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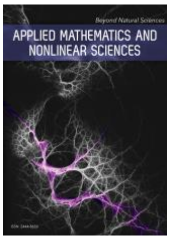

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Analysis of the coupling correlation between environmental protection efforts and economic development level based on artificial intelligence technology

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Abstract

In order to study the influence of environmental protection and economic development level under artificial intelligence technology, and to help achieve the goal of carbon peak in China, this paper studies the coupling degree of socio-economic and ecological environment system, establishes the evaluation index system of coupling between socio-economic system and ecological environment system, calculates the weight of each evaluation index and comprehensive evaluation index by using entropy value assignment method, construct the coupling degree of two systems model, and empirically analyze the coupling degree and coupling coordination socio-economic and eco-environmental systems. In addition, the comprehensive evaluation index of socio-economic and ecological environmental protection systems based on artificial intelligence technology was analyzed. The results show that AI technology benefits environmental protection, the urban economy and environmental protection as a whole are currently in a mutually beneficial symbiosis, and the two systems of ecological environment and high-quality economic development promote each other and develop together. The evaluation indexes of economic scale and economic capacity and social development as a whole are steadily increasing, from 0.00, 0.00, and 0.07 in 2010 to 0.28, 0.15, and 0.53 in 2019, respectively, where the evaluation indexes of economic scale and economic capacity are steadily increasing from 2010 to 2019 due to the rapid development of the tertiary industry, and the evaluation indexes of social development. The evaluation index of the economic scale, economic capacity, and social development drove the rapid development of the economy in 2012-2013, and the rapid development of the economy also led to the rapid development of society. After 2015, the coupling between the two systems has become more and more perfect.

Keywords: Artificial intelligence; Environmental protection; Economic development; Ecological economics; Ecological environment
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1 Introduction

Any human activity of survival and development cannot be separated from the ecological environment as a large system, and economic development activities are closely related to the ecological environment and closely connected [1-2]. In the past, it was believed that ecological protection would limit economic development and that economic development and ecological protection were mutually exclusive and contradictory. “Environmental pollution and ecological degradation are the inevitable results of human economic development, and economic development has to bear the cost of environmental pollution”, and in many countries where economic growth is the macro goal, they use this view as a reason to recklessly destroy the ecological environment to develop production [3-5]. The experience of many western developed countries has warned us not to repeat the same mistakes and take the path of “development before governance” [6]. Green and healthy development of ecological environment is an important part of high-quality development, and the realization of high-quality economic development requires resource-saving, green and healthy development, and only by maintaining the coordinated development of ecological environment and economy can we achieve high-quality national development [7-8]. Pollution has put the ecological environment to a severe test, and countries worldwide have put forward carbon-peaking, carbon-neutral goals. In 2020, China formally put forward the strategic goal of achieving carbon peaking by 2030, and the coordinated development of the socio-economic system and ecological environment has become an important issue in the world, and the degree of coupling between the two is related to the sustainable economic development of a country or region [9-10].

In early studies, scholars did not link ecological environment and economic development but studied them independently. It was not until the mid-1920s that the American scientist McKenzie first proposed the concept of “economic ecology”, arguing that the process of human social development could not be studied solely by economic theory but that human survival and development could not be separated from environmental resources and should be studied by combining the theories of ecology. In the papers [11-12], the term “ecological economics” was introduced to broaden the scope of ecology, the main research objects of this new discipline were introduced in detail, and the relationship between ecological environment and economic development was studied based on ecological-economic coordination theory. The literature [13-15] suggests that accelerated industrialization and exponential growth of the human population will lead to a decline in human well-being. Social conflicts intensify, continued ecological damage, ecosystem collapse, pollution, diseases, disasters, and a series of others fall into a deplorable situation. The literature [16] suggests that the Earth, on which human beings live, is like a spaceship in the universe. Suppose we only focus on economic development and population increase without any limitations. In that case, the resources inside the ship will be consumed sooner or later, leading to the ship's destruction. The literature [17-18] suggests that only by effectively recycling various resources can the Earth's spaceship last in space. The literature [19] puts forward the growth limit theory, pointing out the impact of developing primary and secondary industries on population, resources, and environment and indicating that blindly developing production will deplete resources, and maintaining zero economic growth can avoid such consequences. The literature [20-21] suggests that human beings blindly expand their economic activity areas in pursuit of economic development, but when economic development exceeds the carrying capacity of the environment, it will constrain human development, thus leading to ecosystems on the verge of collapse. In general, pessimists regard the ecological environment as fundamental to human survival and believe that resources and the environment are key constraints to economic development and that the ecological environment must be protected if the economy is to thrive. The literature [22-23] proposes that the scarcity of resources changes with the development of technology due to the market mechanism, which leads people to seek alternative resources to reduce the cost of production and living. The literature [24] suggests that, in contrast to the pessimists, the optimists, while recognizing that technology and various other factors can contribute significantly to economic and social development, also have the problem of ignoring the negative impacts of technology and not paying attention to the ecological environment and sustainable development of resources. Literature [25-26] proposed that new and cleaner technologies should be used to replace polluting and outdated technologies in the economic development cycle and analyzed the changes in the air pollution index to derive the effects of scale, technology, structure, and energy intensity on environmental quality elucidating why the Kuznets curve declines. Literature [27-28] suggested that with the development of the economy, the socio-economy will change to the direction of low pollution and high output, the proportion of industry will continue to decline, and service and technology-intensive industries will dominate, reducing the degree of pollution to the environment. The literature [29-**Error! Reference source not found.** suggested that with the deepening of the understanding of the theory of coordinated development of ecology, environment, and economy, more scholars began to pay attention to the actual level of coordinated development of ecology, environment, and economy, and applied various methods to measure and evaluate the level of coordinated development of the two.

