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Spatial Association Network Structure and Influencing Factors of Carbon Emission Efficiency in China's Logistics Sector

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ABSTRACT

Based on relational data and a network perspective, this study calculates the carbon emission efficiency of China's logistics industry from 2006 to 2021 and analyzes the characteristics of the spatial correlation network structure of this efficiency through social network analysis. The results are as follows: (1) During the study period, the carbon emission efficiency of China's logistics industry exhibited a fluctuating downward trend, with notable regional disparities. Overall, there was an imbalance among regions, with the eastern region showing higher efficiency than the central region, and the central region higher than the western region. (2) From the perspective of the overall network structure, the spatial correlation of carbon emission efficiency in China's logistics industry tended to become closer, with a relatively stable and balanced spatial correlation structure. Additionally, (3) differences in spatial distance, economic development level, energy intensity, urbanization level, and industrial structure had significant impacts on the formation of the spatial correlation network of carbon emission efficiency in China's logistics industry.

KEYWORDS

Carbon Emission Efficiency in Logistics; Spatial Correlation Networks; Influencing Factors; Social Network Analysis

1. INTRODUCTION

In the midst of the contradiction between economic growth and energy consumption, as well as environmental pollution, an increasing number of countries have begun to formulate low-carbon policies aimed at energy conservation and emission reduction to control carbon dioxide emissions. To facilitate the transition of China's economic development from a high-energy-consumption model to a low-carbon one, China has established a series of policies for energy conservation and emission reduction, thereby achieving sustained and high-quality economic and social development. Studying the spatial correlation network of carbon emission efficiency within the logistics industry can provide a new policy perspective for achieving coordinated development in carbon emission efficiency within China's logistics sector. Therefore, investigating the level of low-carbon development in the logistics industry and its spatial effects holds significant importance for constructing a green and coordinated logistics system.

By reviewing relevant research on logistics, this paper finds that current scholarly research outcomes exhibit diverse and multifaceted research elements. However, existing research still has limitations: Firstly, most studies on the influencing factors of carbon emission efficiency primarily utilize econometric models, which have strict requirements for the independence of variables. In contrast, the Quadratic Assignment Procedure (QAP) model avoids such issues and produces more robust regression results than conventional methods. Secondly, at the research subject level, a deeper exploration of the spatial correlation network from a network perspective can more accurately reveal the current status of regional logistics collaboration for energy conservation and emission reduction. Using traditional econometric approaches for spatial research that only consider the "adjacency" effect between two regions fails to comprehensively capture the structural characteristics of the spatial correlation network for carbon emission efficiency in the logistics industry. Therefore, to deeply analyze the temporal and spatial evolution patterns of the logistics industry, this paper will first measure efficiency using the Super-Slacks-Based Measure (SBM) model with undesirable outputs and then conduct quantitative and qualitative analyses of its network structural characteristics based on social network analysis methods. Finally, the QAP model will be employed to dynamically explore the influencing factors of the spatial correlation network structure for carbon emission efficiency in China's logistics industry, aiming to uncover its underlying drivers. This study aims to investigate the spatial correlation network structure and its driving factors for carbon emission efficiency in China's logistics industry, providing scientific references for regional logistics carbon emission reduction.

2. RESEARCH DESIGN

2.1. Measurement of Efficiency

This paper measures the carbon emission efficiency of the logistics industry using the Super-Slacks-Based Measure (SBM) model with undesirable outputs. The model is presented as follows.

$$min\eta = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{p1+p2}(\sum_{r=1}^{p_1}\frac{s_r^+}{y_{rk}}+\sum_{t=1}^{p_2}\frac{s_t^{b-}}{b_{tk}})} \tag{1}$$

$$\text{s.t.} \quad x_{ik} \gg \sum_{j=1,\neq k}^{n} x_{ij}\lambda_j - s_i^-, \forall i;$$

$$y_{rk} \ll \sum_{j=1,\neq k}^{n} y_{rj}\lambda_j + s_r^+, \forall r;$$

$$b_{tk} \gg \sum_{j=1,\neq k}^{n} b_{tj}\lambda_j - s_t^{\mathrm{b}-}, \forall t;$$

