Research on the Spatial Spillover Effect of Carbon Emission Trading on Carbon Emission Intensity

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Abstract. This article is based on panel data from 30 provinces in China from 2006 to 2019, analyzing the spatial spillover effects of carbon emission trading on carbon emission intensity through spatial econometric models. The empirical results indicate that China's carbon emission efficiency has significant regional differences and spatial correlations. Carbon emission trading can significantly reduce the carbon emission intensity of the treatment area, while also having a suppressive effect on the carbon emission intensity of surrounding areas. Based on the above conclusions, this article suggests promoting the opening and innovation of the carbon emissions trading market, increasing monitoring and control of the negative impact of carbon emissions trading, and promoting the optimization and improvement of carbon emissions trading policies.

Keywords: Carbon emissions trading, Spatial spillover effect, Spatial Durbin model.

1. Introduction

In July 2021, the national carbon emission trading market officially launched online trading, which means that the unified national carbon emission trading market will play a more active role in promoting the "dual carbon" goal. In fact, carbon emissions trading is not a new phenomenon. With the official entry into force of the Kyoto Protocol in 2005, the commodity nature of carbon emissions trading has been established. Carbon emissions trading is a market-based environmental policy tool aimed at controlling and reducing greenhouse gas emissions through a pricing mechanism. In practice in our country, the government first sets a carbon emission cap and then distributes this cap to various participating enterprises, known as carbon emission quotas. The government mainly sets carbon emission quotas based on the historical emission data and future emission reduction targets of various enterprises, enterprises purchase or sell these emission rights based on their own carbon emissions situation, thus forming a carbon emission trading market. In addition, China's carbon emission trading system was piloted in some specific provinces and cities, including Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, Shenzhen, etc., before the nationwide system was launched in 2021, forming some good experiences. However, the operational effectiveness of the carbon emissions trading market has not been fully studied and evaluated. At present, research on the impact of carbon emission trading on China's carbon emission efficiency mainly focuses on the analysis of a single pilot market or the comparison of several markets, lacking a systematic and comprehensive analysis nationwide. Moreover, existing studies mainly use traditional regression analysis or panel data analysis, and few scholars have considered the spatial characteristics and effects of carbon emissions in China. Therefore, this article aims to use spatial analysis methods to comprehensively and deeply study the impact of carbon emission trading on China's carbon emission efficiency, and analyze the spatial spillover effects of carbon emission trading on carbon emission efficiency, to provide reference for the improvement and development of China's carbon emission trading market.

2. Literature References and research hypothesis

2.1. Literature References

2.1.1. Research on Carbon Emission Trading

Carbon emission trading is an emission reduction mechanism centered on property rights theory and market trading methods. In 1920, the renowned British economist Pigou proposed in "Welfare Economics" that polluters could be taxed based on the degree of harm caused by pollution. Coase (1960) believed that in a situation where property rights are clearly defined and transaction costs are zero, social optimal allocation can be achieved through free transactions regardless of the initial distribution of property rights.

Carbon emissions trading, as an important tool for mitigating climate change, has attracted widespread attention. Researchers evaluate the impact of carbon emissions trading from different perspectives, with a focus on emission reduction effects and economic benefits. From an international perspective, Gavard et al. (2016) found that after limiting the number of carbon emission permits, companies will actively participate in low-carbon technology innovation. Zhou Kaiguo and Guan Zihuan (2023) used daily trading data from the Intercontinental Exchange (ICE) and the European Energy Exchange (EEX) from 2013 to 2021 to study and found that carbon futures can play a role in hedging and price discovery, and can also strengthen the carbon market's role in reducing carbon emissions.

From a domestic perspective, Huang Xianglan et al. (2018) conducted a quasi-natural experiment to analyze the environmental benefits of China's carbon emissions trading policy. The study found that the carbon trading pilot had a significant policy effect on reducing carbon dioxide emissions and achieved positive environmental benefits. Zhang et al. (2019) found that China's carbon emissions trading greatly promotes carbon reduction in the industrial sectors involved, and this impact shows an overall increasing trend. Hu Jun et al. (2020) found that the implementation of carbon emission trading mechanisms significantly promotes the technological innovation behavior of participating trading enterprises. Zhang Tao et al. (2022) found that carbon emissions trading can alleviate insufficient investment in enterprises and improve their investment efficiency, and this effect is more significant in non-state-owned enterprises. The research group of Nanjing Branch of the People's Bank of China (2022) believes that at present, China's marginal emission reduction costs are in a fast-rising stage. It is necessary to introduce differentiated carbon tax policies because of carbon emission trading, and help carbon emission reduction through the "carbon trading+carbon tax" model. Wang and Zhang (2022) found that China's carbon emissions trading has a significant negative impact on the market power of petrochemical industry enterprises, but has no effect on several other related industries. Liu et al. (2023) found from the perspective of the power industry that China's carbon trading policy significantly promotes carbon reduction in the power industry, and the implementation of carbon trading policies. The longer the time, the stronger the effect.

