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Analysis on the Coupling Coordinative Development Mechanism of Ecological Environment and Logistics Service Trade

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ABSTRACT

This article first takes the "logistics-ecological environment" composite system as the research object, constructs the order parameter index system of the logistics subsystem and the ecological environment subsystem of the scientific system, and establishes the order degree model of the subsystem and the composite system coupling coordination degree model. Then, this paper conducts an empirical study based on the historical data of Province X from 2008 to 2020, calculates the degree of order of the logistics subsystem and the ecological environment subsystem and the coordination degree of the composite system, and analyzes the coupling and coordinated development mechanism of the province's ecological environment and logistics service trade. The results show that the order of the province's logistics subsystem and the ecological environment subsystem and the degree of coupling and coordination of the "logistics-ecological environment" composite system both show a continuous growth trend.

KEYWORDS

Coordinated Development, Coupling Relation, Ecological Environment, Logistics

With the deepening and refinement of the related research on the relationship between economic development level and ecological environment, the research on the relationship between trade and ecological environment has gradually been derived. In 1971, the General Agreement on Tariffs and Trade (GATT) established the Environmental Measures and International Trade Working Group (Tibben-Lembke & Rogers, 2002). Since then, the relationship between trade and the ecological environment has gradually attracted attention from domestic and foreign scholars (Sarkis et al., 2004). In 1995, the WTO Commission on Environment and Trade incorporated trade-related environmental policy issues into the legal framework. At present, the number of research results on the relationship between trade and the environment is considerable (Rondinelli & Berry, 2000). Domestic and foreign scholars mainly conduct theoretical and empirical analysis on the relationship between trade and the environment from two aspects: the impact of international trade on environmental quality and the impact of environmental regulations on international trade (Gonzalez-Benito & Gonzalez-Benito, 2006).

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The impact of international trade on environmental quality is mainly divided into three perspectives (Wei et al., 2012). The first is that the liberalization of trade can promote the sustainable development of the environment. Some scholars have used the pollution demand-supply model and selected SO2 data from 1971 to 1996 to perform fixed-effect and random-effect regression analysis (Xu et al., 2005). Studies have shown that trade-induced technical effects and the scale effect will reduce the pollution concentration by 1.25%–1.5% (Datta et al., 2013). Some scholars have used different econometric methods to investigate the impact of the service trade on China's air, water, and other environmental indicators, and the conclusions show that the technical effect has the effect of pollution reduction to a certain extent (Neto et al., 2014). Based on the empirical analysis of panel data in 30 regions from 1997 to 2014, some scholars have proved that the increase in the level of trade openness will exert the carbon emission suppression effect of trade through transmission mechanisms such as the level of economic development and the intensity of environmental control (Silva, 2017).

The second perspective of the impact of international trade on environmental quality is that international trade will cause aggravation of environmental pollution (Xiong, 2021). For example, some scholars have used a mixed unit input-output model to measure energy consumption and pollutant emissions from commodity exports. The results show that as China's export trade to the world grows, energy consumption intensity and pollutant emission intensity are also rising simultaneously (Arya et al., 2019).

The third perspective is that the relationship between the two is more complicated, and trade has no clear promotion or inhibition effect on the environment (Chisuwa et al., 2019). Some scholars have studied the structural effects of trade on the basis of the pollution paradise hypothesis and the factor endowment theory respectively (Chisuwa et al., 2019), and the conclusions show that the net effect of trade on environmental quality is different depending on the choice of pollutants and dependent variables (Kim et al., 2015).

At present, in the research of coordinated development related to logistics, the coordinated development of logistics and economy is generally studied, while the research on the coordinated development of the composite system composed of logistics and the ecological environment has been carried out very little (Yildiz & Yercan, 2011). Some scholars have evaluated the logistics-eco-environment system of Shandong Province, analyzed the factors affecting the development of the logistics-eco-environment system in various regions of Shandong Province, and put forward some suggestions for the coordinated development of the logistics-eco-environment system in Shandong Province (Giuntini, 1996). Some scholars have constructed an index system for the coupling coordination degree of the logistics economic and ecological environment system and calculated the different comprehensive development level values of the logistics, economic and ecological environment systems in Sichuan Province through the factor analysis method and analyzed these three by using the coupling coordination degree theory (Zowada, 2018). Based on the statistical data of 31 provinces in China from 2005 to 2016, some scholars have used factor analysis and membership function models to study the degree of coordination between regional logistics and the ecological environment and divided the levels of coordination between them (Mindur & Hajdul, 2013).

On the whole, the research on coordinated development related to regional logistics has achieved certain results. However, due to the different perspectives and depths of scholars, the existing research still has the following deficiencies. Most of the research focuses on the coordination relationship between the two subsystems of regional logistics and regional economy, and most of the ecological environmental factors that have an important impact on these two systems have not been considered for research (Ishizaki, 1994). In the construction of the indicator system of the ecological environment system, many of the indicators selected are not closely related to the development of regional logistics, and the environmental factors such as resource occupation, energy consumption, carbon emissions, and so on, directly generated by logistics activities, are not considered. The ecological environment subsystem constructed in this way cannot reflect the nature and characteristics of the "logistics-ecological environment" composite system (Adamczak et al., 2016).

