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Coupled Urbanisation and Ecological Protection along the Yellow River Basin in the Context of Dual Carbon

Liping Wang [1,2], Zhongyi Qu [1,2], Wei Yang [1], Enliang Ren [1] and Tao Tang [3,*]

[1] School of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China
[2] Autonomous Region Collaborative Innovation Center for Integrated Management of Water Resources and Water Environment in the Inner Mongolia Reaches of the Yellow River, Hohhot 010018, China
[3] CAS Key Lab of Low-Carbon Conversion Science and Engineering, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China
* Correspondence: tangt@sari.ac.cn

Abstract: "Peak carbon and neutrality", also known as dual carbon, is the key to solving the problems of energy and industrial low-carbon transformation, and is also fundamental to promoting the development of new industries that protect the environment and conserve resources. Among the cities along the Yellow River Basin, the city of Luoyang in Henan province is strategically vital in the coordinated development of the regional economy. Thus, researching the coupling of urbanisation and ecological protection is an important way to realise the dual carbon goal. To explore the coupling and coordination (CC) between urbanisation and the ecological environment, an index system is built for comprehensively assessing urbanisation and ecological environment (UEE) systems in Luoyang, and a coupling model to measure their coordination degree, quantitatively analyzed the CC process and evolution trend of Luoyang's UEE, and explored the driving factors causing their changes through regression analysis. The results show that the integrated urbanisation development index of Luoyang ranges from 0.7571–0.9497; however, the contribution of the city's population to urbanisation is the lowest at only 5.231%. Therefore, it is suggested that the government and other institutions should pay more attention to coordinating the human–land relationship when planning for urban development. The integrated ecological environment development index ranges from 0.7512–0.8266. The contribution ratio of the ecological environment state and pressure on the ecological environment is relatively high, at 27.9% and 48.7%, respectively. Therefore, the city of Luoyang city should reduce the emission of industrial pollutants and improve the environmental level. In addition, the CC degree of UEE of Luoyang ranges from 0.8131–0.9296 during 2016–2021, with an overall trend of steady increase, and the coupling correlation coefficient of R^2 = 0.9335, with a good overall coupling effect. The results show that Luoyang needs to further accelerate its industrial transformation and upgrading and spatial development strategy, and strive to become an environment-optimised city. This study provides scientific and practical suggestions for the CC development of urbanisation and environment in the city of Luoyang, Henan province, and has reference value for accelerating the realisation of the two-carbon strategy.

Keywords: two-carbon strategy; city of Luoyang; urbanisation system; ecological environment system; coupling coordination degree

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1. Introduction

At present, the construction of ecological civilisation in China takes carbon reduction as the key aim, and the improvement of ecological and environmental quality has changed from quantitative to qualitative changes [1]. The two-stage carbon reduction targets proposed by China are "carbon peaking" and "carbon neutrality". The peaking of carbon refers to a time inflection point when CO_2 emissions change from increasing to decreasing, and peaking target includes the year of peaking and the peak itself. Carbon

neutrality is to make carbon dioxide emissions "break even", that is, to achieve CO_2 "zero emissions" [2]. Achieving the double carbon target is an inevitable requirement for the construction of an ecological civilisation, and the double carbon target is both a challenge and an opportunity for individual provinces and cities [3]. Urbanisation is a predestined choice for China to improve its economic strength, people's lives, and human society [4]. However, the environmental problems arising from the current urbanisation process are becoming more and more prominent, and the deterioration of the ecological environment will restrict the sustainable development of cities. Luoyang is located in the west of Henan province, straddling the middle and lower reaches of the Yellow River. With an area of 15,230 km^2, it is the second largest city in Henan province. Luoyang in Henan province was identified as one of the first eight key industrial cities after the founding of the People's Republic of China, and eight projects in the First Five-Year Plan were settled in the city. In addition, this city is the most influential city among the two provincial capitals of Zhengzhou and Xi'an, which can maximise the advantages of sub-central cities and radiate the economic development of the surrounding areas [5]. Therefore, the city of Luoyang in Henan province has an important strategic position in the coordinated development of the regional economy, and a study on the coupling of urbanisation and ecological protection can help with dual carbon goal [6,7]. Therefore, the research firstly analyses the coupling and coordination (CC) evolution mechanism of urbanisation and ecological environment protection under the two-carbon background and then extracts the corresponding evaluation indexes of urbanisation and ecological environment. Based on the present situation of urban development in Luoyang, Henan province, the corresponding index system is constructed from the two dimensions of time and space. Finally, through the coupling model, the coupling degree between urbanisation and ecological environment of the city of Luoyang is calculated, and corresponding guidance suggestions are put forward. The aim is to analyse the urbanisation and ecological environment in Luoyang, and find ways for harmonious the development of urbanisation and the ecological environment, and to accelerate the achievement of the strategic goals of carbon peaking and carbon neutrality. Improve the competitiveness of urban development, while improving the quality of people's lives, and promote the harmonious coexistence between humans and nature.