2.1.2. Research on Carbon Emission Efficiency

Carbon emission efficiency, as an important environmental efficiency evaluation indicator, can measure the carbon emissions corresponding to a unit of output, which is of great significance for evaluating the carbon emission level of enterprises or industries. Carbon emission efficiency can be divided into single factor carbon emission efficiency and comprehensive factor carbon emission efficiency. The single factor carbon emission efficiency only focuses on the role of a certain production factor in carbon emissions, such as labor, capital, etc; The comprehensive factor carbon emission efficiency considers the combined impact of multiple production factors on carbon emissions. Kaya and Yokobori (1997) first proposed the concept of "carbon emission efficiency under a single factor", defining it as the ratio between gross domestic product (GDP) and total carbon dioxide emissions. Subsequently, some scholars proposed the concept of comprehensive factor carbon emission efficiency to measure the combined impact of multiple production factors on carbon emissions.

2.2. Theoretical Analysis and Hypothesis Formulation

To address climate change and achieve emission reduction targets, the government and enterprises have actively taken various measures, and establishing a carbon emission trading mechanism is one of them. This mechanism treats carbon emission rights as commodities traded in the market, aiming to reduce carbon emissions and improve carbon emission efficiency through market behavior. This section will use public goods theory and internalization externality theory to analyze how carbon emissions trading affects carbon emission efficiency.

Carbon emissions are a public good with nonexclusive and noncompetitive characteristics, and their benefits and costs often do not fully match. Because the environmental benefits generated by emission reduction actions may not necessarily belong entirely to oneself, companies may not be willing to bear the cost of emission reduction. The carbon emission trading mechanism endows carbon emission rights with economic value, making enterprises more willing to increase emission reduction investment, improve carbon emission efficiency, and obtain emission reduction benefits. By setting reasonable emission reduction targets and carbon emission quotas, the efficiency and fairness of emission reduction can be improved, and the achievement of environmental protection goals can be promoted. This mechanism combines the interests of enterprises and governments, achieving the unity of economic benefits, environmental benefits, and social benefits.

The theory of internalizing externalities holds that if the costs or benefits generated by externalities can be internalized, then the problem of externalities can be solved. Carbon emissions are a negative externality, and the environmental pollution generated by corporate carbon emissions can have a negative impact on society and public interests, but companies often do not proactively internalize these costs. The carbon emissions trading system helps companies internalize the external costs of carbon emissions, making them more focused on environmental protection and resource utilization, thereby improving carbon emission efficiency.

The Porter hypothesis suggests that appropriate environmental regulations can promote technological innovation in enterprises, thereby improving productivity and competitiveness, but whether they can offset the compliance costs of enterprises still requires specific analysis. In practice, policy makers need to comprehensively consider the impact of environmental regulations on enterprises to achieve a virtuous cycle of environmental protection and economic development.

Firstly, carbon emissions trading can promote enterprises to adopt cleaner and low-carbon production methods. Carbon emissions trading has introduced a quantitative allocation and trading mechanism for carbon emissions. Enterprises must conduct appropriate analysis and evaluation of their own carbon emissions to obtain sufficient emission rights. This makes enterprises pay more attention to emission reduction and clean production, thereby helping to improve carbon emission efficiency. Secondly, carbon emissions trading can incentivize enterprises to engage in technological and management innovation. Carbon emissions trading includes a pricing mechanism for carbon emissions, and enterprises need to constantly innovate to improve production efficiency and reduce carbon emission costs. The introduction of technological innovation and management innovation can enhance the innovation capability of enterprises and further promote the improvement of carbon emission efficiency. Finally, carbon emissions trading can promote companies to gain a competitive advantage in the market. For enterprises that can reduce carbon emissions, the carbon emissions trading mechanism will bring direct economic benefits and enhance their competitive advantage.