Based on this, this article starts from the perspective of sustainable development of the logistics industry, takes the “logistics-ecological environment” composite system as the research object, and builds the sequence parameter index system of the logistics subsystem and the ecological environment subsystem of the scientific system based on the relevant theories of synergy. Then, it establishes a sub-system order model and composite system coupling coordination model. The historical data of X province from 2008 to 2020 is used to conduct regional empirical research, the order degree of the logistics subsystem and the ecological environment subsystem and the coordination degree of the “logistics-ecological environment” composite system is calculated, and the coordinated development mechanism of the ecological environment and the logistics service trade coupling is analyzed.

Furthermore, traditionally, the research on the relationship between trade and environment mainly focuses on the direct impact of trade policies on environmental quality and how environmental regulations affect trade flows. This study broadens this perspective by taking logistics as an important part of trade that affects and is affected by the ecological environment. This method can provide a more comprehensive understanding of how trade affects the environment, not just of traditional indicators. Establishing a subsystem order model and composite system coupling coordination model not only provides empirical evidence for the relationship between logistics and ecological environment but also provides a reliable analytical tool for evaluating the dynamics of this relationship. This model can be used as the basis for policy makers and researchers to evaluate and improve the sustainability of logistics practice.

RELATED WORK

The spiral propulsion relation between the modern logistics and the city economy represents the characteristics of the cooperating development. The inner coupling mechanism and stages of the city logistics and economic development are discussed first, followed by an analysis of the order parameter of the coupling of the city economy and the logistics and evaluation analysis model and methods of the coupling of the city economy and logistics based on the artificial neural network (Xie et al., 2008). Based on analyzing the coupling foundation and coupling contents between small- and medium-sized enterprises cluster and the supply chain alliance, Lian (2011) finds that an enterprises cluster provides the superior ecological environment for supply chain alliance building and developing. Supply chain relationship is the basic economic relation within the enterprises cluster, and supply chain alliance is developing a direction of cluster operating mechanism. Through the design of economic development, logistics development, and the ecological environment index system, the economic development, logistics development, and eco-environment development level of 30 provinces and cities in China from 2008 to 2017 are analyzed by using the entropy method and coupling coordination degree model, and the spatial characteristics of regional economic development, logistics development, and ecological environment are analyzed by using ArcGIS software (Zhang et al., 2020). There are situations where the level of coupling coordination is not high; the coordinated growth of economic development, logistics development, and ecological environment is mainly driven by economic development and logistics development to clarify the endogenous relationship and coupling coordination mechanism of a coordinated development between the economy, an ecological environment, and a health system. At the same time, the entropy method and the coupling coordination model are used to analyze and measure the coupling coordination relationship between the economy, the ecological environment, and the health system of China’s green production from 2009 to 2016 (Hou et al., 2021). In achieving the coordinated development of the logistics industry, new urbanization and the ecological environment is significant for improving the efficiency of the logistics industry, urbanization level, and environmental quality, but there are few studies that consider all three together. Ye et al. (2022) take the perspective of the coupled and coordinated development of the logistics industry, new urbanization, and the ecological environment, which can provide references for enterprises and governments to make sustainable industrial and urbanization development strategies.

In order to promote the high-quality development of the ecological environment in the Yellow River Basin, Huang et al. (2022) studied the coordinated development of tourism, the ecological environment, and public service in the Yellow River Basin by treating tourism, the ecological environment, and public service as a whole. The results show that tourism and public service in the Yellow River Basin are closely related, and the protection of the ecological environment and tourism development are not contradictory. Wu et al. (2022) first quantified ULUE and ECC by super-efficiency DEA, DPSIR framework, and entropy-TOPSIS from a coupling perspective, attempting to compensate for the lack of clarity regarding urban sustainability constraint factors . These findings also illustrate the analysis framework and coupling mechanism mentioned in this paper that can act as a nexus between interdisciplinary perspectives to enhance the understanding of changing social-ecological systems, thus serving urban sustainable development.

With the logistics industry becoming an important part of economic development, logistics activities have given rise to various environmental problems, which affect the sustainable development of the ecological environment. At the same time Tian et al. (2022) investigate the spatial effect of each influencing factor on the coordination level.

MATERIALS AND METHODS

Coupling Coordination Degree Model Construction

This study integrates analytic hierarchy process (AHP), entropy weight method, linear weighted summation and other quantitative methods, and constructs a comprehensive evaluation model.

Index System

This paper selects typical order parameter indicators that can represent the respective development status and characteristics of the regional logistics subsystem and the ecological environment subsystem, and then uses the analytic hierarchy process to construct a regional "logistics" composed of three levels: subsystem level, element level, and index level. The coordinated development of a three-level indicator system for the "ecological environment" complex system is shown in Table 1.