2. Related Work

At present, under the vision of achieving the double carbon goal, the issue of the coordinated development of urbanisation and ecological environment (UEE) has gradually attracted the attention of government departments and academics, and has become an important issue facing many cities. Yw A et al. used the CC degree and spatial autocorrelation for the spatial characteristics of the coordination degree of UEE in the Yangtze River Delta region, and the research results have important implications. The conclusion is implicated for achieving the coordinated development of UEE [8]. Shang Y et al. conducted spatial and temporal changes research in the CC relationship between urbanisation and the development of coastal cities in Guangdong, and the CC relationship in the region has been improving [9]. Chen H et al. used a coupling coordination model, and a linear regression and grey correlation analysis model to study the coupling of UEE in backward regions. This method provides interactions examining between backward regions and theoretical foundations [10]. Peng S et al. used the coupled coordination model to explore the coupling of UEE in the Yangtze River Economic Zone [11]. Wang J et al. used the coupled coordination model to investigate the coupling of UEE in the Guanzhong region. For scientifically evaluating the coupling of UEE in the Guanzhong region, three years of nighttime lighting and MODIS data were combined, and an overall coupling model and coordination model were applied. It is suggested that the coordinated coupling of UEE is needed [12].

Gao Y et al. empirically studied the ecological carrying capacity of ecotourism in Henan province using the entropy value method and the fuzzy integral evaluation method as examples. The results indicate that environmental pollution management in Henan

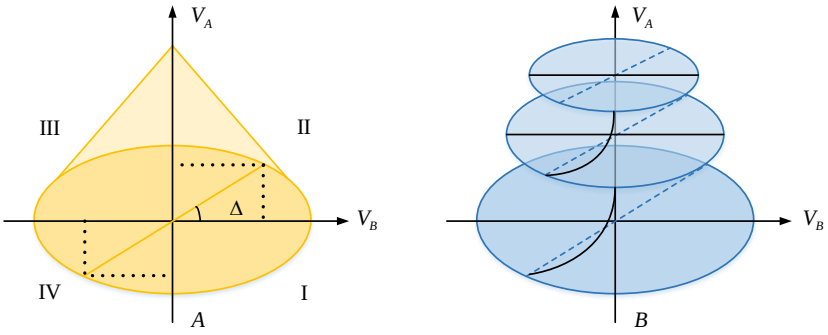
province limits the ecological carrying capacity of ecotourism in Henan province [13]. Yin X et al. examined urbanisation and its impact on vegetation carbon pools from a remote coupling perspective, and the results indicate that urbanisation is more intensively concentrated in the Yangtze River Basin, and that Henan has significantly higher carbon emissions and is the main driver of urban expansion in other provinces [14]. Sun X et al. measured the coupled urbanisation coordination of 13 cities. The results show that the coupled coordination of urbanisation in the south-central and northern Henan provinces is generally low [15]. Shen et al. built a system for new urbanisation and water ecological civilisation evaluation, and comprehensively analysed the current situation and coupled coordination of water ecological civilisation development and urbanisation. The results show that the gap between provinces is gradually narrowing over time [16]. Li B et al. used a grey correlation analysis model to quantitatively analyse the factors influencing agricultural eco-efficiency in Henan province. The results showed that the agro-ecological environment in Henan province from 2015–2019 is gradually improving [17].

It is clear from numerous studies that the research on the CC between carbon emissions are limited in terms of industrial structure and environmental protection at home and abroad. The city of Luoyang in Henan province has an important strategic position in China's coordinated development of regional economies, and a study on the coupling of UEE protection is an important way to achieve the dual carbon goal. This study, therefore, presents an in-depth analysis of the coupled urbanisation–ecological protection relationship in the city of Luoyang in a dual carbon context.

3. Indicator System and Model Construction for Coupled UEE Coordination

3.1. Mechanisms and Pathways of CC Evolution of Urbanisation and Ecological Protection under the Dual Carbon Target

Achieving the dual carbon goal is one of the key strategies for building eco-cities and green cities, and a fundamental path to address the country's ecological construction and to promote urbanisation and low-carbon reforms [18]. Promoting urbanisation is an inevitable choice to reduce ecological pressure, overcome ecological vulnerability, and make the best use of resources [19]. The ecological environment is oppressively affected by urbanisation, but it can also have a positive effect on it. Figure 1 shows the interaction of UEE [20,21].



(a) The stages that the whole system goes through in an evolutionary cycle

(b) Advanced coordinated symbiosis of urbanization and ecological environment

Figure 1. Interaction and stress relationship of UEE.

As shown in Figure 1, the whole process of urbanisation is a process of development in which all its dimensions interact with the integrated system of ecosystems under stress. It is essentially a spiral of interaction and coercion between the development and limitation circles, from a low coordinated symbiosis to highly coordinated development [22,23]. When urbanisation and the ecological environment develop in a coordinated and orderly manner, a positive feedback mechanism occurs between the two, as shown in Figure 2.

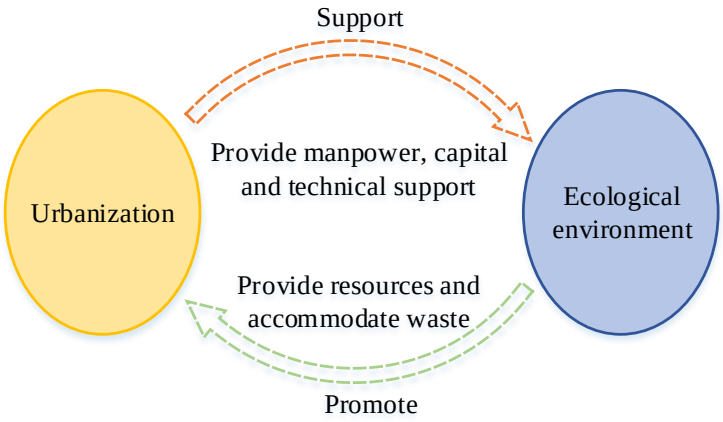


Figure 2. Positive feedback mechanism of UEE.

