coordination types of 16 cities in 2020 and made specific analyses based on the coupling coordination status of 2010 and 2015. Meanwhile, we used ArcGIS software (ArcGIS10.8, created by the Environmental Systems Research Institute of the United States, from Redlands, CA, USA) to draw spatial distribution maps of the coupling coordination level of urban development and the ecological environment of each prefecture-level city in 2010, 2015 and 2020, which can make the results more visual (as shown in Figure 4).

The first category is the reluctantly coordinated: there are four cities including Hefei, Huangshan, Chuzhou and Tongling. Hefei and Huangshan had all dropped from the intermediate coordination stage to the reluctantly coordinated stage, while Chuzhou and Tongling had been in the reluctantly coordinated stage. Hefei as the political, economic and cultural center of Anhui Province, had focused on innovation and promoted the social and economic development of the city in recent years, but had ignored the development of the ecological environment, which led to an increasing gap between urban development and the ecological environment. Huangshan is an excellent tourist city in China; the gap between urban development and the ecological environment was narrowing, but the comprehensive index of ecological environment was still declining, which made the coupling coordination level of urban development and ecological environment low. Chuzhou is the central

city of the Nanjing metropolitan circle and Hefei economic circle, with rich tree species and mineral resources. Its continuous development of the economy promotes urban development and this had been narrowing the gap between urban development and the ecological environment, but the comprehensive index of both was still low, so Chuzhou is placed in the stage of reluctant coordination. Tongling city is a resource-based city and was making efforts to alleviate the dilemma of resource depletion and promote urbanization development, but the damage caused by resource exploitation to the ecological environment could not be ignored, thus Tongling is reluctantly coordinated.

Table 4. Coupling coordination between urban development and the ecological environment in 16 prefecture-level cities.

Prefecture and City	2010	2015	2020
Hefei	0.782	0.730	0.515
Huaibei	0.573	0.545	0.471
Bozhou	0.530	0.556	0.494
Suzhou	0.472	0.510	0.420
Bengbu	0.564	0.586	0.465
Fuyang	0.435	0.519	0.457
Huainan	0.504	0.463	0.326
Chuzhou	0.516	0.549	0.508
Lu'an	0.500	0.553	0.448
Ma'anshan	0.583	0.572	0.498
Wuhu	0.680	0.638	0.481
Xuancheng	0.545	0.598	0.489
Tongling	0.583	0.558	0.532
Chizhou	0.614	0.615	0.495
Anqing	0.530	0.572	0.473
Huangshan	0.640	0.684	0.569

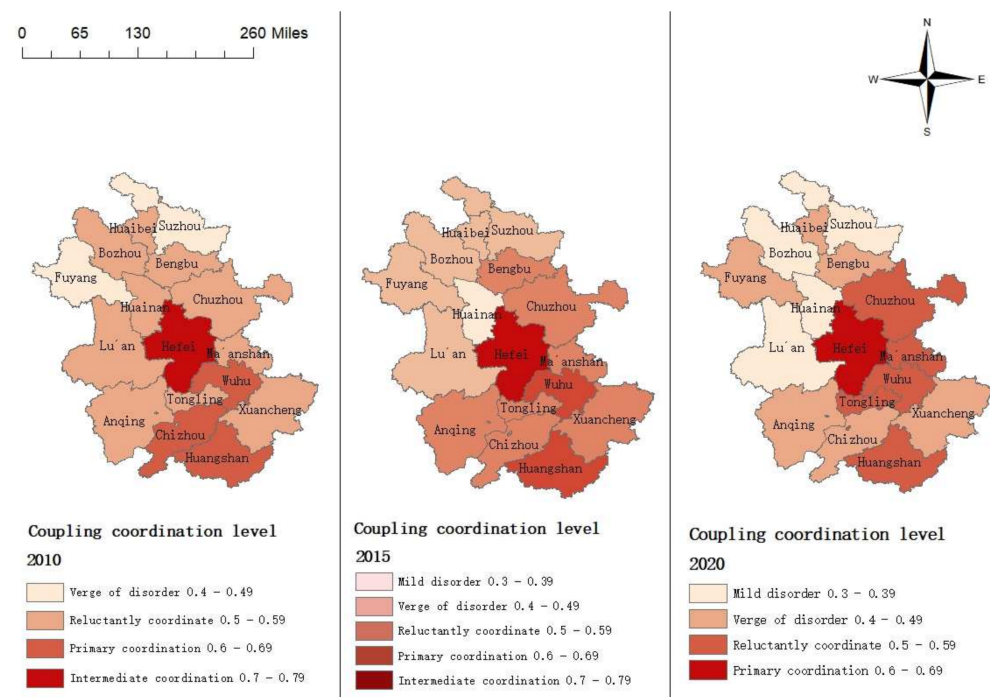


Figure 4. Spatial distribution of the degree of coupling coordination between urban development and ecological environment in 16 prefecture-level cities.