The logistics subsystem index system consists of two elements: input and output. The investment in the logistics system is the material basis and necessary guarantee for the development of the logistics industry. The investment in the logistics system by a region is directly related to the development of regional logistics and has an impact on the output effect of the logistics system. The investment in the logistics system includes construction capital investment and human resource investment. The corresponding indicators include fixed asset investment in the logistics industry and the proportion of the number of employees in the logistics industry . The output of the logistics system reflects the results achieved by the regional logistics industry in the development process and is an intuitive assessment of the development effect of regional logistics. It can be reflected by indicators such as the added value of the logistics industry, the volume of freight, and the proportion of the added value of the logistics industry in regional GDP.

The index system of the ecological environment subsystem is composed of two elements: resource and environment. Resources are an indispensable material basis in the development of regional logistics. If resources are scarce, it will restrict the development of logistics in the region to a certain extent. Resource elements reflect the extent to which regional logistics uses resources. Pollutant emissions in the development of regional logistics, especially carbon emissions, directly affect environmental quality, while soil and water governance reflect the current situation of regional environmental improvement. Environmental factors measure the impact of logistics industry development on the ecological environment from the two aspects of pollution and governance.

Table 1. Index System of Coupled and Coordinated Development

Subsystem Layer	Element Layer	Index Layer	Indicator Attributes
Logistics subsystem S1	Investment	Fixed asset investment in logistics industry (100 million yuan) E11	Positive
		The proportion of the number of employees in the logistics industry in the total number of employees (%) E12	Positive
	Output	Added value of logistics industry (100 million yuan) E13	Positive
		Freight turnover (100 million tons/km) E14	Positive
		Freight volume (10,000 tons) E15	Positive
		The added value of the logistics industry accounts for the proportion of regional GDP (%) E16	Positive
Ecological environment subsystem S2	Resource	Energy consumption intensity of logistics industry (ton/10,000 yuan) E21	Reverse
		Road network density (km/km^2) E22	Positive
		Truck tonnage (10,000 tons) E23	Positive
	Environment	Carbon emission intensity of logistics industry (ton/10,000 yuan) E24	Reverse
		Forest coverage rate (%) E25	Positive

Order Parameter Index Weight

The entropy weight method provides an objective way to assign weights to different indicators based on their variability. By reducing subjective bias, this method ensures that the indices which show more variation (and therefore potentially have a greater impact on the system's order) are given appropriate significance. This step is vital for accurately reflecting the relative importance of each indicator in the overall evaluation of coordination between logistics and the environment.

The entropy weight method is an objective approach to assigning weights to various indicators in a system. Unlike subjective methods that rely on expert opinions or preferences, the entropy method bases the weights on the inherent information contained within the data itself. The "entropy" here refers to a concept borrowed from thermodynamics and information theory, representing the degree of disorder or randomness. In the context of weighting indicators, it measures the variability or usefulness of the information provided by each indicator. Indicators that offer more unique or varied information (higher entropy) are considered more important and thus assigned higher weights, and its essence is to use the information utility value contained in the indicator to calculate the weight, which can avoid the influence of subjective factors. In complex systems, indicators can be classified as either forward or reverse. Forward indicators are those where higher values directly correspond to better outcomes or more desirable states. Reverse indicators, on the other hand, work oppositely: lower values indicate better outcomes. For instance, in an environmental quality assessment, a low pollution level (a reverse indicator) is preferable, whereas in economic performance evaluation, high GDP growth (a forward indicator) is desirable. To apply the entropy method effectively, all indicators must be aligned in terms of their directionality—meaning they all should behave like forward indicators, where higher values are better. This necessitates converting reverse indicators through specific mathematical transformations. The passage mentions a "subtraction uniform formula" for this purpose. Assuming that there are m objects and n indicators, the subtraction uniform formula of the i-th indicator is:

$$x_{ij}^{'} = maxx_{ij} + minx_{ij} - x_{ij}, i = 1,2,\cdots n, j = 1,2\cdots m \tag{1}$$

Order Degree of Order Parameter Index

The concept of order degree is introduced to quantify how each indicator contributes to the subsystem's state of organization or development. This calculation distinguishes between positive and reverse indicators, acknowledging that not all factors influence the system in the same direction. This nuanced approach allows for a more precise measurement of each subsystem's status and its evolution over time.

This article assumes that k has a composite mechanism formed by the interaction of subsystems to form a composite system $\mathrm{S} = \left\{S_1, S_2, \cdots S_j, \cdots S_k\right\}$, where S_j is the jth subsystem of the composite system, $j = 1,2 \cdots k$. For the subsystem, $\mathrm{j} \in \left[1, \mathrm{k}\right]$. Let the order parameter variable in the development and evolution process be $\mathrm{e}_j = \left\{e_{j1}, e_{j2}, \cdots e_{ji}, \cdots e_{jn}\right\}$, where e_{ji} is the order parameter component, and $\alpha_{ji} \le e_{ji} \le \beta_{ji}$, β_{ji}, α_{ji} are the upper and lower limits of the critical point of component e_{ji}, n is the number of sequence parameter components (namely indicators), and n≥1, i∈[1,n].