When the carrying capacity of the ecological environment can hold the urbanisation as in Figure 2, human and financial resources and technology from urbanisation are obtained to achieve better ecological goals. The ecological environment provides air, water and land for urbanisation, and absorbs the waste generated by urbanisation, thus promoting urbanisation. UEE completes positive feedback and forms a positive cycle. When urbanisation surpasses the ecological carrying capacity, the two will be in a state of chaos and disorder, forming negative feedback, as shown in Figure 3 [24,25].

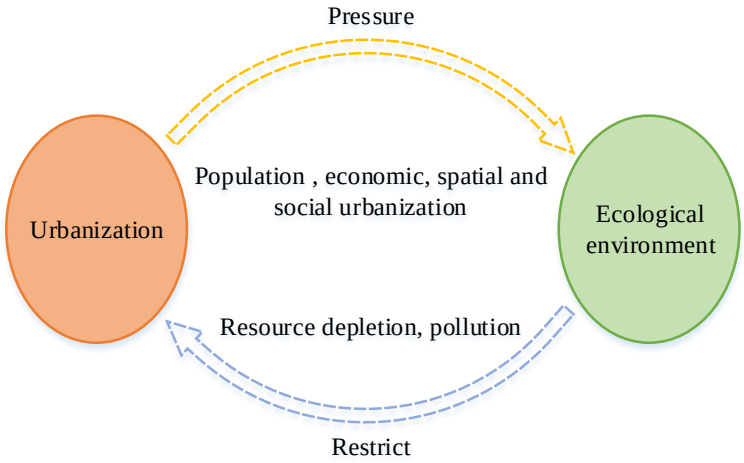


Figure 3. Negative feedback mechanism of UEE.

Urbanisation places a burden on the ecosystem in four ways as shown in Figure 3: demographic, economic, spatial, and social urbanisation. When the pressure on the ecosystem exceeds its carrying capacity, the ecosystem will not be able to solve the problems of pollution and resource depletion arising from urbanisation in a timely manner, and these problems will in turn increase the burden on the ecosystem. In addition, if environmental pollution and resource depletion problems cannot be solved in time, they will in turn constrain urbanisation. The evolution of the CC degree of UEE is driven by the interaction of the two system elements. Based on the interactive coercive relationship, the two can be studied as a composite system, and the evolution equation of this conforming system is as shown in Equation (1).

$$\begin{cases} A = \frac{df(RE)}{dt} = \Delta_1(RE) + \Delta_1(U), V_A = \frac{d_A}{dt} \\ B = \frac{df(U)}{dt} = \Delta_2(RE) + \Delta_2(U), V_B = \frac{d_B}{dt} \end{cases} \quad (1)$$

In Equation (1), $f(RE), f(U)$ represents the dominant part of the conforming system. A, B represents the evolutionary states of the urban subsystem and the ecological subsystem under the influence of exogenous factors, respectively, and A and B interact with each other. V_A, V_B represents the rate of evolution of the two subsystems under their own and external influences. If the rate of evolution is V, then $V = f(V_A, V_B)$. Δ represents the angle between V and V_A or V_B. In an evolutionary cycle, there are four stages for the system, namely, low-level coordinated symbiosis (I), coordinated development (II), limit development (III), and spiral (IV), as shown in Figure 4.

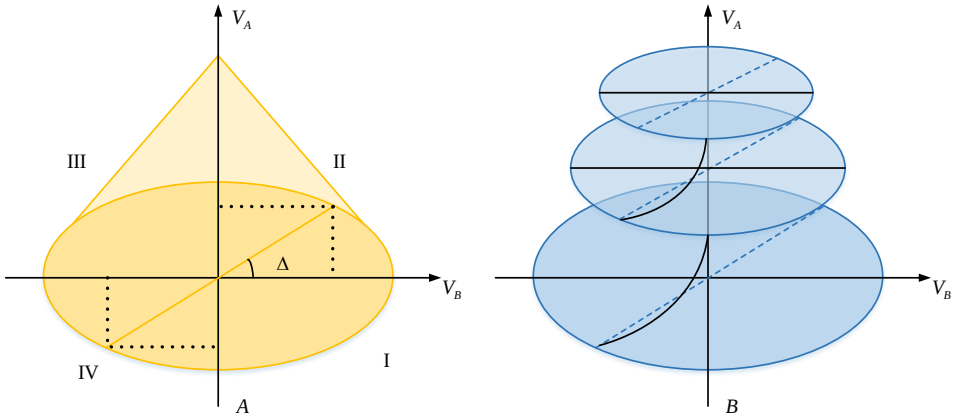


Figure 4. Coupling development of changes of UEE.

As shown in Figure 4, when $-90^{\circ} < \Delta \leq 0^{\circ}$, the system is in stage (I). Urbanisation in this period is slow and basically free from ecological constraints, and the impact of urbanisation on the ecological environment is about zero. When $0^{\circ} < \Delta \leq 90^{\circ}$ is used, the system is in stage (II). Urbanisation in this period has shown its coercive effect, while the constraints imposed by the ecological environment on urbanisation have gradually come to the fore, and the contradiction between the two has begun to emerge. At $90^{\circ} < \Delta \leq 180^{\circ}$, the system is in stage (III). This is a period of rapid urbanisation and the process is increasingly damaging to the ecological environment, and the contradictions between the two are intensified and become more intense. There are two directions of evolution of the system: firstly, the contradiction between ecology and urbanisation is irreconcilable, the system disintegrates and collapses, and civilisation regresses. The second is that after human regulation and control, the harmonious coupling between the two develops in a benign way, forming an advanced harmonious symbiosis, as in Figure 4B, when $-180^{\circ} < \Delta \leq -90^{\circ}$ is in place, the system is in stage (IV). Urbanisation and ecology in this period see a reorganisation of the interactive coercive relationship and a shift to a mutually reinforcing relationship, with the whole system reaching a state of advanced coordinated symbiotic development [26,27].