This paper analyzes the interaction between two or more entities or systems by constructing a coupled coordination degree model. The prediction of the system construction model with uncertainty is carried out by identifying the magnitude of differences between different elements of each system, i.e., correlation analysis, and on this basis, the original data series are analyzed to find out their evolution laws and generate a series that conforms to the laws mentioned above, and the coupling degree of first-tier cities and new first-tier cities is predicted and analyzed by constructing a relevant mathematical model, and the social economy and the comprehensive evaluation index of eco-environmental protection system based on artificial intelligence technology were analyzed. Improving ecological environment quality is the requirement and foundation of high-quality development, and the comprehensive systematic evaluation and study of the coupling and coordination of ecological environment and high-quality economic development based on AI technology has important theoretical and practical significance for ecological, environmental protection as well as high-quality development.

2 Coupling model of environmental protection efforts and economic development level based on artificial intelligence technology

2.1 Coupling model

Coupling is mainly used to analyze the degree of association of two and more entities or systems in the development process of mutual influence, a coupling degree that numerically represents the degree of association coupling of these two systems.

The two systems of economic high-quality development and ecological environment operate together in the social environment, and the degree of dependence, influence, and constraint between them constitute the system coupling degree of ecological environment and economic high quality. The specific model construction process is as follows: first, assuming $x_1, x_2, x_3, \cdots, x_m$ that these m indicators indicate economic high-quality development then.

$$f(x) = \sum_{i=1}^{m}\left(w_i x_i\right) \tag{1}$$

$f(x)$ in the above equation denotes the comprehensive evaluation index of the economic quality development system, w_i is the weight of the i-th evaluation index of the economic quality development system, and x_i is the value of the i-th index of the economic quality development system after the standardization process. Then, assuming that $y_1, y_2, y_3, \cdots, y_n$ is the n-th indicator in the ecological environment system, then.

$$g(y) = \sum_{j=1}^{m} \left(w_j y_j \right) \tag{2}$$

In the above equation, $g(y)$ is the comprehensive evaluation index of the ecosystem, w_j is the weight of the j-rd evaluation index of the ecosystem, and y_j is the j-th index of the ecosystem after standardized treatment.

Finally, the coupling degree evaluation model of ecological environment and high-quality economic development is calculated by applying the $f(x)$ and $g(y)$ obtained from the calculation of equation (1) and equation (2) as

$$C = \left\{ \frac{f(x)g(y)}{[f(x)+g(y)]^2} \right\}^{1/k} \tag{3}$$

In the above equation, $f(x)$ indicates the comprehensive evaluation index of the economic high quality development system, $g(y)$ is the comprehensive evaluation index of the ecological environment system; C is the coupling degree of the two systems, $C \in [0,1]$, when $C = 0$, it means that the indicators between the ecological environment system and the economic high quality system do not depend on each other and the correlation degree is extremely low; when $C = 1$, it means that the coupling degree of the ecological environment system and the economic high quality system reaches the peak, and the elements in the system promote each other benignly and develop in an orderly way; k is the constant that regulates the coupling degree of the system, and k is taken as 2 for the ecological environment system and the economic high-quality development system studied in this paper.

2.2 Coupling coordination degree model

The coupling degree indicates the degree of association and coupling of two systems, which does not reflect the coordination between the systems, so it is necessary to measure the level of coordinated development of two systems of economic quality development and ecological environment with the help of the coupling coordination degree model. The specific formula is as follows.

$$D = \sqrt{C \bullet T} \tag{4}$$

$$T = af(x) + bg(y) \tag{5}$$

In the above equation, D denotes the coupling coordination degree of the ecological environment and economic quality development systems; T is the comprehensive coordination index of economic quality development and ecological environment. The main significance is to measure the influence of the ecological environment system and economic quality development system on D; a 、b is the coefficient to be determined, in this paper, the importance of economic quality development system and ecological environment system in the social environment is considered to be the same, so it is taken as $a = b = 0.5$.

Referring to the relevant research of previous scholars, this paper divides the coupling degree and coupling coordination degree into 4 stages and 8 coordination degrees specifically, as shown in Table 1.

Table 1. Coupling degree and coupling coordination level classification criteria

	Judgment criteria	Stage	Phase Characteristics
Coupling degree C	(0-0.3]	Low-level coupling stage	System in disorder
	(0.3-0.5]	Antagonistic phase	The systems are in a state of mutual opposition and incompatibility
	(0.5-0.8]	Breaking-in stage	The system is gradually moving towards order as it grinds against each other
	(0.8-1]	High-level coupling stage	Optimal condition and orderly system development
Coupling coordination D	[0-0.10)	Severe disorders	The level of integrated and coordinated development among systems is low, and the overall coordinated development is at a dysfunctional stage
	[0.10-0.30)	Moderate disorder	
	[0.30-0.40)	Mild disorders	
	[0.40-0.50)	On the verge of disorder	
	[0.50-0.60)	Primary Coordination	The system enters a phase of coordinated and orderly development, and the systems begin to develop in tandem with each other
	[0.60-0.70)	Intermediate Coordination	
	[0.70-0.90)	Good coordination	
	[0.90-1.00)	Quality Coordination	Optimal state, simultaneous development between systems

2.3 Gray prediction model GM (1,1)

Gray prediction is mainly a way to predict the construction of models for uncertain systems. Gray prediction mainly identifies the magnitude of differences between different elements of each system, i.e., to analyze their correlations. On this basis, the original data series are analyzed to find their evolution patterns, generate a series that conforms to the above-mentioned patterns, and predict them by constructing a relevant mathematical model. The following steps are required to construct the model.