$$1-\frac{1}{p1+p2}(\sum_{r=1}^{p_1}\frac{s_r^+}{y_{rk}}+\sum_{t=1}^{p_2}\frac{s_t^{b-}}{b_{tk}}) > 0;$$

$$s_i^-,\ s_r^+,\ s_t^{\mathrm{b}-},\ \lambda_j \gg 0,\ \forall i,r,t,j$$

In the formula,η denotes the efficiency value of the decision-making unit (DMU). If this value is greater than 1, it indicates that the efficiency is at an effective level; otherwise, there is inefficiency. y, m, $p1$ and $p2$ represent the number of indicator variables for inputs, desirable outputs, and undesirable outputs, respectively. $k$denotes the evaluated DMU. x_i, y_{rk} and b_{tk} represent the slack variables for inputs, desirable outputs, and undesirable outputs, respectively.

2.2. Social Network Analysis

2.2.1. Network Construction

This paper employs a modified gravity model to construct the spatial correlation network for carbon emission efficiency in China's logistics industry. The specific model is as follows:

$$Q_{ij} = k_{ij} \times \frac{ACE_i \times ACE_j}{\frac{D_{ij}^2}{(ag_i - ag_j)^2}},\ k_{ij} = \frac{AG_i}{AG_i + AG_j} \tag{2}$$

Q_{ij}represents the gravity intensity of carbon emission efficiency in the logistics industry between the i and j provinces (municipalities or autonomous regions) in China, $ACE_i, ACE_j, AG_i, AG_j, ag_i, ag_j$ denote the carbon emission efficiency, gross domestic product (GDP) of the logistics industry, and per capita GDP of the logistics industry, respectively, between the i and j provinces (municipalities); k_{ij}denotes the contribution rate of i province to Q_{ij}; D_{ij}^2 denotes the geographic distance between provinces and municipalities (replaced by the distance between provincial capitals).

2.2.2. Analysis of Influencing Factors

In this paper, the QAP (Quadratic Assignment Procedure) model is selected to convert "relational" data into matrix form and perform regression processing and analysis on the matrices. The specific model is as follows:

$$Q = f(W, ED, EI, UR, IS, GOV, OPEN, TRS) \tag{3}$$

In the formula, Q represents the 0-1 matrix of the spatial correlation network for carbon emission efficiency in the logistics industry among provinces and municipalities in China. W represents the spatial adjacency matrix between provinces and municipalities. $ED, EI, UR, IS, GOV, OPEN$ and TRS represent the matrices of differences in economic development level, energy intensity level, urbanization level, industrial structure level, government support level, openness to the outside world, and transportation level, respectively.

2.2.3. Data Sources

The research sample in this paper consists of 30 provinces in China as network nodes, spanning the period from 2006 to 2021. The basic data are sourced from the "China Statistical Yearbook," "China Energy Statistical Yearbook," and "China Tertiary Industry Statistical Yearbook.

3. EFFICIENCY ANALYSIS

Based on the non-expected output super-efficiency SBM model, this paper calculates the carbon emission efficiency of the logistics industry in 30 provinces in China from 2006 to 2021 using MATLAB 2021b software. The country is divided into three major regions: East, Central, and West. The specific results are shown in Figure 1.