In summary, the carbon emission trading mechanism can improve carbon emission efficiency by promoting enterprises to adopt low-carbon and cleaner production methods, incentivizing technological and management innovation, and facilitating competitive advantages in the market. Therefore, this article proposes hypothesis 1.

H1: Carbon emissions trading has a positive impact on reducing carbon emissions in the region.

The "pollution shelter" hypothesis suggests that when developed countries implement environmental protection policies, high polluting and high energy consuming industries are transferred to developing countries, which helps alleviate environmental problems in developed countries. However, environmental problems in developing countries become more severe. At the same time, after transferring production, these enterprises often take advantage of the lower environmental standards and weaker regulatory measures in developing countries to continue polluting the environment, further deteriorating the environmental conditions in developing countries. This phenomenon indicates that the implementation of environmental policies may lead to the spatial transfer of environmental pollution, resulting in negative spatial spillover effects. The carbon emission trading mechanism within the same country may also generate similar negative spatial spillover effects. On the one hand, due to the quantitative allocation and trading mechanism of carbon emission allowances, enterprises need to purchase carbon emission allowances when carbon emission quotas are insufficient, resulting in an increase in production costs. To reduce costs, companies may adopt a strategy of shifting production to surrounding areas, leading to worsening environmental pollution problems and negative spatial spillover effects. On the other hand, due to the carbon emission trading mechanism restricting and regulating the carbon emissions of enterprises, those enterprises that cannot meet emission requirements will face the risk of being forced to shut down or reduce production capacity. To avoid this risk, companies may choose to shift production to surrounding areas to bypass carbon emission restrictions, which can also result in negative spatial spillover effects. In summary, this article proposes hypothesis 2.

H2: Carbon emissions trading may have negative spatial spillover effects on carbon emissions in surrounding areas.

3. Research Design

The spatial weight matrix required for the spatial econometric model in this article is defined using the two most common methods in spatial econometrics. One is the spatial weight matrix under the adjacency rule, which displays the adjacency relationship between two regions. The specific definition is:

$$w_{ij}=\begin{cases} 1, when\ region\ i\ is\ adjacent\ to\ j \\ 0, when\ region\ i\ and\ j\ are\ not\ adjacent \end{cases}$$

The other is the spatial weight matrix defined based on geographical distance:

$$w_{ij}=\begin{cases} 0, when\ i=j \\ 1/dij, when\ i\neq j \end{cases}$$

Among them, dij represents the distance between the geometric center coordinates of region i and region j calculated by latitude and longitude.

Table 1. Variable Definition

Variable Type	Variable Name	Variable Symbol	Variable Declaration
Explained Variable	regional carbon emission intensity	Carbon	Natural logarithm of the ratio of regional carbon emissions to GDP
explaining variable	carbon emission trading	ETS	Annual cumulative trading volume of carbon emission quotas in each province
control variable	level of economic development	PGDP	Logarithmic calculation of per capita GDP
	foreign investment	FDI	Actual investment amount of foreign-funded enterprises
	environmental regulation	EU	Investment amount for industrial pollution control
	urbanization rate	UR	Urban permanent population/total permanent population at the end of the year
	industrial structure	ISU	The proportion of added value of the secondary industry to the regional gross domestic product

The spatial correlation in spatial econometric models is mainly caused by the dependent variable, independent variable, or error term. The Spatial Durbin Model (SDM) is a relatively general model that can not only measure the spatial correlation of the three aspects mentioned above, but also be transformed into a Spatial Lag Model (SLM) or Spatial Error Model (SEM) under different coefficient settings.

$Carbon_{it} = \alpha_0 + \rho\, WCarbon_{jt} + \beta ETS_{it} + \theta_j WETS_{jt} + \gamma X_{it} + \mu_i + v_t + \varepsilon_{it}$

The specific explanations of each major variable are shown in Table 1.

4. Empirical Analysis

4.1. Spatial Characteristics of Carbon Emission Intensity

According to statistical data, there are significant differences in carbon emission efficiency among different regions in China. The carbon emission efficiency in the eastern region is generally higher than that in the central and western regions, and the carbon emission efficiency in the southern region is also generally higher than that in the northern region.

This article uses Moran's I index and Geary's C index to conduct global spatial autocorrelation tests. The Moran's I index reflects the similarity of unit attribute values in spatially adjacent or neighboring regions. The value of Moran's I index is generally between [-1,1], less than 0 indicates negative correlation, equal to 0 indicates no correlation, and greater than 0 indicates positive correlation. The closer it is to -1, the greater the difference or less concentrated the distribution between units; The closer it is to 1, the closer the relationship between units and the more similar their properties are; If it is close to 0, it indicates that there is no correlation between the units. The value of Geary's C is generally between [0,2], with values greater than 1 indicating negative correlation, values equal to 1 indicating no correlation, and values less than 1 indicating positive correlation.