The first step is to perform a data test to ensure the feasibility of the model, and the test here is a cascade test.

Let the initial non-negative data sequence be

$$X^{(0)} = \left\{x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(n)\right\} \tag{6}$$

The model can be constructed only when all the values of the stage ratio $\sigma(k)$ fall within the calculated range $\left(e^{\frac{2}{n+1}}, e^{\frac{2}{n+1}}\right)$. The formula and the range of values for the level ratios are

$$\sigma(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)} \tag{7}$$

$$\sigma(k) \in \left(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+1}}\right) \tag{8}$$

The perturbation of $x^{(0)}$ can be weakened by obtaining a first-order cumulative sequence of $x^{(0)}$ after the cumulative operation.

$$x_k^{(1)} = \sum_{i=1}^{k} x_i^{(0)}, k = 1, 2, \cdots, n \tag{9}$$

$Z^{(1)}$ is the sequence generated by the mean of the immediate neighbors of $X^{(1)}$

$$Z^{(1)} = \left\{z^{(1)}(2), z^{(1)}(3), \cdots, z^{(1)}(n)\right\}$$
$$z^{(1)}(k) = \frac{1}{2}\left(x^{(1)}(k) + x^{(1)}(k-1)\right) \tag{10}$$

The differential equation corresponding to the GM(1,1) model can be derived as

$$x^{(0)}(k) + az^{(1)}(k) = b \tag{11}$$

where $z^{(1)}$ is the background value of the GM(1,1) model.

Construct the data matrix B and the data vector Y, respectively.

$$B = \begin{bmatrix} -z(2)1 & \\ -z(3)1 & \\ \vdots & \vdots \\ -z(n)1 & \end{bmatrix} Y = \begin{pmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{pmatrix} \tag{12}$$

Then the column of least squares estimated parameters of the grey differential equation satisfies.

$$u = \begin{bmatrix} a & b \end{bmatrix}^T = \left(B^T B\right)^{-1} B^T Y \tag{13}$$

where a is the development coefficient b is the amount of gray effect.

The model is built and solved for the generated and reduced values. The prediction model is obtained by solving according to Equation.

$$\hat{x}^{(1)}(k)=\left[x^{(0)}(1)-\frac{b}{a}\right]e^{-a(k-1)}+\frac{b}{a},k=1,2,\cdots,n \tag{14}$$

After cumulative subtraction, the reduced predicted values are obtained.

The accuracy test criteria of the gray prediction model are shown in Table 2.

Table 2. Accuracy test standard

Grade	P Value	C Value
Very good	≥0.95	≤0.35
Good	≥0.8	≤0.5
Qualified	≥0.7	≤0.65
Failure	<0.7	>0.65

3 Analysis of the coupling correlation between environmental protection and economic development based on artificial intelligence technology

3.1 Coupling index system

Based on the above theoretical connotations, this paper uses the city-level panel data from 2006 to 2018 as a sample to construct an evaluation system for coupling environmental protection and high-quality economic development in Chinese cities. Specifically, it includes six first-level indicators, namely, ecological environment level, ecological environment pressure, ecological environment protection, economic scale, economic capacity, and social development, as shown in Table 3.

Table 3. Weights of coupled socio-economic and eco-environmental system evaluation indicators

Target layer	Criteria layer	Criteria layer	Indicator layer	Indicator attributes	Weight/%
Ecosystem System	Ecological Environment Level	25.54	Green space per capita	Positive	9.09
			Greening coverage area	Positive	7.68
			Water quality standard rate of water function area	Positive	8.76
	Ecological Environment Pressure	37.55	Sulfur dioxide emissions	Negative	18.7
			Solid waste emissions	Negative	12.3
			Smoke and dust emissions	Negative	6.65
	Ecological Environment Protection	36.93	Sewage treatment rate	Positive	4.26
			Sulfur dioxide removal volume	Positive	7.6
			Solid waste disposal volume	Positive	18.87
			Soot Removal capacity	Positive	6.44
Socio-Economic System	Economic scale	27.55	Gross Regional Product	positive	8.66
			Fiscal revenue	Positive	9.85
			Per capita gross regional product	Positive	8.79
	Economic Capacity	15.12	Per capita consumption expenditure of urban residents	Positive	7.96
			Total Import and Export	Positive	7.24
	Social Development	57.40	Per capita disposable income of urban residents	Positive	9.99
			Per capita income of farmers	Positive	9.05
			Total retail sales of social goods	Positive	9.94
			Number of health institutions in the city	Positive	19.88

			Number of days with good or better environmental quality	Positive	8.66

3.2 Coupling performance

In this paper, the coupling performance is mainly measured in three aspects: ecological benefits, economic benefits, and social benefits, with a total of 13 three-level indicators. In terms of environmental governance benefits, air quality, habitat environment, solid waste treatment, and sewage treatment are measured; in terms of economic development benefits, economic growth, export benefits, investment attractiveness, output quality, and income level are measured; in terms of social sharing benefits, sanitation conditions, medical conditions, and cultural conditions are measured.