When e_{ji} is a positive index, the index value increases, the order degree of the system increases. When e_{ji} is a reverse index, the index value increases, and the order degree of the system decreases. In this way, the order parameter index efficacy function of each subsystem can be used to measure the degree of contribution of each order parameter index to the order of the subsystem, to obtain the order of subsystem S_j. The calculation expression of the parameter index (component) e_{ji} is as (2):

$$u_j\left(e_{ji}\right) = \begin{cases} \dfrac{e_{ji} - \alpha_{ji}}{\beta_{ji} - \alpha_{ji}}, e_{ji} \text{ is positive} \\ \dfrac{\beta_{ji} - e_{ji}}{\beta_{ji} - \alpha_{ji}}, e_{ji} \text{ is negative} \end{cases} \tag{2}$$

$\mathrm{u}_\mathrm{j}\left(e_{ji}\right) \in \left[0,1\right]$, the greater the value, the greater the contribution of the index e_{ji} to the order of the subsystem.

The Degree of Order of Subsystems

By aggregating the contributions of all indicators, the model calculates the overall order degree of each subsystem. This step is crucial for understanding the current state of both the logistics and ecological subsystems individually, providing a foundation for assessing their coordination.

The order degree of the subsystem reflects the sum of the contributions of all the components of the order parameter variable e_j to the order degree of the subsystem Sj (Ye et al., 2022). It can be obtained by performing integrated operations on each $u_j\left(e_{ji}\right)$. This paper uses the linear weighted summation method to calculate it. That is, the order degree of the subsystem $u_j\left(e_j\right)$ is:

$$u_j\left(e_j\right) = \sum_{i=1}^{n} w_i u_j\left(e_{ji}\right), w_i \ge 0, \sum_{i=1}^{n} w_i = 1, \tag{3}$$

Among them, w_i is the weight of the i-th order parameter index, $u_j\left(e_j\right) \in \left[0,1\right]$. The greater $u_j\left(e_j\right)$, the greater the contribution of e_j to the order of the subsystem S_i, the higher the order of the subsystem, and vice versa (Zhang et al., 2020).

Coordination of Composite Systems

Finally, the model evaluates the coordination between the logistics and ecological subsystems by comparing the change in their order degrees over time. This dynamic assessment captures not just the static state of coordination but also how the relationship between these two systems evolves. The use of a coordination degree formula offers a quantitative measure of how well the subsystems are aligned in their development, highlighting areas of harmony or conflict.

For a given initial time t0, we suppose the order of subsystem S_j is $u_j^0\left(e_j\right), j = 1,2,\cdots k$. When the overall development of the composite system evolves to time t_1, if the order degree of the subsystem S_j is $u_j^1\left(e_j\right), j = 1,2,\cdots,k$, then the coordination degree C of the composite system is (Chen et al., 2022):

$$\mathrm{C} = \lambda \cdot \left[\left\|\prod_{j=1}^{k} u_j^1\left(e_j\right) - u_j^0\left(e_j\right)\right\|\right]^{1/k} \tag{4}$$

$$\lambda = \min\left[u_j^1\left(e_j\right) - u_j^0\left(e_j\right) \neq 0\right] / \left|u_j^1\left(e_j\right) - u_j^0\left(e_j\right) \neq 0, j = 1,2,\cdots k\right| \tag{5}$$

$u_j^1\left(e_j\right) - u_j^0\left(e_j\right)$ is the change range of the order of the subsystem S_j from t_0 to t_1, and there is $\left[u_j^1\left(e_j\right) - u_j^0\left(e_j\right)\right] \in \left[-1,1\right]$, $C \in \left[-1,1\right]$. The larger the value, the higher the coordinated development of the composite system and vice versa (Chun et al., 2020).

RESULTS

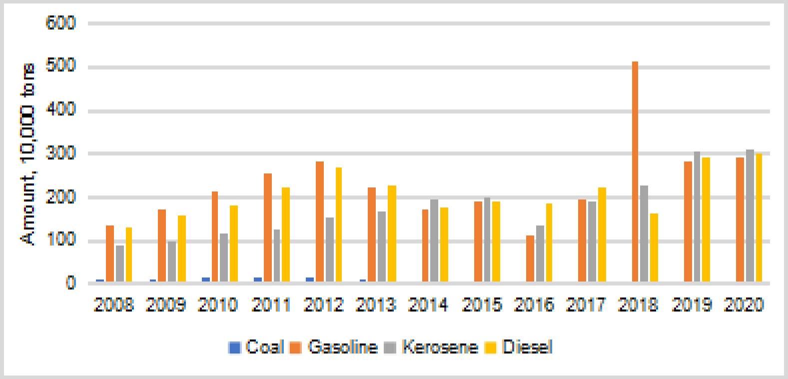
According to the statistical data in the “China Energy Statistical Yearbook,” from 2008 to 2020, the province’s logistics industry energy consumption types mainly included raw coal, gasoline, kerosene, diesel, natural gas, and electricity, and the consumption of each type of energy is shown in Figure 1.

When calculating the total energy consumption of the logistics industry in the province, it is necessary to convert various types of energy consumption into standard coal consumption. The result of the conversion is shown in Figure 2.