The second category is the verge of disorder: there are mainly 11 cities in this category. The three cities of Chizhou, Xuancheng and Wuhu had remained unchanged in the level of

urbanization, but their comprehensive ecological environment index was declining, and thus their primary coordination was changed into the verge of disorder. Huaibei City, Bozhou City, Bengbu City, Lu'an City, Anqing City and Ma'anshan City had equipment manufacturing, chemical industry, processing or the manufacturing industry as their main industries, but the level of urbanization was developing slowly, and the environment was damaged due to economic development. Thus, their coupling coordination status changed from reluctantly coordinated to the verge of disorder. Suzhou and Fuyang were on the verge of disorder. Although Suzhou City had the largest cloud computing data center in East China and implements the "chain-length system" for ten key industries, the overall urbanization development was still slow, and the environmental protection efforts were not enough, thus it had always been on the verge of disorder. Fuyang City, as a major food production city, paid attention to the industrialization of the construction industry and agriculture, but it did not pay enough attention to urban development and ecological environment protection; thus, it was placed on the verge of disorder category.

The third category is mild disorder which is characteristic of mainly Huainan city. Huainan, as a typical resource city, has its energy production based on coal and electricity. Coal mining and decline in the utilization of industrial solid waste has made the level of urbanization and ecological environment quality of the coupling coordination level became the lowest, and the coupling coordination degree kept falling from 2010 to 2020. The ecological environment pressure would hinder the development of economy, and then affect the development of the city. Thus, the state of coordination between the two system in Huainan city went from the verge of disorder to mild disorder.

5. Conclusions and Suggestions

5.1. Conclusions

It is of great significance to analyze the coupling and coordination between urban development and the ecological environment for realizing high quality development of urbanization and the ecological environment. In this paper, we used a coupling coordination model to analyze the spatio-temporal pattern change characteristics of the coupling coordination development between urban development and the ecological environment in Anhui Province, and the following conclusions were drawn:

1. From the time series analysis of the comprehensive index of urban development and the ecological environment, the level of urbanization in Anhui Province was constantly improving, showing the characteristics of rapid social urbanization development, large fluctuation of economic urbanization, slow urbanization process of population and slow growth of spatial urbanization. The quality of the ecological environment was constantly improving, showing the characteristics of rising ecological environment pressure levels and protection, among which the ecological environment pressure had a great impact on the ecological environment;
2. From the time series analysis of coupling degree and coupling coordination degree between urban development and the ecological environment, the coupling coordination relationship between urban development and the ecological environment in Anhui Province had been continuously improved. Coupling degree was above 0.9 in most cases, showing a stable trend. Coupling coordination degree kept an overall rising trend from mild maladjustment to a high-quality coordination stage;
3. The spatial evolution of coupling coordination degree between urban development and the ecological environment of 16 cities in Anhui province in 2010, 2015 and 2020 was analyzed. It was found that the coupling coordination development process of 16 cities in Anhui Province was different, and by 2020, it mainly involved three types: reluctant coordination, verge of disorder and mild disorder.

5.2. Suggestions

Based on the goal of "carbon peaking and carbon neutralization", the paper constructs an evaluation index system for the coordinated development of urban development and

the ecological environment. This empirical research uses the entropy method and coupling coordination degree model and analyzes the spatial-temporal differentiation characteristics of the coupling coordination degree of urbanization and ecological environment in 16 prefecture-level cities in Anhui Province from 2010 to 2020. According to the research results, some policy implications are proposed, such as improving the comprehensive level of the ecological environment system, promoting the coordinated coexistence of urban development and ecological environment, and narrowing the developmental differences of cities within the region.