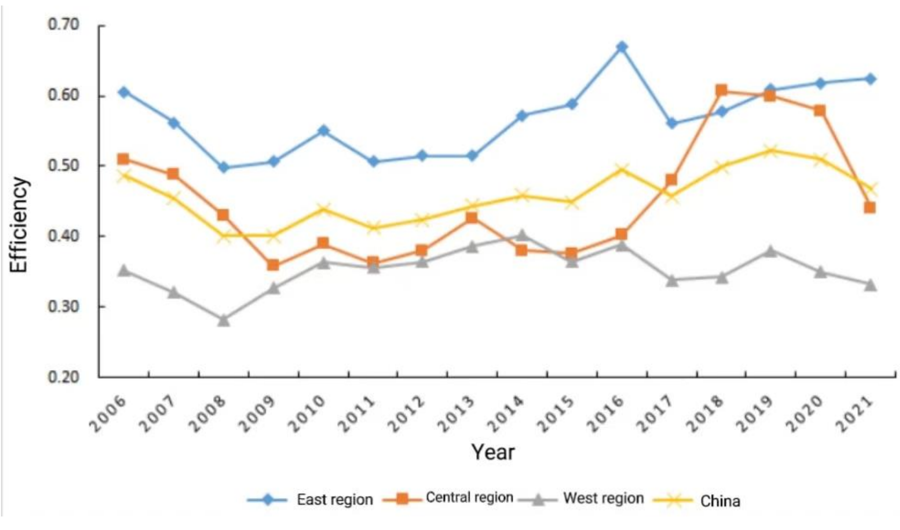

Figure 1. Average Carbon Emission Efficiency of the Logistics Industry in China from 2006 to 2021

From a nationwide perspective, during the study period, the carbon emission efficiency of the logistics industry in China exhibited minimal changes, and there was a significant imbalance in the carbon emission efficiency of the logistics industry among provinces and municipalities. From a regional perspective, during the study period, the average efficiency in the eastern region ranged from 0.499 to 0.669, consistently above the national average. The average efficiency in the central region ranged from 0.358 to 0.607, exceeding the national average in some years. In contrast, the average efficiency in the western region ranged from 0.282 to 0.402, consistently below the national average. Overall, there was an imbalance among regions, with the eastern region > the central region > the western region. From the perspective of provinces and municipalities, the carbon emission efficiency of the logistics industry in China has improved to varying degrees from 2006 to 2021, but the gap between provinces and municipalities remains significant. In terms of averages, Hebei, Guangdong, Ningxia, and Anhui had higher efficiency levels, while Sichuan, Xinjiang, Fujian, and Qinghai had lower efficiency levels, consistently below 0.3.

4. ANALYSIS OF NETWORK STRUCTURE CHARACTERISTICS

4.1. Analysis of Overall Characteristics

As illustrated in Figure 2, each node represents one of the 30 provinces and municipalities studied in this paper. The lines connecting these nodes demonstrate the interconnections in efficiency among provinces and municipalities, while the direction of arrows reflects the spillover relationships in efficiency between them. With the continuous development of the logistics industry, the spatial correlation among provinces and municipalities has been increasingly strengthened, gradually presenting a complex and tight spatial correlation network structure, in which no province or municipality can be "isolated" from the network. Moreover, the spatial correlation in carbon emission efficiency of the logistics industry among provinces and regions has transcended geographical boundaries, maintaining close ties not only with neighboring provinces and municipalities but also with non-neighboring ones, forming complex net-like spatial correlation network characteristics within the region. In other words, among the 30 provinces and municipalities in China, the carbon emission efficiency of the logistics industry in one province or municipality may be influenced by others, gradually connecting with each other. The spatial correlation network structure of carbon emission efficiency in the logistics industry provides a basis for energy conservation and emission reduction in the regional logistics industry and offers guidance for the formulation of relevant policies.

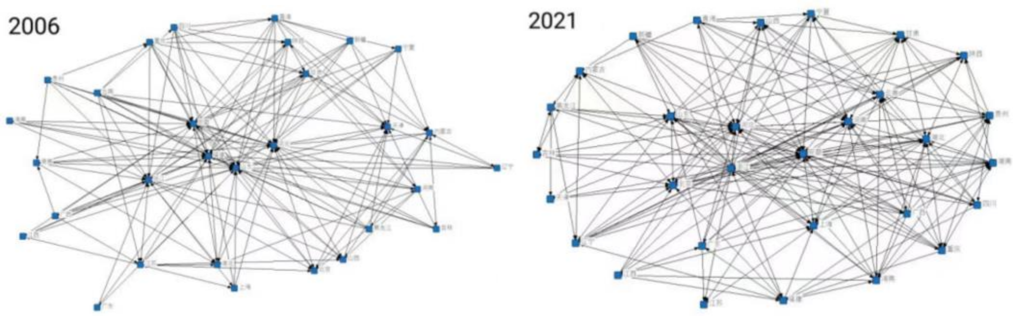

Figure 2. Evolution of Spatial Correlation Network for Carbon Emission Efficiency of the Logistics Industry in China