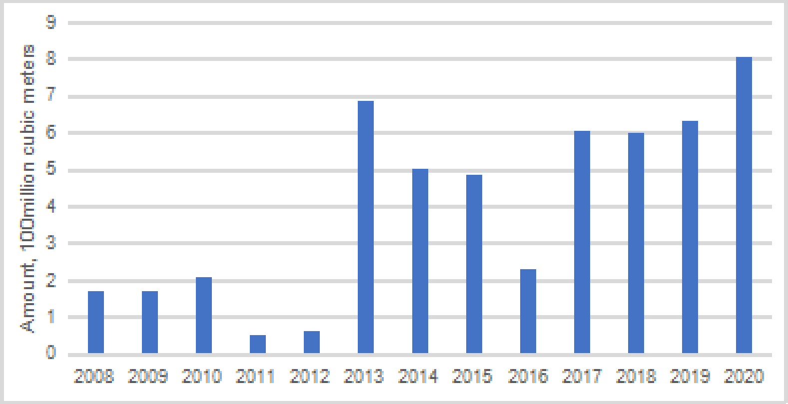
The CO2 emissions generated by logistics activities come from direct CO2 emissions or indirect CO2 emissions caused by various energy and materials consumed in logistics activities (Rong et al., 2023). Due to the diverse types of materials consumed in logistics activities, such as various packaging materials, pallets, labels, etc., it is difficult to calculate the CO2 emitted in the logistics process in a unified way. In addition, the monitoring data of carbon emissions in China’s logistics industry is not yet perfect, so this article uses the direct energy consumption method of logistics operations to calculate carbon emissions. The CO2 emissions generated by logistics activities are calculated by converting the actual energy consumption of logistics activities. The specific calculation formula is as shown in (6):

$$\mathrm{Q} = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n} E_i \cdot NCV_i \cdot CEF_i . COF_i \tag{6}$$

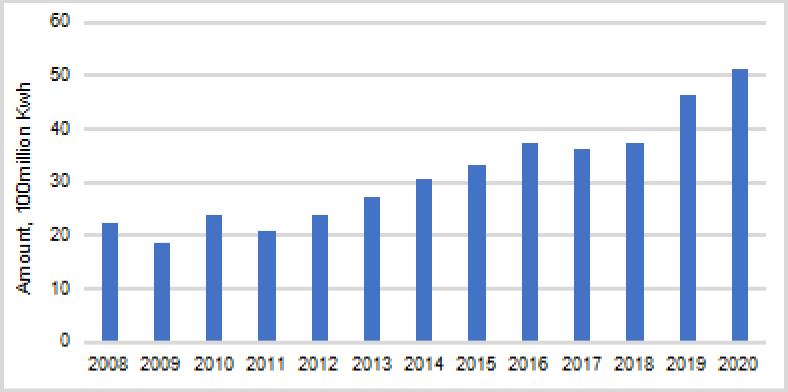
Figure 1. Raw Data on Consumption of Various Types of Energy in the Logistics Industry



(a) Coal, gasoline, kerosene and diesel



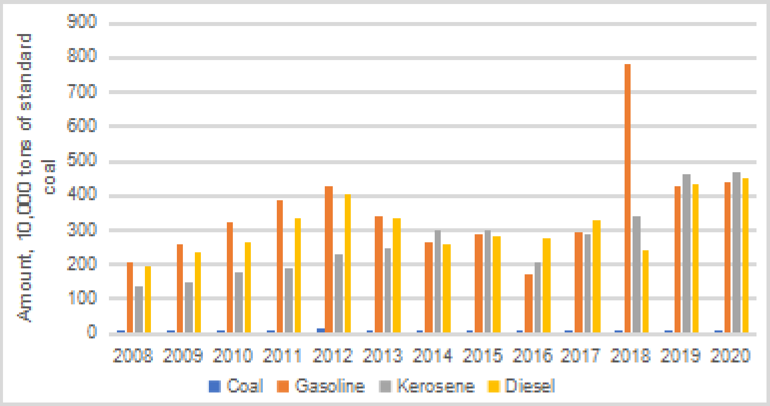
(b) Natural gas



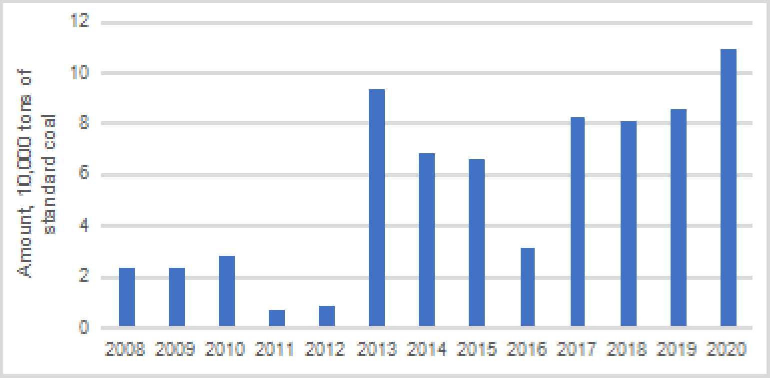
(c) Electricity

As shown (6), the CO2 emission measurement model of the regional logistics industry is calculated where Q is the total carbon emissions, i is the type of energy, E_i is the consumption of the i-th energy, NCV_i is the average low-level calorific value, and CEF_i is provided by IPCC CO2 emission factor, COF is the carbon oxidation factor, and the default is 1. Therefore, $NCV_i \cdot CEF_i.COF_i$ is the CO2 emission coefficient of fossil gas energy. The CO2 emissions and total carbon emissions of all types of energy in the logistics industry in province X from 2008 to 2020 are shown in Table 2.