5.2.1. Improve the Level of Comprehensive Index to Achieve High-Quality Urban Ecological Development

According to the results of city development and the ecological environment comprehensive index analysis, it is found that urban development and the ecological environment comprehensive index level in Anhui province are rising, but the gap between each subsystem was bigger, and a rising trend is not very stable, so Anhui province should narrow the gap between each subsystem, so as to promote the comprehensive index of level improved steadily. In terms of social development, Hefei is the provincial capital city and ranks first in social development in the whole province. Other cities should learn from Hefei's advanced experience and start from guaranteeing the basic livelihood of urban residents. For example, the number of college students per 10,000 population in Bozhou, Suzhou, Fuyang and Xuancheng is too low, so primary and secondary education should try to cultivate more high-quality talents. Fuyang still has a low number of doctors per 10,000 people, so we should improve the health service system and improve the treatment of health service personnel. In terms of economic development, resource-exhausted cities such as Huaibei and Tongling should develop emerging industries under the background of big data and promote the integrated development of primary, secondary and tertiary industries. Hefei, Wuhu and Ma'anshan should take advantage of the integrated development trend of the Yangtze River Delta, give full play to their resource advantages and increase investment; Huangshan should make reasonable use of the unique advantages of urban development to develop tourism and promote economic development. From the perspective of population development, Anhui province should accelerate the development of population urbanization and formulate preferential policies to attract rural populations to move to cities, especially in Bozhou, Suzhou, Fuyang and Lu'an, where the urbanization rate of the permanent population is low, and they should increase employment opportunities and raise wages to avoid the loss of personnel. From the perspective of spatial development, according to *Anhui province's new urbanization plan (2021–2035)*, Anhui province should speed up the construction of spatial urbanization, rationally plan the layout, improve the efficiency of space utilization, strengthen the communication between Hefei and other cities, strengthen the cohesion and give emphasis to the collaborative construction of various cities. From the perspective of ecological environment development, according to the "Fourteenth five-year plan" for ecological environment protection of Anhui Province, Anhui province should increase investment in ecological protection, improve the level of ecological environment, develop environmental protection industry, promote energy conservation and emission reduction and promote the realization of "double carbon" goals. For example, Huaibei, Wuhu, Chizhou and Huangshan should improve the comprehensive utilization rate of industrial solid waste. Ma'anshan and Tongling should speed up the regulation of industrial wastewater discharge. In general, only by steadily improving the level of urban development and ecological environment development can we realize the high-quality development of urban ecology.

5.2.2. Improve the Level of Coupling and Coordination to Realize the Coordinated Development of Urban Ecology

The analysis results of the level of coupling and coordination between urban development and the ecological environment point out that the overall level of coupling and coordination in Anhui Province in 2020 is relatively high, but the level of each city is still

low, indicating that the coordination between urban development and ecological environment in each city is low. Huainan is in the stage of mild disorder, and the level of urban development and ecological environment index is not high. To this end, Huainan should clarify its own problems, pay attention to the protection of the environment while developing the industry, strictly control various factories, severely punish factories with excessive emissions and actively promote urbanization. Huaibei, Bozhou and the other 11 cities that are on the verge of disorder should shift their focus to coordinating the relationship between urban development and the ecological environment, rather than developing the two separately. For example, Huaibei should pay more attention to the relationship between urban development and the ecological environment during industrial transformation. Four cities, including Hefei, are in the stage of reluctance to coordinate, so they should continue to optimize and coordinate the relationship between urban development and the ecological environment. While actively promoting urban development, they should always pay attention to environmental issues, so that the environment can become a booster for urban development. In general, the degree of coupling and coordination in Anhui Province in 2020 is relatively high, but the overall level cannot represent the level of each city. In order to improve the level of coupling and coordination between urban development and the ecological environment and realize the coordinated development of urban ecology, it should first be clear that the ecological environment is part of urban development. An important part of the process that cannot be ignored is that both the living environment and the working environment are closely related to people, and people are the main force of urban development. Therefore, a good ecological environment will bring people a comfortable living and working environment, thereby improving people's sense of happiness and belonging. Secondly, in addition to ideological understanding, it is necessary to take action. Starting from the top-level design, the government should formulate strict laws and regulations to restrain enterprises and citizens from destroying the environment. In 2018, Anhui issued *The implementation measures for compensation for ecological environment damage in Anhui Province (Trial)*, which provides a legal basis for punishing environmental damage. Starting from social morality, society should vigorously publicize the protection of the environment through various publicity channels and promote the coordinated development of the urban and ecological environments. Starting from individual citizens, citizens should strictly practice protecting the environment and start from themselves. Finally, they should learn from the successful experience of other cities and apply them to the coordinate the relationship between urban development and the ecological environment in Anhui Province by combining with the specific conditions of Anhui Province, to further improve the level of coupling coordination.