3.2. An Evaluation Index System for UEE in the Context of Dual Carbon

The city of Luoyang in Henan province has experienced rapid urbanisation in recent years, but its conflicts with ecological pressures have also become increasingly significant [28]. According to the coupled and coordinated evolution mechanism of urbanisation and ecological environment protection under the background of double carbon, the corresponding evaluation indexes of urbanisation and ecological environment are extracted, and according to the current situation of urban development in the Luoyang area, Henan province, the corresponding index system is constructed from the two dimensions of time and space.

The dual carbon target is conducive to promoting urban environmental governance and is of great significance to the urban ecosystem. Therefore, based on the dual carbon strategic target and the corresponding index selection principle, this paper constructs the evaluation index system of Luoyang urbanisation and the ecological environment system.

The research mainly analyzes the CC relationship of UEE in the city of Luoyang, Henan province by establishing the time-space measurement system of urbanisation and ecological environment. This study drew on relevant results and first decided to construct a system of evaluation indicators for accurate evaluation. To eliminate the effects of the order of magnitude and magnitude of the data, as well as the positive and negative directions, the data needed to be standardised. The indicators chosen can be positive or negative: the larger the positive indicator, the better the development conditions of the system, and vice versa, the smaller the positive indicator, the more unfavourable the development conditions of the system. The process of standardising positive indicators is shown in Equation (2) [29].

$$X'_{ij} = \frac{X_{ij} - X_{\min j}}{X_{\max j} - X_{\min j}} \tag{2}$$

In Equation (2), i represents the year, j the indicator number, X_{ij} the original value, and X'_{ij} the normalised value of the positive indicator. $X_{\max j}, X_{\min j}$ are the maximum and minimum values of the indicator in the study year, respectively. The standardization process for replication tables is shown in Equation (3).

$$X''_{ij} = \frac{X_{\max j} - X_{ij}}{X_{\max j} - X_{\min j}} \tag{3}$$

In Equation (3), X''_{ij} denotes a negative indicator normalised value. After normalisation, all values are in the range of [0, 1]. The entropy is objective evaluation that can avoid the subjectiveness of humans as well as overcome the overlapping information seen in multiple indicators, and is applied in sustainability assessment and socio-economic research. Entropy is used to determine the weighting of indicators. It measures uncertainty, and the smaller the value, the higher the variation in the indicator value, which means that the indicator gives more information the greater the weighting of the indicator [30,31]. Firstly, the proportion of standardised sample indicators in the urbanisation indicator system is calculated as in Equation (4).

$$P_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij} \tag{4}$$

In Equation (4), y_{ij} denotes the ith sample of the jth indicator and p_{ij} denotes the proportion of y_{ij}. The entropy in the urbanisation indicator system is settled, as in Equation (5).

$$e_j = -\frac{1}{\ln(m)} \times \sum_{i=1}^{m} p_{ij} \times \ln p_{ij} \tag{5}$$

In Equation (5), each indicator's entropy is e_j and m represents the sample size of each indicator. The redundancy factor j for the indicator f_j is shown in Equation (6).

$$f_j = 1 - e_j \tag{6}$$

Finally, the weights of the indicators are calculated as shown in Equation (7).

$$w_j = (1 - e_j) / \left(n - \sum_{j=1}^{n} e_j\right) \tag{7}$$

In Equation (7), n represents the number of indicator types. The combined level of development of the underlying indicator Y_{ij} is shown in Equation (8).

$$Y_{ij} = W_j \times X'_{ij} \tag{8}$$

The combined development level of the Tier 1 indicators Y_i, as shown in Equation (9).

$$Y_i = \sum_{j=1}^{n} Y_{ij} \tag{9}$$

In the urbanisation system there are m samples and n indicators. The evaluation of the urbanisation level is calculated by integrating the internal indicators and using a linear weighted summation method to evaluate the urbanisation level, as in Equation (10).

$$U = \sum_{i=1}^{m} \sum_{j=1}^{n} w_i y_{ij} \tag{10}$$

In Equation (10), w_j represents j indicator's weight, and y_{ij} represents the i sample of the j indicator. There are m samples and n indicators in the ecosystem, which are evaluated by constructing the ecological security pressure-state-response model and integrating the internal indicators with the linear weighting method formula shown in Equation (11) [32].

$$ESI = \sum_{i=1}^{m} \sum_{j=1}^{n} w_i y_{ij} \tag{11}$$

3.3. Model Construction of Coupled UEE Coordination

In the process of urbanisation, the expansion of built-up areas, increased population density, and changes in industrial structure have led to excessive resource consumption and environmental pollution [33]. Ecosystems are limited in the services they can provide and have a constraining effect on urbanisation. If the demand for and damage to the ecosystem exceeds a certain limit, then urbanisation will be limited. The degree of coupling (CD) is the dynamic correlation of more than two systems that interact with each other to achieve coordinated development, i.e., it reflects the interdependence and constraints among systems [34,35]. The degree of coordination is the benign coupling size, which can reflect the coordination degree, and is constructed on the basis of the coupling degree to describe the system health [36,37]. When the CC degree is high, it represents more mutual promotion and development of the system towards a benign, harmonious, and orderly direction. As in Equation (12), the formula for calculating the coupling degree is as follows.