The overall trend and dynamic mechanism of the coupling level of national cities From the overall national level, the coupling level of environmental protection and high-quality economic development in China has continuously increased from 2006 to 2018. As shown in Figure 1, the coupling level between environmental protection and high-quality economic development was only 12.6 in 2006. As of 2018, China's coupling index reached 19.6, an increase of 47.5% compared to 2006, with a compound annual growth rate of 3.5%. In order to reveal the drivers and sources of the continuous growth of the coupling level in China, this paper further decomposes the coupling index into coupling performance. In terms of the drivers of the overall coupling level in the country, coupling performance contributes the most and grows the fastest, coupling depth comes second, while coupling foundation is weaker and growth is slow.

In terms of coupling performance, the index scores are consistently higher than the other two indicators and show a rapid increase of up to

65.4%. Compared with this, the national level of coupling depth grew at a more moderate rate in the early period and accelerated from 2013. The possible reason for this is that as China entered a new era of socialism in 2012, the new development concept and supply-side structural reform were promoted, making the original development mode, structure and kinetic energy then accelerate the adjustment. However, compared with the coupling depth index and coupling performance, the coupling basis index has the lowest contribution level and slow growth. This reflects that the foundation for coupling environmental protection and high-quality economic development is still weak at the national level, and the key conditions for environmental quality, economic development, and technological innovation still need to be improved.

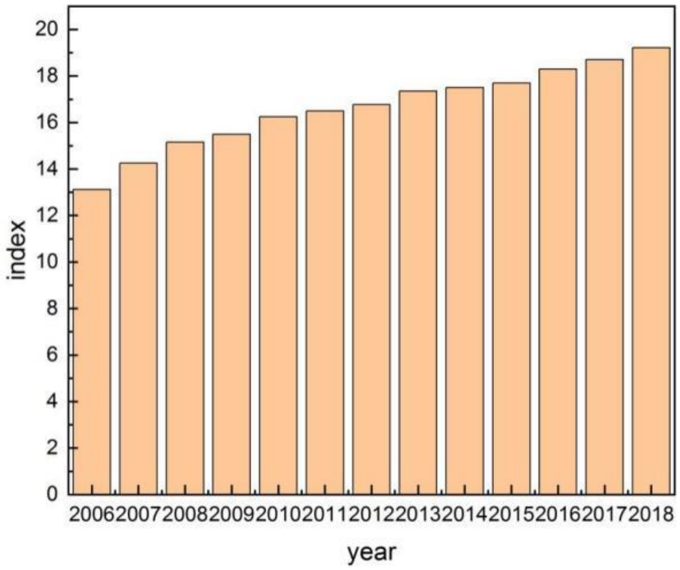

Figure 1. Overall level of coupling

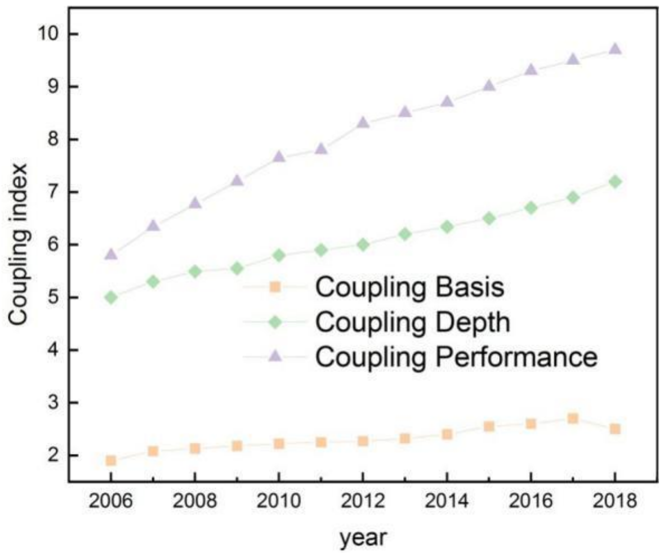

Figure 2. Coupling performance

Note: The total coupling index is the sum of the three major level indices of coupling basis, coupling depth, and coupling performance, and the value at the national level is the arithmetic average of 210 cities' total coupling index scores. All index scores are converted into percentages (in %).

The secondary decomposition of the index reveals that technological progress, development mode change, and environmental governance performance are the three key factors affecting the overall national

The three key factors of the coupling level. Technological progress is the core driver for promoting coupling. The intensity of environmental governance is the key support for promoting coupling. Environmental governance performance is the top driver, which is also the main reason for the highest contribution of the coupling performance index. In terms of dynamic trends, the growth rate of the environmental governance effectiveness index has accelerated significantly since 2012. The reason behind this is that since entering the new era of socialism, Xi Jinping's thought of ecological civilization has been thoroughly implemented, and the “ten articles” on the atmosphere and water and the environmental pollution battle have been carried out in-depth, making environmental pollution control achieve obvious results.

3.3 Evolution of coupling levels in first-tier cities

According to the classification criteria of “2021 City Business Attractiveness Ranking”, this paper classifies 210 prefecture-level cities and above into first-tier cities and new first-tier cities according to their administrative levels and classifies the remaining cities into other city categories. Among them, the coupling level of first-tier cities is shown in Figure 4, and the coupling performance is shown in Figure 3.