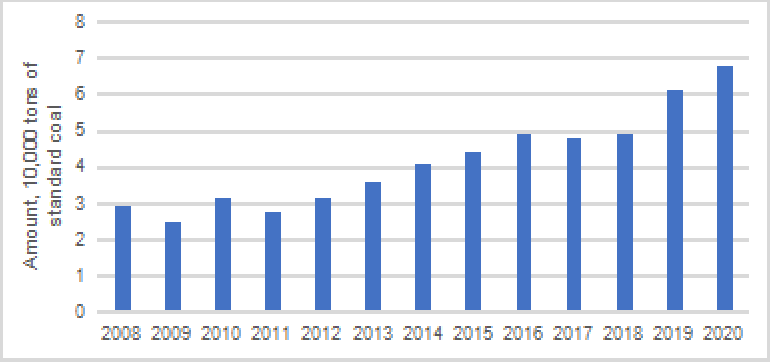
Figure 2. The Consumption of Various Types of Energy in the Logistics Industry Converted Into Standard Coal (10,000 Tons of Standard Coal)



(a) Coal, gasoline, kerosene and diesel



(b) Natural gas



(c) Electricity

After calculating the total energy consumption and total carbon emissions of the regional logistics industry, all the data of all the indicators of the coordinated development index system of the “logistics-ecological environment” composite system in X province are calculated, as shown in Table 3.

Using the index data in Table 3, the entropy weights of the sequence parameter indexes of the logistics subsystem and the ecological environment subsystem are calculated respectively, as shown in Figure 3.

Table 2. CO2 Emissions of Various Types of Energy in the Logistics Industry (10,000 Tons of CO2)

Year	Coal	Gasoline	Kerosene	Diesel	Natural Gas	Electricity
2008	24.18942	413.9224	279.7361	427.4729	3.83895	21.84012
2009	26.51574	522.4912	303.6248	515.4002	3.92875	18.24903
2010	28.04508	650.9857	371.0586	580.1002	4.69205	23.18067
2011	34.50708	781.7992	392.6901	725.9664	1.14495	20.40173
2012	37.11342	864.9804	477.4919	876.9115	1.3919	23.44486
2013	23.694	684.49	518.2782	728.2632	15.4905	26.62499
2014	14.001	528.533	615.2124	567.1279	11.3597	30.03017
2015	14.06562	577.4469	621.4511	619.0173	10.97805	32.44706
2016	14.001	343.4046	427.8335	597.181	5.18595	36.40999
2017	13.61328	590.568	593.2674	716.0996	13.67205	35.47063
2018	13.37634	1572.57	710.6105	525.0729	13.44755	36.45891
2019	10.3392	865.0719	957.8366	945.6229	14.1884	45.36326
2020	12.7086	888.3236	966.0189	980.5932	18.0947	50.18727

Table 3. Index Values of the Index System For the Coupled and Coordinated Development of the Composite System

Year	Logistics Subsystem						Ecological Environment Subsystem				
	E11	E12	E13	E14	E15	E16	E21	E22	E23	E24	E25
2008	265.42	2.89	381.26	918.32	67452	5.16	1.49	0.28	71.03	3.42	28.99
2009	384.68	2.95	452.32	970.71	75123	5.21	1.47	0.39	73.82	3.36	30.29
2010	453.26	3.04	513.41	1062.31	71436	4.93	1.56	0.43	86.53	3.58	32.12
2011	702.13	3.21	572.43	1580.62	114736	4.65	1.59	0.49	94.34	3.59	30.92
2012	1409.23	3.35	525.31	1595.63	118963	3.72	2.04	0.54	135.19	4.58	34.48
2013	1782.43	3.27	584.13	1817.53	136521	3.46	1.76	0.59	165.23	3.96	35.21
2014	2145.63	3.2	639.32	2017.43	159325	3.23	1.41	0.61	210.68	3.23	35.46
2015	2462.36	2.93	710.23	2263.21	179652	2.99	1.33	0.63	233.83	3.14	35.67
2016	2673.95	2.86	752.66	2274.26	168512	2.89	0.93	0.67	268.84	2.25	35.87
2017	3081.16	3.01	1067.82	2578.23	161324	3.92	0.96	0.69	306.45	2.16	35.9
2018	2298.12	2.85	1217.39	2436.59	156789	4.12	0.82	0.7	304.23	4.87	36.11
2019	3963.07	2.59	1478.63	2567.63	161243	4.53	0.94	0.71	330.42	2.16	36.98
2020	4620.43	2.58	1608.32	2701.32	173456	4.41	0.92	0.72	395.24	2.1	38.16

In this paper, when calculating the order degree of the sub-system order parameter index, the self-comparison method is adopted to set the lower limit of the critical point of the index as the minimum value in the same index, and the upper limit as the maximum value in the same index. We calculate the order degree of the order parameter index of the logistics subsystem and the ecological environment subsystem respectively, as shown in Figure 4.