$$C = \left\{ \frac{U_1 \times U_2 \times \cdots U_n}{\prod (U_i + U_j)} \right\}^{1/n} \tag{12}$$

In Equation (12), C is the coupling level between n systems and the level U_i of integration of the subsystems. The magnitude of the coupling is determined by the subsystem U_i. Since the study measures the CD consisting of two subsystems, urbanisation and ecology, the coupling degree equation of n = 2 is shown in Equation (13).

$$C = \left\{ \frac{U_1 \times U_2}{U_1 + U_2} \right\}^{1/2} \tag{13}$$

In Equation (13), C is the two systems' coupling, urbanisation, and ecology, and U_1, U_2 represent the combined urbanisation level and urban ecology level, respectively. The values of $U_1 U_2$ are in the range of 0–1 and therefore the coupling degree C is also in between. At $C = 0$, the coupling is minimal, the inter-system and intra-system elements are irrelevant, and the system will move towards no development and is in a state of practice-free independence. When C is close to 1, larger coupling means a higher interaction degree. Coordination is the property of the elements within the evolution of a system to be in harmony with each other [38]. The healthy development of a city is predicated on the ecological environment carrying capacity, which in turn is influenced by the city development. If the use of resources, pollutant emissions, and the carrying capacity of the ecological environment are harmonised, the self-cleaning capacity of it can be fully utilised and the harmonious development of the ecological system and the urbanisation system can be achieved. CCDM can better evaluate the coupling degree and harmonisation of UEE. The formula of the coupling degree D coordination of UEE is shown in Equation (14) [39].

$$D = (C \times T)^{1/2} \tag{14}$$

In Equation (14), T denotes the integrated coordination index of the urbanisation and the ecosystem. T is calculated as shown in Equation (15).

$$T = \alpha U_1 + \beta U_2 \tag{15}$$

In Equation (15), α, β are all coefficients to be determined. Since urbanisation and ecology are equally important, $\alpha = \beta$. D ranges from 0 to 1. The closer to 1 means that U_1, U_2 is at a high CC level, and the relationship between the two is at a high level of mutual promotion, with a more harmonious coupling. The closer it is to 0, the more it means that U_1, U_2 is in the antagonistic stage where mutual constraints are not necessary. With reference to existing studies, the degree of coordination was classified into five types, as shown in Table 1.

Table 1. Classification standards for coordinated development of urbanisation and ecological environment.

Classification	Coordination Degree	Coordinated Development Type
Coordinated development	$0.80 < D \leq 1.00$	Highly coordinated development
	$0.60 < D \leq 0.80$	Moderate coordinated development
Balanced development	$0.40 < D \leq 0.60$	On the verge of a dysfunctional recession
Decline of imbalance	$0.20 < D \leq 0.40$	Moderate dysfunctional recession
	$0.00 < D \leq 0.20$	Severe dysfunctional recession

In order to identify the main affecting elements of the CC relationship of the system, the study used regression analysis to analyse the relationship between its indicators and the parameter goodness-of-fit values R^2 were used to check the applicability of the model [40]. Non-parametric correlation statistics were used to explain the non-linear relationships, and the exponential regression model was formulated as in Equation (16).

$$Y = a + bc^{dx} \tag{16}$$

In Equation (16), x represents the urbanisation index value and Y the value of ecological value. a, b, c, d are coefficients of the model. Due to the variability of development in different regions, the study also introduces coefficients of variation to express differences in the coordinated development of UEE in provinces and municipalities. The coefficient of variation is a discrete statistic that measures serial observations, and the index measures the differences between regions and is calculated as in (17) [41].

$$CV = \sigma / \mu \tag{17}$$

In Equation (17), variation coefficient is CV, μ is the arithmetic mean, σ is the standard deviation.

4. Evaluation and Analysis of the Coordination Degree of UEE Coupling along the Yellow River Basin in the Context of Double Carbon

4.1. Comprehensive Analysis of Urbanisation and Ecological Indicator Systems in the Context of Dual Carbon

In the process of comprehensive UEE evaluation, the selection and establishment of a reasonable indicator system is the basis for studying the relationship between the two. Six principles should be followed as far as possible in the selection of indicators, namely scientificity, feasibility, independence, hierarchy, comprehensiveness, and representativeness. Firstly, to make an accurate assessment of the level of development of the urbanisation system, a corresponding indexing system needs to be established. Based on the principles of indicator selection, the study selects indicators that represent the level of urbanisation in four aspects, demographic, economic, spatial, and socio-urban, and the specific index system and the weights it accounts for are in Table 2.

Table 2. Comprehensive index system and weight results of urbanisation in city of Luoyang.

Target Layer	Level 1 Indexes	Weight (%)	Level 2 Indexes	Weight (%)
Urbanisation	Population	18.416	Percentage of non-agricultural population (%)	6.724
			Employment in tertiary industry (%)	4.535
			Density of population (person/km^2)	5.231
	Economy	37.514	GDP per capita (CNY)	7.317
			Tertiary industry output as a percentage of GDP (%)	11.423
			Per capita retail sales of consumer goods (CNY)	10.253
	Space	25.421	Proportion of urban construction land area in municipal district area (%)	9.822
			Per capita urban road area (m^2/person)	5.685
	Society	23.546	Number of college students per 10,000 (people)	7.129
			Public library holdings per 100 persons (volume)	4.632
			Beds in health institutions per 10,000 people (capita)	4.785
			Per capita disposable income of urban residents (CNY)	5.213

As can be seen from Table 2, economic urbanisation, with a weighting of 37.514%, makes the largest contribution to integrated urbanisation. This is followed by spatial urbanisation, with a weighting of 25.421%. The increasing economic level and the expanding spatial area are the main driving forces in Luoyang. Social urbanisation is in third place, indicating that the city needs to improve its social urbanisation. The weight of population urbanisation is only 18.416%, indicating that population and spatial resources are not in harmony, and that government agencies and others should focus more on controlling population numbers and coordinating the relationship between people and land in the city when formulating urban development policies. For example, Figure 5 shows the trend of urbanisation development in the city of Luoyang from 2016–2021.