In terms of the total coupling index, the four first-tier cities all show a steady increase and maintain the ranking of Beijing > Shanghai ≈ Shenzhen > Guangzhou.

Shenzhen > Guangzhou. By decomposing the total coupling index of each city, this paper also finds some new features. First, in the case of Beijing, the rapid increase in the coupling depth, especially the kinetic energy conversion index, has always put its coupling level in the first place, especially the contribution of the number of green patent applications and the total retail sales of social consumer goods is most prominent. Secondly, in the case of Shanghai and Shenzhen, although the coupling levels are generally similar, Shenzhen has a significant advantage in the coupling base, while Shanghai has a slight advantage in the coupling depth and performance. The contraction of urban road area per capita and the slowdown of the natural population growth rate in Shanghai are the main factors limiting the improvement of their coupling bases. Thirdly, in the case of Guangzhou, the coupling level has the most rapid momentum to improve, but its relatively low coupling performance leads to a lower coupling level than other first-tier cities. Its most important driving force comes from the rapid improvement of the coupling base, especially the significant advantage of the scale of students enrolled in general higher education institutions and the rapid improvement of financial investment in science, technology, and education. However, Guangdong's economic development and social sharing benefits are relatively low, and public infrastructure, such as sanitation and culture, still needs to be strengthened.

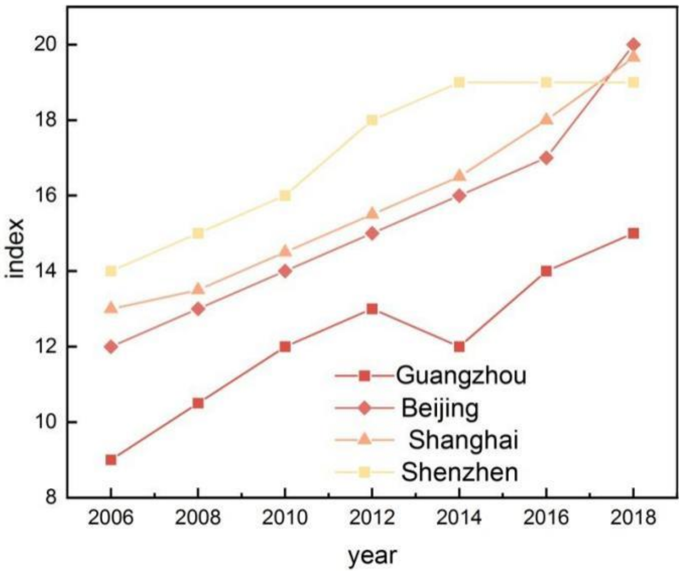

Figure 3. Coupling Performance for First-tier cities

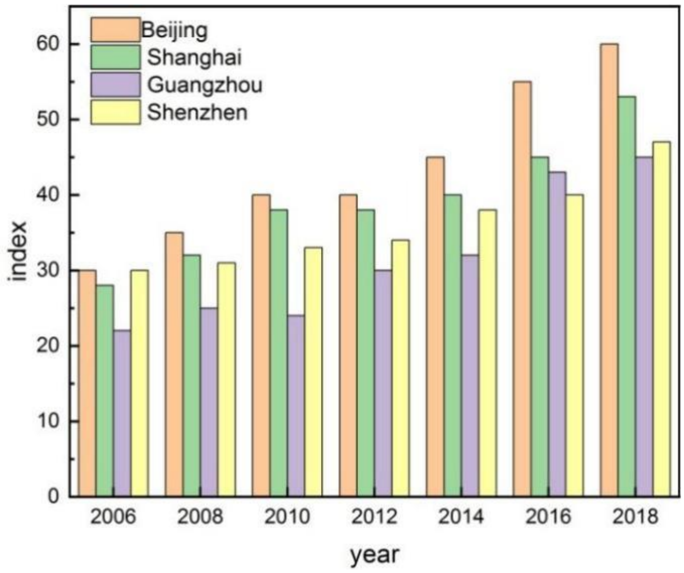

Figure 4. Total Coupling Index for First-tier cities

3.4 Evolution of coupling levels in the new first-tier cities

This paper also analyzes the coupling level and its spatial and temporal trend evolution in 15 new first-tier cities, as shown in Table 4. The coupling level of environmental protection and high-quality economic development in these cities is higher than the national average because of their economic base, factor endowment advantages, major strategic policy support, or excellent livable environment. Regarding spatial differences in the coupling, eastern, central, and new first-tier cities have advantages in coupling development. According to Table 4, Dongguan, Chengdu, and Wuhan ranked as the top three new first-tier cities in the eastern and central parts of the country, respectively, in the 2018 coupling total index ranking. From the top ten, a similar regional distribution characteristic is also shown. From the trend change of the coupling, the central new first-tier cities have been particularly rapid in terms of improvement, while the east has steadily declined, while the northeast has rapidly fallen. From 2006 to 2018, Chongqing, Wuhan, Chengdu, and Xi'an were the cities with the fastest ranking improvement, especially Chengdu and Wuhan were second only to Dongguan by 2018. In contrast, Shenyang fell from third place in 2006 to thirteenth in 2018.