4.2. Analysis of Individual Characteristics

In directed graphs, degree centrality includes out-degree and in-degree. Specifically, out-degree primarily measures the radiation impact of a node on other nodes within the overall network, while in-degree focuses on assessing a node's ability to attract and concentrate elements from other nodes within the network. Degree centrality effectively measures the status of each province or municipality within the network. Among them, provinces and municipalities with higher degree centrality values, such as Zhejiang, Anhui, Hebei, and Shandong, occupy a dominant position in the spatial correlation network. These areas generally have higher in-degrees, indicating their advantageous geographical locations and transportation facilities, relatively abundant resource allocations, and top-ranking efficiency levels nationwide. Provinces and municipalities with lower degree centrality values include Xinjiang, Sichuan, Shaanxi, and Shanxi, which occupy a subordinate position in the spatial correlation network, have weak correlations with other provinces and municipalities, and exert a relatively minor influence on the overall spatial correlation of carbon emission efficiency in the logistics industry. From the perspective of in-degree and out-degree, Beijing, Anhui, and Hebei have significantly higher in-degrees than out-degrees, indicating that these areas benefit more from the spatial correlation network and exhibit a notable siphon effect. Yunnan, Xinjiang, and Qinghai have higher out-degrees than in-degrees, demonstrating a net spillover effect, as these areas flow towards central and eastern regions under the siphon effect, with relatively significant spillover effects.

The differences in betweenness centrality are pronounced, with a range of 14.705. Zhejiang, Hebei, Anhui, and other areas have significantly higher betweenness centrality values than other regions, indicating that these areas serve as intermediaries in the network, occupy intermediate positions among nodes, and have strong control over resources. Various elements converge and engage in transaction activities in these areas before further diffusing to other regions. Due to their geographical locations, logistics infrastructure, and other advantages, these areas play a bridging role in the spatial correlation network. Notably, the betweenness centrality of most provinces and municipalities is below the average, suggesting that most regions play a relatively minor intermediary role in the network and need to improve their resource control capabilities.

The average closeness centrality is 71.26. Among them, Anhui, Beijing, Hebei, Shandong and seven other provinces and municipalities have closeness centrality values above the average, indicating that these provinces and municipalities function as central actors in the spatial correlation network. They are prone to spatial correlations with other provinces and municipalities, can fully utilize the transmission effect of the network to quickly absorb the technological level of the logistics industry from surrounding areas, and influence the carbon emission efficiency of the logistics industry in other provinces and municipalities, serving as central actors in the spatial correlation network. Additionally, twenty provinces and municipalities, including Xinjiang, Qinghai, Jiangxi, and Heilongjiang, have closeness centrality values below the average, indicating that these areas have limited influence on the carbon emission efficiency of the logistics industry in other provinces. Shanghai and Jiangsu may have approached a certain stage of development ceiling, making it difficult to effectively absorb elements from other provinces and municipalities, while most western regions have relatively limited external element output, which also weakens their correlations and influence with other provinces and municipalities to a certain extent.

Overall, the roles of provinces and municipalities within the network exhibit complex and diverse characteristics. Through in-depth analysis of degree centrality, closeness centrality, and between centrality, we find that the analysis results are generally consistent, particularly highlighting the significant core-periphery structure within the network. Beijing, Hebei, Anhui, and other areas are closely connected with other regions within the network, occupy central positions, and play important intermediary roles. In contrast, Yunnan, Xinjiang, Qinghai, and other areas are located in peripheral regions due to their remote geographical locations and relatively lagging infrastructure, have weaker correlations with other provinces and municipalities, and are more susceptible to the impacts and influences of other provinces and municipalities on their efficiency development.

Table 1. Individual Characteristics of Spatial Correlation Network for Carbon Emission Efficiency in the Logistics Industry in 2021