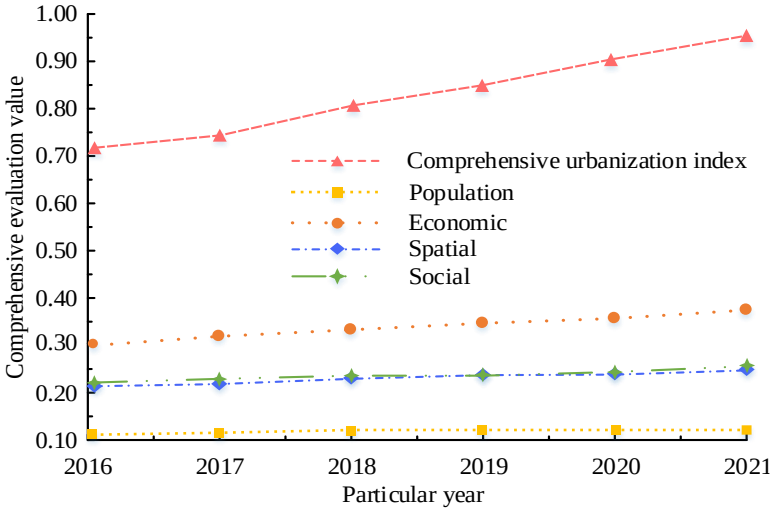


Figure 5. Change trend of the city of Luoyang's integrated urbanisation system.

From Figure 5, the city of Luoyang's urbanisation level over the period of 2016–2021 generally increased with a range of 0.7571–0.9497 for the composite urbanisation development index. Four of the urbanisation indicators show a similar growth trend to that of the composite urbanisation, indicating that the economy is expanding, the industrial structure has been optimised, and the scale of land use is maintaining a steady upward trend in the city's urbanisation process over the period. In Figure 5, the overall development of population urbanisation has been slower and has remained stable, which is due to the fact that the population density indicator negatively affects urbanisation and therefore

maintaining its stable trend is beneficial to urbanisation. The study has established a system of ecological indicators for the city of Luoyang in terms of ecological state, pressure, and governance, with the corresponding secondary indicators and their weights shown in Table 3.

Table 3. Comprehensive indicator and weight of Luoyang ecological environment system.

Target Layer	Level 1 Indexes	Weight (%)	Level 2 Indexes	Weight (%)
Ecological environment	State	27.9	Total water resources per capita (m^3)	7.7
			Park green area per capita (m^2)	14.5
			Green coverage rate of built-up area (%)	7.3
			Forest coverage (%)	15.6
	Pressure	48.7	GDP/capita (CNY)	17.8
			Industrial wastewater discharge per capita (t)	16.1
			Per capita industrial sulfur dioxide emissions (t)	15.9
			Industrial smoke and dust emission per capita (t)	10.4
			Energy consumption per unit GDP ($t \cdot 10^{-4}$ CNY, based on standard coal)	6.3
	Administer	21.7	Sewage treatment plant's centralised treatment rate (%)	5.1
			Comprehensive industrial solid waste utilisation rate (%)	10.8
			Domestic garbage harmless treatment rate (%)	5.4

As can be seen from Table 3, ecological stress has the greatest weighting at 48.7%. This is followed by the state of the ecological environment, with a weighting of 27.9%. It can be deduced that the pressure and state of the ecological environment are the primary elements that evolve the integrated system of the ecological environment in Luoyang. Among them, GDP/capita contributes the most, accounting for 17.8%, indicating that the city's output is higher, which indirectly leads to the increase in environmental pressure. During the urbanisation of the city, industrial wastewater, waste gas, and smoke emissions have had a serious impact. Among the indicators of ecological environment status, the most important one is the forest coverage rate, which reaches 15.6%. As a result, the pressure on the environment is increasing and this is the underlying cause of the evolution of the ecological environment. To ensure the elephantine cycle of the entire ecosystem in the city of Luoyang, the pressure of industrial pollutant emissions must be reduced. For example, Figure 6 shows the trend of the integrated level of ecological system changes in the city of Luoyang from 2016–2021.

From Figure 6, the comprehensive development index of ecological environment in the city of Luoyang during 2016–2021 ranged from 0.7512–0.8266, decreased rapidly during 2016–2018, and picked up slightly during 2019–2021, with a stable overall change trend. From the three indicators of the ecological environment system, the index of the ecological environment pressure changed greatly in this period, and the other indicators remained stable. With the pressure index as a negative indicator, the smaller the starting and ending number, the greater the emissions of industrial pollutants. It can be seen that the state of industrial pollutant discharge in Luoyang is relatively stable. The results show that the management level of ecological environment in Luoyang still needs to be improved.