Figure 3. Entropy Weight of Order Parameter Index

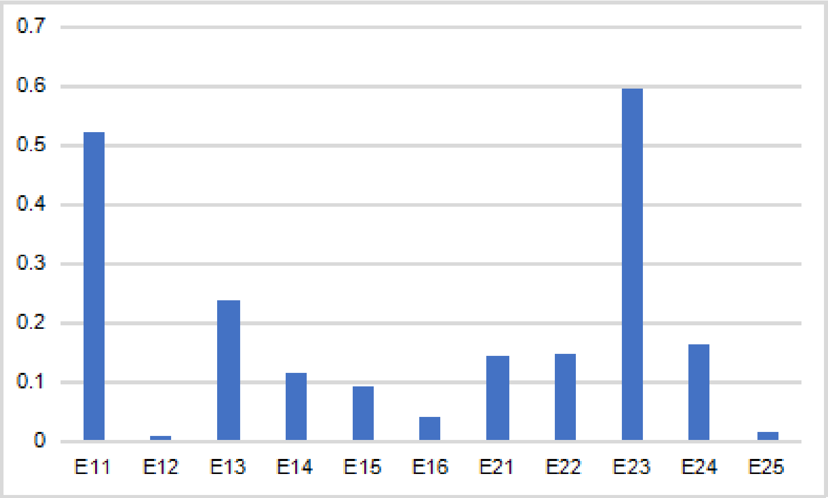
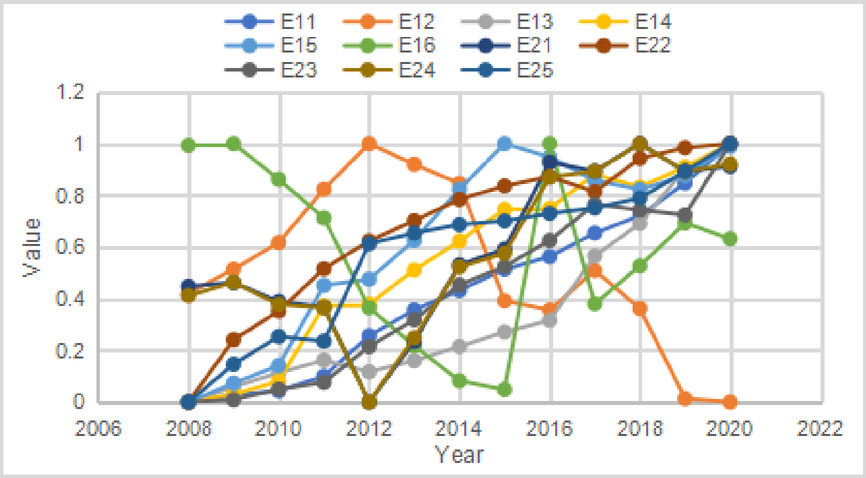


Figure 4. The Order Degree of the Order Parameter Index of the Logistics Subsystem and the Ecological Environment Subsystem

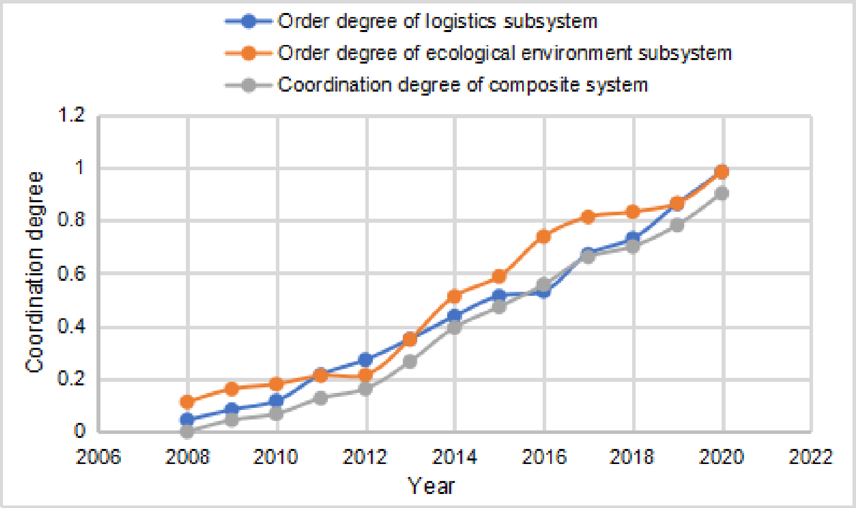


We calculate the order degree of logistics subsystem and ecological environment subsystem from 2008 to 2020. On this basis, using 2007 as the base period of the development survey, the coordination degree of the "logistics-ecological environment" composite system in province X from 2008 to 2020 relative to the base period is calculated, as shown in Figure 5.

As can be seen from Figure 5, from 2008 to 2020, the degree of coordination of the province's "logistics-ecological environment" composite system has been increasing every year, showing a steadily rising trend, and reaching a peak in 2020. The province's "logistics-ecological environment" composite system is in a continuous and stable state of coordinated development, and the level of coordinated development is constantly improving.