Table 4. Total index and ranking of new first-tier coupling

City	2018 Score	2018 Year Ranking	Δ(2016)	Region
Dongguan	0.3578	1	0	East
Chengdu	0.34	2	4	West
Wuhan	0.33	3	6	Middle
Hangzhou	0.33	4	0	East
Nanjing	0.32	5	-3	East
Chongqing	0.31	6	8	West
Suzhou	0.309	7	0	East
Xi'an	0.301	8	4	West
Zhengzhou	0.3	9	2	Middle
Tianjin	0.2998	10	-5	East
Changsha	0.2968	11	-1	Middle

Qingdao	0.28	12	-4	East
Shenyang	0.249	13	-10	Northeast
Ningbo	0.24	14	1	East
Foshan	0.23	15	-2	East

Note: The cities listed in the table are the 15 New Tier 1 cities, and the criteria for delineation are listed in the 2021 City Business Attractiveness Ranking. Δ (2006) represents the change in the total coupling index (EEI) ranking in 2018 relative to 2006. If the value is positive, it represents the degree of ranking increase in 2018; if it is negative, it represents the degree of ranking decrease; if it is 0, it means no change. “Region” represents the economic region to which the city belongs, i.e., Eastern, Central, or Northeastern.

4 Measurement of coupled coordination between ecological environment and economic quality development

The coordination index T and the coupling coordination degree D are calculated according to the model formula, and the mean value is taken to obtain the overall system coupling coordination degree.

From Table 5, we can see that from 2006 to 2020, the coupling coordination degree between the two systems of ecological environment and economic quality development in the province and region increased from 0.58 to 0.7. The coupling coordination degree had increased from barely coordinated at the beginning to primary coordination until 2020 when it reached the intermediate coordination degree. The overall development has been steady to good in the past 15 years. From 2008 to 2019, the degree of coupling and coordination between the two systems reaches the primary level of coordination. By 2020, the two systems will reach an intermediate level of coordination. 2020 will see a comprehensive victory in the battle against poverty, but many poor townships and counties are located, and economic development has made a “qualitative” leap. Soil erosion and other ecological problems have also been alleviated, and many ecological restoration projects have progressed. If this trend continues, “good coordination” and “quality coordination” will soon be achieved.

Table 5. Environmental protection and economic development even and coordination degree

Year	Coordination index T-value	Coupling coordination degree D value	Coordination level	Degree of coupling coordination
2006	0.448	0.584	6	Barely coordinated
2007	0.468	0.599	6	Barely coordinated
2008	0.454	0.67	6	Barely coordinated
2009	0.475	0.687	7	Primary coordination
2010	0.464	0.677	7	Primary coordination
2011	0.453	0.676	7	Primary coordination
2012	0.456	0.675	7	Primary coordination
2013	0.451	0.672	7	Primary coordination
2014	0.42	0.64	7	Primary coordination
2015	0.43	0.643	7	Primary coordination
2016	0.43	0.632	7	Primary coordination
2017	0.434	0.621	7	Primary coordination
2018	0.534	0.623	7	Primary coordination

2019	0.522	0.66	7	Primary Coordination
2020	0.587	0.712	8	Medium Machine Coordination

Regional divergence in the degree of coupling and coordination of urban economic quality development and environmental protection The degree of coupling and coordination of urban economic quality development and environmental protection in northwest cities was better than that in southeast cities from 2004 to 2018, and the horn widened after 2007, and the divergence in the degree of coupling and coordination between northwest and southeast cities gradually increased. In order to reveal the gap between the coupling of urban economic development and environmental protection and its sources, this paper uses the Dagum Gini coefficient method to measure the development differences among regions, as shown in Table 6. The Dagum method decomposes the overall regional differences into three parts: intra-regional differences (within groups), inter-regional differences (between groups), and hyper-variance density, where the hyper-variance density originates from the phenomenon of cross-overlap between different regions. The mean value of coupled coordination between economic quality development and environmental protection in northwestern cities is better than that in southeastern cities, but the coupled coordination between economic quality development and environmental protection in some southeastern cities will exceed that in some northwestern cities, thus triggering the cross-over between regions.

Table 6. Dagum Gini coefficient for coupled and coordinated urban economic development and environmental protection

Year	Overall differences	Differences between groups	Within-group differences		Contribution			Contribution rate		
			Southeast	Northwest	Gw	Gnb	Gt	Gw	Gw	Gt
2004	0.098	0.1006	0.1192	0.0889	0.0466	0.0033	0.0465	50.00%	2.47%	47.53%
2005	0.1045	0.107	0.1153	0.096	0.0534	0.0073	0.0451	50.00%	6.82%	43.18%
2006	0.1126	0.1151	0.1225	0.1058	0.0562	0.0106	0.0456	50.00%	9.43%	40.57%
2007	0.0938	0.0961	0.1073	0.0833	0.0469	0.0049	0.0419	50.05%	5.23%	44.72%
2008	0.1155	0.1179	0.1209	0.1102	0.0577	0.0159	0.0419	50.00%	13.73%	36.27%
2009	0.1184	0.1211	0.1321	0.1087	0.0592	0.0116	0.0477	50.00%	9.68%	40.32%
2010	0.1174	0.1199	0.1156	0.1198	0.05454	0.016	0.0427	50.00%	13.65%	36.35%
2011	0.1137	0.1162	0.1147	0.1151	0.0568	0.0125	0.0444	50.00%	10.89%	39.11%
2012	0.1091	0.1114	0.112	0.1076	0.056	0.016	0.0389	50.00%	14.31%	35.69%
2013	0.1027	0.1052	0.105	0.1054	0.0521	0.0039	0.0473	50.05%	3.80%	46.15%
2014	0.1118	0.1141	0.1195	0.1214	0.0559	0.0174	0.0387	49.96%	15.49%	34.55%
2015	0.1039	0.1062	0.1043	0.1029	0.0519	0.015	0.0389	50.00%	12.50%	37.50%
2016	0.1059	0.1081	0.1083	0.1019	0.053	0.014	0.0355	50.00%	16.41%	33.59%
2017	0.1076	0.1097	0.1006	0.1109	0.054	0.0134	0.0353	49.95%	17.30%	32.75%
2018	0.1036	0.1059	0.1082	0.0994	0.052	0.015	0.0379	50.00%	13.49%	36.51%

Note:

1) Gw is the intra-group variation, Gnb is the inter-group variation, and Gt is the hypervariable density variation;

2) The sum of Gw, Gnb, and Gt equals the overall variation.