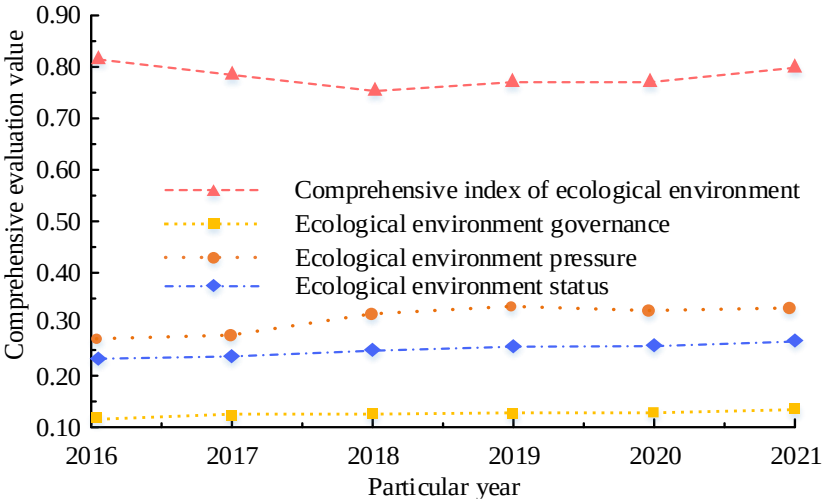


Figure 6. Ecological environment system comprehensive level change trend in the city of Luoyang.

4.2. Analysis of Coupled UEE Coordination in the Context of Dual Carbon

The coupling degree is the interaction between two or more systems. It tells the interdependence and constraints degree between the systems. The degree of coordination is the benign coupling size in coupled interactions, which tells the goodness of coordination. By collating statistics on the CC dynamics of the four subsystems of urbanisation and the ecological environment in the city of Luoyang from 2016–2021, and after regression analysis of the coupling curves, the study obtained a coupling relationship diagram, as shown in Figure 7.

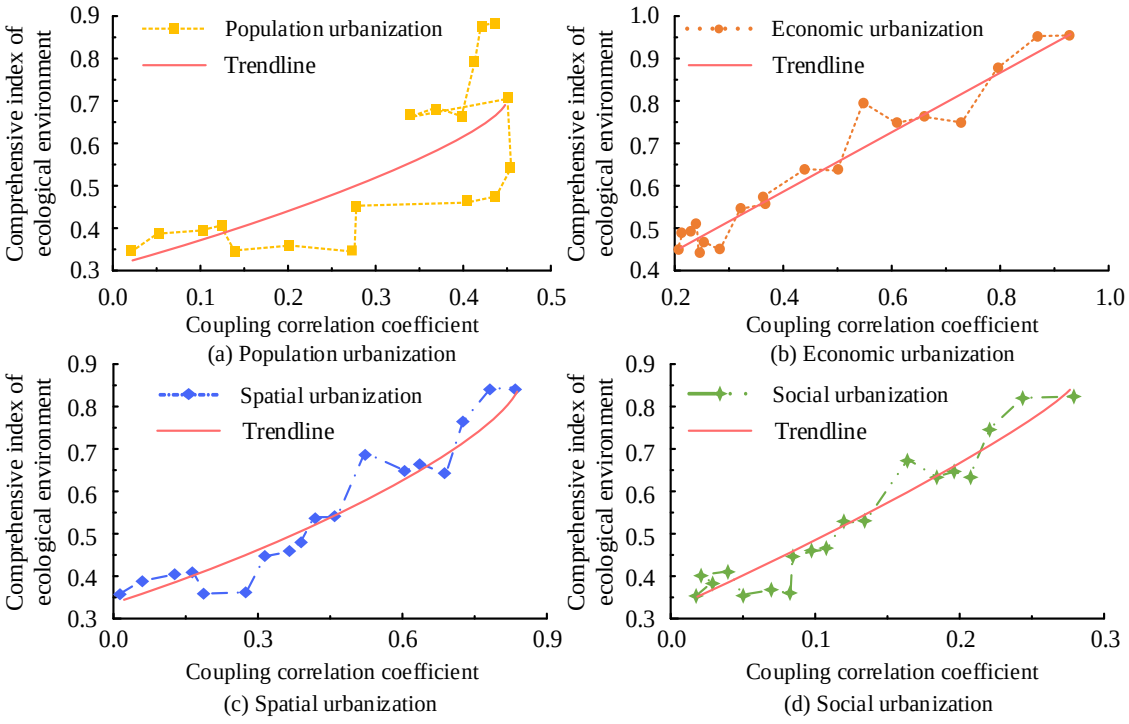


Figure 7. CC of four urbanisation subsystems and ecological environment.

From Figure 7a,d, the coupled correlation coefficients between population and social UEE are 0.459 and 0.278, respectively. They both show a limited influence on the ecological environment. In Figure 7b, the coupled correlation coefficient between economic UEE is the highest at 0.936, indicating the highest correlation between the two and that economic

urbanisation is the most significant cause of change in the upper terrace of Luoyang. The goal of urban development of sustainability in the city is to reduce the environmental pressure generated per unit of economy. As can be seen from Figure 7c, the spatial urbanisation and ecology by coupling correlation coefficient is 0.879, second only to the economic city and ecology coupling correlation coefficient. This indicates that in the urbanisation of the city of Luoyang, the urban built-up area is expanding. The study applied the CC degree model of UEE system to analyse the coupling relationship and the coordination degree. In Figure 8, the CC curves of the UEE system in the city of Luoyang were plotted and trend lines were fitted to the calculated data in order to reflect the coupling and evolution of the two systems more clearly.