Regions	Degree centrality			Betweenness centrality	Closeness centrality
	out-degree	in-degree	point centrality		
Anhui	7	20	75.862	8.300	87.900
Beijing	3	17	58.621	4.229	79.300
Fujian	7	8	37.931	1.273	69.000
Gansu	8	8	41.379	0.559	70.700
Guangdong	9	3	34.483	0.940	67.200
Guangxi	11	2	41.379	0.588	70.700
Guizhou	11	7	44.828	1.038	72.400
Hainan	10	6	41.379	0.848	70.700
Hebei	4	25	86.207	9.582	93.100
Henan	8	13	58.621	2.947	79.300
Heilongjiang	7	3	27.586	0.375	63.800
Hubei	10	9	55.172	1.937	77.600
Hunan	10	5	44.828	0.742	72.400
Jilin	6	3	24.138	0.147	62.100
Jiangsu	1	4	13.793	0.025	56.900
Jiangxi	6	5	27.586	0.223	63.800
Liaoning	5	10	37.931	1.055	69.000
Inner Mongolia	5	7	27.586	0.485	63.800
Ningxia	7	6	34.483	0.394	67.200
Qinghai	8	4	31.034	0.505	65.500
Shandong	6	14	62.069	4.516	81.000
Shanxi	5	9	34.483	0.394	67.200
Shaanxi	6	7	34.483	0.332	67.200
Shanghai	3	11	41.379	1.525	70.700
Sichuan	8	3	31.034	0.436	65.500
Tianjin	2	5	17.241	0.050	58.600
Xinjiang	7	1	27.586	0.472	63.800
Yunnan	13	8	51.724	2.375	75.900
Zhejiang	28	2	96.552	14.730	98.300
Chongqing	9	5	34.483	0.551	67.200
Mean	7.667	7.667	42.529	2.052	71.260

5. ANALYSIS OF NETWORK STRUCTURE CHARACTERISTICS

5.1. Correlation Analysis

This paper intends to employ the Quadratic Assignment Procedure (QAP) correlation analysis in UCINET 6.0 software to analyze the influencing factors of the network formation mechanism. The number of random permutations is set to 5000, and the dependent variable and selected independent variables are imported into the software. The specific results are presented in Table 2.

Table 2. Correlation Analysis

Variable Name	Actual correlation coefficient	Significance	Mean of correlation coefficients	Standard deviation	P⩾0	P<0
Spatial adjacency matrix	-0.101	0.017	0.000	0.045	0.983	0.017
Economic development level	0.289	0.000	0.000	0.046	0.000	1.000
Energy intensity	0.174	0.006	0.001	0.046	0.006	0.994
Urbanization level	0.268	0.000	0.000	0.040	0.000	1.000
Industrial structure	-0.114	0.008	0.000	0.053	0.992	0.008

5.2. Regression Analysis

This study further utilizes UCINET 6.0 software to conduct a QAP regression test on the eight influencing factors selected in the previous section. To address the issue of multicollinearity among the factors, a random permutation of 10,000 times is selected. The specific regression results are presented in the following Table 3.

Table 3. Regression Analysis

Variable Name	Standardized coefficient	Significance	Large proportion	Small proportion
Spatial adjacency matrix	-0.059	0.070	0.931	0.070
Economic development level	0.197	0.000	0.000	1.000
Energy intensity	0.119	0.008	0.008	0.992
Urbanization level	0.088	0.012	0.012	0.989
Industrial structure	-0.183	0.000	0.000	1.000
Intercept term	0.157	0.000		

Specifically, the regression coefficient of the spatial adjacency matrix is significantly negative at the 10% significance level, indicating that the geographical distance between provinces and cities affects the spatial correlation of carbon emission efficiency in the logistics industry to some extent. Additionally, this result suggests that neighboring regions are more susceptible to spatial influences, and provinces and cities closer in geographical distance have a greater likelihood of spilling carbon emissions through transportation and other means. This is because the development models of adjacent provinces and cities are relatively similar, and those closer in distance are more likely to form situations of joint pollution control and environmental protection, thereby promoting collaborative governance of carbon emissions.

The coefficient of variation in economic development levels is significantly positive at the 1% level, revealing that differences in economic development levels between provinces and cities have a significant impact on the strength of spatial correlations. Greater differences in economic development levels among provinces and cities will help further strengthen the spatial connections in carbon emission efficiency of the logistics industry. The reason for this is that economic development levels reflect the scale and technological development of the logistics industry among provinces and cities. The closer the economic development levels are, the more similar the economic output per unit of carbon emissions will be among provinces and cities. In addition, provinces and cities with higher levels of economic development will attract capital inflows from other provinces and cities, thereby improving the low-carbon technology level of the logistics industry. Meanwhile, provinces and cities with significant differences in economic development levels may be more equipped with the conditions and potential to implement carbon trading, allowing provinces and cities with weaker economic development capabilities to obtain economic benefits in the carbon trading market, and promoting the transfer and sharing of carbon reduction benefits among provinces and cities, thereby forming a tighter spatial correlation network.