As seen in Table 6, the overall difference in the coupled coordination of high-quality coupled urban economic development and environmental protection from 2004-2018 widens from coupled 0.0978 to 0.1037 in fluctuations, and the divergence between cities shows signs of intensification. The Gini coefficient in 2009 was the highest in the sample period at 0.1185. The possible reason for the coupling is that China's economic growth in this period was driven by government-led investment coupling, and the stronger the financial power of local governments, the more they could drive rapid economic growth through investment coupling. Municipalities under direct jurisdiction, provincial capitals (capitals) coupled with cities with superior resources are more likely to achieve better economic coupling and high-quality development performance, which triggers the Matthew effect and leads to the widening of the regional gap between economic coupling and high-quality development and environmental protection coupling and coordination. The coefficient of variation coupling of economic quality development of cities from 2004 to 2009 increased from 63.95% to 100.28%, while the coefficient of variation coupling of environmental protection remained relatively stable during the same period, which confirms that economic factors caused the expansion of regional gap coupling of coupling coordination. Coupling from the source of the gap analysis, the intra-group coupling variation of urban coupling coordination degree dominates, and its contribution remains at 50% for a long time. The coupling key is that the impact of the super-variable density in the decline of the inter-group differences coupling gradually expanded. Its contribution rose from 2.47% in 2004 to 17.30% in the 2017 coupling year and fell back to 13.49% in 2018. The gap between the northwest and southeast city coupling coordination degree tends to increase. Considering that Inner Mongolia is not coupled in the traditional sense of the northwest, we will remove the coupled cities above the prefecture level in Inner Mongolia. The coupling coordination degree of economic quality development and environmental protection of northwest cities is still higher than that of southeast cities, but the gap is slightly reduced coupling, however, the difference between the two regions still tends to expand. The gap between the coupling coordination degree of northwest and coupled southeast cities mainly comes from the level of economic high-quality development coupling. The ratio of the average economic high-quality coupling development between northwest and southeast cities from 2004-2018 increased from 1.053 to 1.490, while the coupling environmental protection level of the two regions is extremely close. The magnitude of differences and trends of changes within the coupled southeast and northwest groups are also not coupled the same. The intra-group variation of coupled coordination in northwestern cities is smaller than that in coupled southeastern cities, indicating that the coupled coordination of high-quality economic development and environmental protection is more balanced in northwestern cities than in southeastern cities. The intra-group differences of coupled southeast cities show a decreasing trend in fluctuation during the sample observation period.

5 Comprehensive evaluation index analysis of socio-economic and eco-environmental protection system

The comprehensive evaluation index of the ecological environment system from 2010 to 2019 is shown in Figure 5. The ecological environment level shows a rising trend, then falling, and then rising. The ecological environment evaluation index from 2010 to 2013 fell from 0.25 to 0.17, then to 0.11 in 2014, and gradually rose from 2015 to increase to 0.26 in 2019, which shows the ecological environment in this period. This indicates that the development of the ecological environment level has been slow during this period. The comprehensive evaluation index of ecological and environmental pressure has been fluctuating from 2010 to 2014, showing a minimum value of 0.09 in 2014, and has been on an upward trend after 2015, from 0.17 to 0.27 in 2019. In general, economic development and the emission of pollutants into the environment have increased the pressure on the ecosystem, but the level of environmental protection is also fluctuating and increasing, and the ecosystem development is still relatively stable.

The comprehensive evaluation index of socio-economic system is shown in Figure 6, the evaluation indexes of economic scale and economic capacity and social development as a whole show a steady increasing trend, from 0.00, 0.00 and 0.07 in 2010 to 0.28, 0.15 and 0.53 in 2019 respectively, among which the evaluation indexes of economic scale and economic capacity are steadily increasing from 2010 to 2019 Due to the rapid development of the tertiary industry, the evaluation index of social development had a small fluctuation in 2012-2013 economic scale economic capacity and social development led to the rapid development of the economy, and the rapid development of the economy at the same time led to the rapid development of society, The trend of the comprehensive evaluation index of socio-economic and ecological environment system is shown in Figure 7 The evaluation index of socio-economic system first experienced a slow growth period, and the overall The overall evaluation index of socio-economic and eco-environmental systems showed a steady increase from 0.07 in 2010 to 0.96 in 2019, which was mainly influenced by the fluctuation of the evaluation index of eco-environmental pressure and eco-environmental protection, and increased from 2010 to 2013, reaching a great value of 0.52; from 2014 to 2015, the evaluation index decreased to a minimum of 0.32; After 2015, the overall evaluation index was on the rise, and by 2019, it had reached 0.67. From the perspective of the consistency of the development of socio-economic and eco-environmental systems, the level of ecological development between 2010 and 2014 was significantly greater than the level of social development and the gap between the two gradually narrowed, and the level of development of both was consistent in 2015, and the level of ecological development was greater than the level of social development from 2016 to 2017. The level of socio-economic development was significantly greater than the level of ecological development, and the gap between the two gradually increased after 2017.