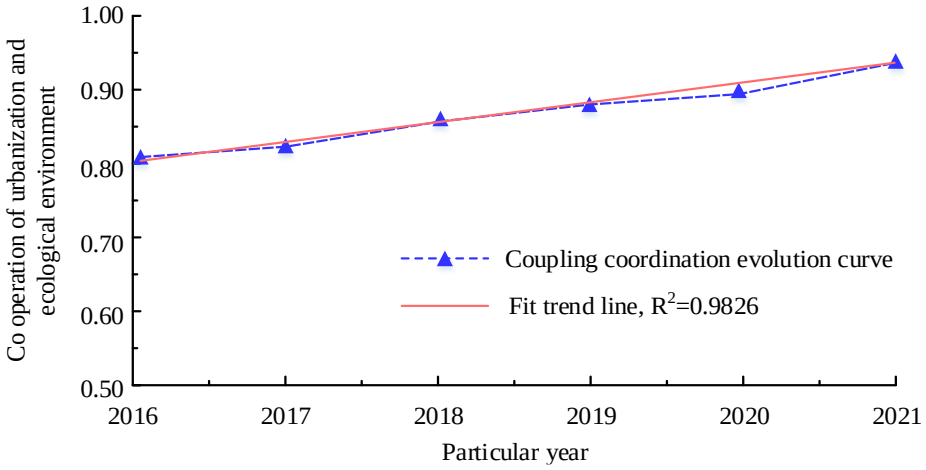


Figure 8. Degree of coupling coordination of UEE.

In Figure 8, the coordination degree of UEE coupling in the city of Luoyang ranges from 0.8131 to 0.9296, with a steady upward trend in general. The system is highly coupled and at the stage of "high coordination—ecological stagnation". Although there is a high CC degree of UEE in Luoyang, the rate of urbanisation still needs to be strictly controlled in future development to ensure ecological protection.

5. Discussion

The comprehensive urbanisation development index of the city of Luoyang from 2016 to 2021 ranged from 0.7571 to 0.9497. During this period, the economic scale was expanding and the land use scale maintained a steady rising trend in the process of the city's urbanisation. The trend of economic, spatial, and social urbanisation and comprehensive urbanisation are the same, which indicates that the economy of the city of Luoyang is continuously rising, the industrial structure is optimised, and the scale of land use is also expanding. However, the contribution of population urbanisation in this city is the lowest, only 5.231%, and population and space resources are not coordinated. Therefore, it is suggested that the government and other institutions should pay more attention to control the number of the population and coordinate the relationship between people and land when planning urban development.

Eco-environment state and pressure are the main factors leading to the evolution of an eco-environment comprehensive system in the city of Luoyang, accounting for 27.9% and 48.7%, respectively. This shows that reducing industrial pollutant emissions and improving the environmental level are the key to ensuring a virtuous cycle of the whole ecosystem in Luoyang. In addition, the coupling correlation coefficient between economic urbanisation and ecological environment is the highest at 0.936, indicating that the correlation between the two is the highest, and the economic city is the main reason for the change of Luoyang. The key to sustainable urban development in this city is to reduce the environmental pressure generated by each unit of the economy.

The coupling coordination degree ° UEE in the city of Luoyang ranged from 0.8131–0.9296, showing a steady rising trend on the whole. The coupling correlation coefficient R^2 of the two was 0.9335, indicating a good coupling effect. The internal performance of the system is highly coupled, and the coordination level is at the "highly coordinated—ecological environment stagnation" stage. To sum up, in order to realise the coordinated and sustainable development of urbanisation and ecological environment in Luoyang city, it is necessary to further optimise the city's spatial development strategy and solve the contradiction between humans and space. At the same time, we need to speed up industrial transformation and upgrading and adjust the economic structure. It is more important to strengthen ecological protection and strive to become an environment-optimised city.

6. Conclusions

A study on the coupling of urbanisation and eco-environmental protection in the city of Luoyang, Henan province, is vital for achieving the national dual carbon goal. The study presents an in-depth analysis of the CC degree of the integrated system and subsystems of UEE in the city of Luoyang from 2016–2021, based on the elaboration of the mechanism of the coupled and coordinated evolution of UEE. The results show that the weight of economic urbanisation is 37.514% during 2016–2021, and its contribution to integrated urbanisation is the largest. This is followed by spatial urbanisation with a weighting of 25.421%. This indicates that the increasing economic level and the expanding spatial area are the main driving forces in Luoyang. In addition, ecological and environmental pressure has the highest weight of 48.7% in this period. The state of the ecological environment is the next most important factor, with a weighting of 27.9%. This indicates that the pressure and state of the ecological environment are the main factors leading to the evolution of the integrated system of the ecological environment in Luoyang City. The range of the urbanisation comprehensive development index in the city of Luoyang during 2016–2021 is 0.7571–0.9497; the range of the ecological environment comprehensive development index is 0.7512–0.8266; and the range of coupling coordination of UEE in Luoyang City is 0.8131–0.9296, with a steady enhancing pattern in general, and the coupling correlation coefficient of them R^2 = 0.9335, with a good overall coupling effect. Although the coupling coordination relationship between the integrated system and subsystems of UEE in Luoyang City is obtained in a more accurate way, there are still certain shortcomings. Due to the complex interaction between urbanisation and the ecosystem, the study only considered the relationship between the integrated system and subsystems, and did not carry out in-depth discussion on the interaction between the subsystems. Therefore, it is hoped that the comprehensive and accurate assessment will continue to be improved in future studies.

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