The coefficient of variation in energy intensity levels significantly affects the strength of the spatial correlation network at the 1% level. The regression coefficient is significantly positive, indicating that this factor positively promotes the formation of the network with a significant impact. The reason for this is that energy intensity level is one of the important indicators for measuring the green technology development level of the logistics industry. Higher energy intensity levels usually mean that carbon reduction technologies in the logistics industry are relatively mature, and carbon emission efficiency can be further improved. Provinces and cities with lower energy intensity levels have lower technological development levels, leading to resource waste. As the government has actively supported cross-provincial exchanges and cooperation for a long time, and emphasized the need to further strengthen and promote in-depth cooperation, technical exchanges, and resource sharing between provinces and cities with higher and lower green technology levels, this promotes the green and efficient development of the logistics industry.

The coefficient of variation in urbanization levels is significantly positive at the 5% level, indicating that differences in urbanization levels between provinces and cities have a significant impact on the spatial correlation strength of carbon emission efficiency in China's logistics industry, and also showing that with greater differences in this factor, the spatial correlations among provinces and cities will be stronger. The reason for this is that urbanization levels have a significant impact on regional economic development, which can be demonstrated through various means such as population size and consumption levels, thereby having a profound impact on regional economic development. The development scale of the logistics industry in regions with lower urbanization levels is relatively limited, while the development scale of the logistics industry in regions with higher urbanization levels is more mature, making it easy for high-level regions to drive the development of the logistics industry in low-level regions. Coupled with the support of national regional integration policies, this will further strengthen exchanges and cooperation in the logistics industry among provinces and cities, thereby forming networked correlations.

The coefficient of variation in industrial structure levels is significantly negative at the 1% level, indicating that increasing differences in industrial structure levels will inhibit the formation of the network, while provinces and cities with similar industrial structures are more likely to have close spatial connections. The reason for this is that with the implementation of regional coordinated development strategies, industrial exchanges among provinces and cities are close, and similar industrial agglomerations and chains are required in the process of industrial exchanges and transfers, which further necessitates similar transportation and technological infrastructures. Therefore, the smaller the differences in industrial structures among provinces and cities, the more spatial correlations in carbon emission efficiency of the logistics industry will exist.

6. CONCLUSION

Firstly, from the perspective of the measurement results of carbon emission efficiency in the logistics industry, the efficiency values are generally low and exhibit fluctuating trends, indicating that the level of carbon emission efficiency in China's logistics industry still needs further improvement. Regionally, the efficiency development curves of China's three major regions show that the eastern region maintains a leading position, followed closely by the central region, while the western region lags significantly behind the eastern and central regions but still demonstrates a trend of catching up. Additionally, the average carbon emission efficiency of the logistics industry in the western region remains at a relatively low level.

Secondly, from the perspective of the spatial correlation network structure, the carbon emission efficiency of China's logistics industry has gradually exhibited intricate spatial correlations within regions. From the overall network structure, the carbon emission efficiency of China's logistics industry presents a structural characteristic of "dense in the east, dispersed in the middle, and sparse in the west" within the spatial correlation network. From the individual network structure, there is a significant imbalance in the spatial distribution of node provinces and cities. Provinces and cities in the eastern region have a higher concentration and influence in terms of carbon emission efficiency in the logistics industry, while the improvement of carbon emission efficiency in the central and western regions gradually spreads and influences surrounding areas.

Lastly, various influencing factors all contribute to the formation of the spatial correlation network for carbon emission efficiency in the logistics industry. Spatial distance, economic development level, energy intensity, urbanization level, and industrial structure significantly impact the construction of the spatial correlation network for carbon emission efficiency in the logistics industry. Among them, differences in economic development level, energy intensity, and urbanization level are conducive to promoting network formation, while similar spatial distances and industrial structures can better facilitate the formation of spatial correlation networks.

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