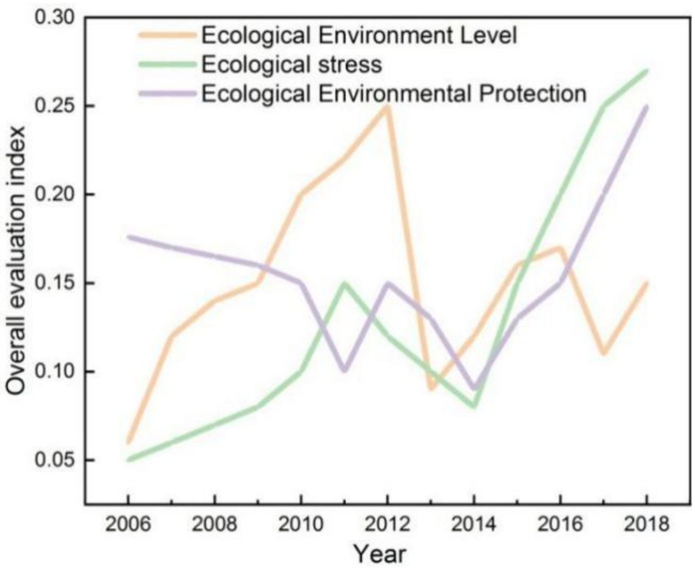

Figure 5. Comprehensive evaluation index of the

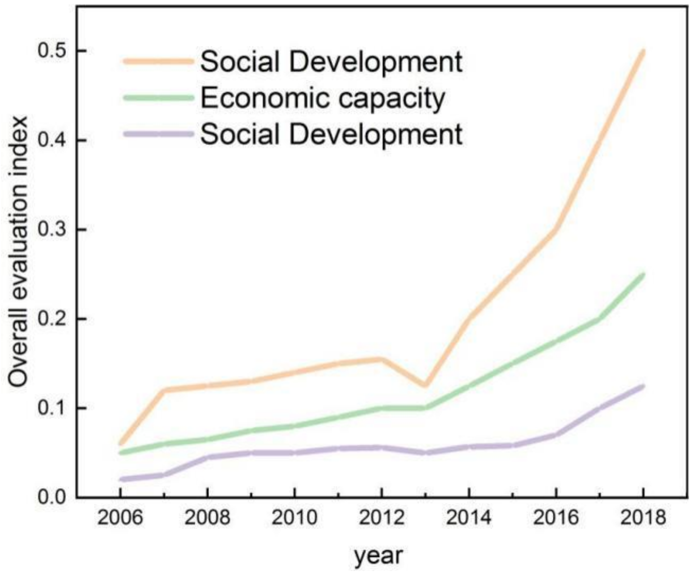

Figure 6. Comprehensive evaluation index of the socio-economic system

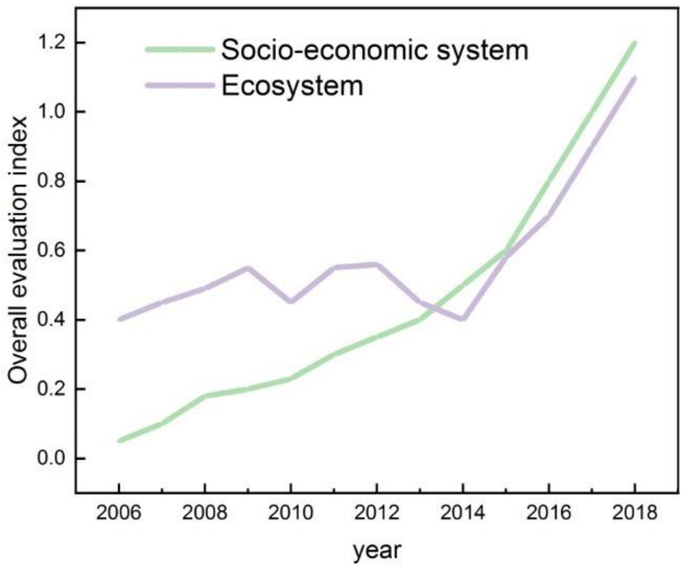

Figure 7. Trend of the integrated evaluation index of socio-economic and eco-environmental systems

6 Conclusion

This paper evaluates the coupling relationship between socio-economic and ecological environmental systems, constructs a model of the coupling degree between socio-economic and ecological environmental systems, and empirically analyzes the coupling between socio-economic and ecological environmental systems from 2006-2018, with the following findings:

To establish a coupled socio-economic and ecological environment evaluation index system, the socio-economic system includes three aspects: economic scale, economic capacity, and social development. From the perspective of symbiotic competition, the urban economy and environmental protection are currently in a mutually beneficial symbiosis. The ecological environment and high-quality economic development promote each other and develop together. In the past decade, the economic development level has been increasing yearly. The ecological environment development level has been fluctuating. However, the overall trend is up, and the upward trend of the socio-economic system is greater than that of the ecological environment system. The coupling between the socio-economic and ecological environment systems has fluctuated from 2010 to 2015, and the two systems are in the stage of continuous adjustment and adaptation.

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