Correspondingly, the order of the province's logistics subsystem and the ecological environment system has also shown a rising trend, indicating that both subsystems have achieved orderly development and are in a good and orderly growth state. The order degree of the logistics subsystem

Figure 5. The Development Trend of Order Degree of Logistics Subsystem and Ecological Environment Subsystem and Coordination Degree of "Logistics-Ecological Environment" Composite System



has been rising steadily, and the rising speed has increased slightly since 2013. The order degree of the ecological environment subsystem increased slowly before 2013, and the rising speed greatly improved since 2013. However, the degree of order and growth of these two subsystems was the same every year, indicating that they had a relatively consistent development speed. This trend of orderly development within the two subsystems and relatively synchronized growth between each other shows that the development relationship between the two subsystems is coordinated and jointly determines that the coordination degree of the composite system shows a continuous upward trend of change.

Figure 5 shows that from 2008 to 2020, the phased evolution characteristics of the coordination degree of the province's "logistics-ecological environment" composite system are obvious. The coordinated development process of the logistics and ecological environment in this province is divided into two more obvious stages. In the first stage, during the three years from 2008 to 2012, the province's "logistics-ecological environment" composite system has a low degree of coordination, and the growth of the coordination degree of the composite system is slow. At this stage, the level of coordinated development of logistics and the ecological environment is relatively low. The speed is slow. Further analysis finds that during this period, the order of the ecological environment subsystem was low, although it was increasing, but the growth rate was small.

During this period, the development of the logistics subsystem lags behind the ecological environment subsystem, and its contribution to the coordination degree of the composite system is lower than that of the ecological environment subsystem. The two subsystems with low orderliness work together to lead to the coordination of the composite system. The level of development is not high, but because the two subsystems are relatively consistent in development speed, the development structure of the composite system is more reasonable, and it is also in a relatively low level of coordination. At the same time, it can also be seen that the indicators "Logistics Industry Energy Intensity" and "Logistics Industry Carbon Emission Intensity" had been increasing until 2011 and reached their peak in 2011. It shows that before 2012, the province mainly relied on the extensive development of high energy consumption, high pollution, and high emission characteristics to realize the development of the regional logistics industry. It was a development model at the expense of ecological environment and was not conducive to sustainable development.

In the second stage, during the 10 years from 2011 to 2020, the degree of coordination of the province's "logistics-ecological environment" composite system increased significantly each year compared to the prior year. The degree of coordination increased 0.1265 from 2011 to 2020. The annual average growth rate was 0.9023, and the average annual growth rate was 0.078. Compared with the first stage, the degree of coordination improved significantly, forming a period of rapid growth, indicating that the province's logistics and ecological environment coordinated development level continued to rise rapidly. Correspondingly, the orderliness of the logistics subsystem and the ecological environment subsystem both achieved substantial growth. The logistics subsystem had an average annual growth rate of 0.09402 while the ecological environment subsystem had an average annual growth rate of 0.08709, and the orderliness of the two subsystems increased annually. The growth rate is not much different, indicating that the two subsystems have achieved a greater degree of simultaneous development. During this period, the order of the ecological environment subsystem was slightly higher than that of the logistics subsystem, which was the main driving force for the coordinated development of the composite system and had a greater contribution to the improvement of the coordination of the composite system. From 2011 to 2016, the order of the ecological environment subsystem increased faster than the logistics subsystem, but after 2016, the order of the logistics subsystem increased faster than the ecological environment subsystem. By 2019 to 2020, the degree of order and the increase rate of the two subsystems were basically the same, achieving a very ideal coordinated development, and it has also promoted the coordination degree of the "logistics-ecological environment" composite system to achieve basically the same increase and reach the maximum.

CONCLUSION

(1) This paper takes the "logistics-ecological environment" composite system as the research object, constructs the logistics subsystem and the ecological environment subsystem sequence parameter index system guided by the sustainable development theory, and then uses the principle of synergy to establish the order degree model of the system and the coordination degree model of the "logistics-ecological environment" composite system.

(2) The degree of order of the logistics subsystem and the ecological environment subsystem and the coordination of the "logistics-ecological environment" composite system have shown a continuous growth trend, indicating that the province's logistics and ecological environment are in a stable and coordinated development state, and the level of coordination is improving steadily.

(3) From the perspective of evolution, the coordinated development of logistics and ecological environment in the province is divided into two stages according to its change characteristics. The first stage of the coordinated development of the complex system is not very high, and the growth is slow. The main reason is the development level of the two subsystems is low and the development speed is slow. The rapid growth of the coordination degree of the composite system in the second stage indicates that the level of coordinated development of logistics and ecological environment in the province has continued to rise rapidly.

(4) In conclusion, this research significantly advances our understanding of the complex interplay between logistics operations and ecological sustainability. It provides a comprehensive framework for assessing and enhancing the coordination within the "logistics-ecological environment" composite system, offering valuable insights for scholars, policymakers, and practitioners dedicated to fostering sustainable development. These models enable a more nuanced analysis of the dynamics within the system, offering a quantitative tool for assessing the level of coordination and sustainability. This methodological approach can be applied to other regions or sectors, facilitating broader research on sustainable development and system coordination.

DATA AVAILABILITY

The figures and tables used to support the findings of this study are included in the article.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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