5.2.3. Narrow the Regional Development Gap and Achieve Integrated Urban Ecological Development

According to the urban development and the ecological environment on the space coupling coordination relationship of contrast, it is found that 16 cities in Anhui province have an obvious difference in the spatial coupling coordination degree, and the regional development still has a gap; thus, to optimize development patterns and resource allocation, promote regional free flow of production factors, improve resource utilization and sharing of coordination, we must strive to achieve in-depth coordinated development with neighboring areas [26]. All municipal governments should combine the material level and the system level to improve overall coupling and coordination. For example, Hefei should give full play to its leading role, take the lead in establishing an ecological environment protection alliance, establish extensive cooperation with relevant departments and research institutions of various cities and establish long-term working mechanisms such as new energy technology sharing and environmental protection experience sharing so as to further strengthen the coordination and linkage of all municipal levels in urban ecological development. At the same time, it is also necessary to give full play to the radiation role of the provincial capital cities and actively promote the development of surrounding cities. In

addition, as a sub-central city of the Yangtze River Delta urban agglomeration, Hefei can actively coordinate the development of its own advantageous resources in the Yangtze River Delta Urban agglomeration, so as to provide better help to the surrounding cities. Other cities with low economic development level should be deeply aware of the importance of narrowing the regional development gap for urban development and the ecological environment and adhere to the local conditions. They must not blindly learn from the successful experience of other cities and instead make corresponding policy arrangements based on their own actual conditions, refining the spatial plate of regional policy guidance. Second, we must promote the integration of basic public services at the core and promote the coordinated development of the urban and ecological environments with an emphasis on the factors of production and resource sharing, to play the potential of urban development as the main line, to optimize talent training, technical innovation, industrial transfer, etc., as the means for exploring the inhibition of mechanisms of regional gaps. Finally, we should continue to deepen the opening-up and cooperation, break through the limitations of our own conditions, realize regional cooperation and jointly deal with ecological and environmental problems from the aspects of infrastructure connectivity, so as to promote the integrated development of cities and realize the integrated development of urban ecology. Anhui province should play the role of planning as a whole, according to the respective advantages and disadvantages of these cities, through the overall coordination of the allocation of resources and optimize the industrial layout reasonably. This will help poor coupling coordination degrees of cities beyond their bottleneck. The coordination of urban development and the ecological environment can occur through gradual absorption of excellent experiences from other provinces and cities, narrowing the gap among regions, so as to achieve urban and ecological development.

6. Limitation

The paper analyzes the space-time evolution characteristics of the coupling coordination relationship between urban development and the ecological environment in Anhui Province, which has certain significance for the future of urban development and ecological environment protection in Anhui Province. However, there are also shortcomings: firstly, although the indicator system is built in combination with the “double carbon” target, it is not comprehensive enough. Moreover, it is still difficult to effectively measure and quantify urban development and the ecological environment by using “double carbon” related technical standards. Secondly, although the external factors affecting urban development and the ecological environment can be seen from the research, there is a lack of research on the internal factors affecting the coupling and coordination between urban development and the ecological environment. Thirdly, although the coupling coordination model can better describe the coupling coordination relationship between urban development and the ecological environment, it cannot predict the future development of cities. Therefore, the next step will be to improve the team’s research ability and further improve the indicator systems of urban development and ecological environment systems based on the “double carbon” goal. Using “double carbon” related technical standards to effectively measure urban development and ecological environment, analyzing the internal influence factors of urban development and the ecological environment, selecting scientific prediction methods to predict and analyzing the coupling and coordination relationship between urban development and the ecological environment will help develop them in the future.

Author Contributions: Conceptualization, L.Q. and M.S.; methodology, H.Y. and M.S.; validation, L.Q., M.S. and H.Y.; formal analysis, L.Q., M.S. and H.Y.; resources, L.Q.; writing—original draft preparation, L.Q. and M.S.; writing—review and editing, L.Q. and M.S.; visualization, L.Q. and H.Y.; supervision, L.Q.; project administration, L.Q.; funding acquisition, L.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Soft Science Research Project of Housing and Urban-Rural Development Department of Anhui Province, grant number 2022-RK024; Social Science Innovation and Development Project of Anhui Province, grant number 2020CX042; Philosophy and Social Science Planning Project of Anhui Province, grant number AHSKY2020D13; Cooperative Education Program of Ministry of Education, grant number 202002237018; Education, Teaching and Research Project of China Association for Construction Education, grant number 2021005; Teaching Research Project of Anhui Jianzhu University, grant number 2021jy34; National Innovation Project for College Students, grant number 202210878067; Key Research Project of Humanities and Social Sciences of Anhui Province, grant number SK2019A0653, SK2020A0269.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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