According to the results in Table 2, Moran's I index is greater than 0, and Geary's C index is greater than 0 but less than 1. Both testing methods indicate a spatial positive correlation between China's carbon emission efficiency.

Table 2. Moran’s, I Index and Geary's C Index of Carbon Emission Intensity

Year	Moran’s I	p value	Geary’s C	p value
2006	0.430***	0.000	0.716	0.113
2007	0.214***	0.005	0.983	0.931
2008	0.364***	0.000	0.724*	0.065
2009	0.405***	0.000	0.591***	0.002
2010	0.367***	0.001	0.619***	0.005
2011	0.263**	0.013	0.681**	0.020
2012	0.245**	0.020	0.693**	0.024
2013	0.205**	0.040	0.707**	0.042
2014	0.151*	0.100	0.702*	0.054
2015	0.130	0.143	0.708*	0.060
2016	0.142	0.108	0.675**	0.043
2017	0.127	0.137	0.680*	0.051
2018	0.119	0.153	0.677*	0.051
2019	0.121	0.148	0.675**	0.049

4.2. Model Setting Verification

Firstly, the Hausman test is used to determine whether the model uses random effects or fixed effects. According to Table 5, both the 0-1 adjacency weight matrix and the geographic distance weight matrix passed the significance test at the 1% level. Therefore, the spatial econometric model should choose to use both spatial and temporal fixed effects.

Secondly, to determine which of the three most used spatial econometric models, namely spatial lag model (SAR), spatial error model (SEM), and spatial Durbin model (SDM), is more in line with the research content of this paper, Lagrange Multiplier (LM) test is conducted. The test results in

Table 5 show that neither the 0-1 adjacency weight matrix nor the geographic distance weight matrix passed the Robust LM lag test, and it cannot be determined which model to use. Because the Spatial Durbin Model (SDM) is a relatively universal model that can be transformed into Spatial Lag Model (SAR) or Spatial Error Model (SEM) under different coefficient settings, this article chooses to use the Spatial Durbin Model (SDM).

Finally, to validate the validity of using the Spatial Durbin Model (SDM), this paper employs the Likelihood Ratio (LR) test and Wald test. The results of LR test and Wald test are shown in Table 3. The 0-1 adjacency weight matrix and geographic distance weight matrix both passed the significance test at the 1% level, rejecting the null hypothesis that the spatial Durbin model can degenerate into a spatial lag model or a spatial error model. In summary, it is reasonable to ultimately choose the Spatial Durbin Model (SDM) as the research model in this article.

Table 3. Measurement Method Inspection Results

		0-1 adjacency weight matrix		distance weight matrix	
		statistic	p value	statistic	p value
LM	SEM	128.954	0.000	26.426	0.000
	SLM	28.239	0.000	3.204	0.073
Robust LM	SEM	100.749	0.000	23.225	0.000
	SLM	0.033	0.855	0.003	0.960
LR	SDM&SAR	95.050	0.000	109.990	0.000
	SDM&SEM	82.020	0.000	110.540	0.000
Wald	SDM&SAR	100.340	0.000	124.820	0.000
	SDM&SEM	95.630	0.000	130.490	0.000
Hausman	space	75.445	0.000	75.445	0.000
	time	113.153	0.000	113.153	0.000

4.3. Hypothesis Test Results

To explore the impact of carbon emission trading on carbon emission efficiency, the empirical results of this paper are shown in Table 4.

It can be observed that the explanatory variable carbon emissions trading is significantly positive, indicating that carbon emissions trading has a positive effect on improving carbon emission efficiency. Hypothesis 1 of the study has been validated. This may be because carbon emission trading can provide economic incentives for enterprises to reduce carbon emissions. Through the competition and reward mechanism of the carbon market, it guides enterprises to innovate and improve in emission reduction and trading, promotes the adjustment and optimization of industrial structure, and drives the green transformation of the economy.

The construction of infrastructure such as "West East Gas Transmission" and "West East Electricity Transmission" can to some extent solve the problem of inconsistency between domestic energy demand and the spatial distribution of natural resources. To eliminate the influence of China's "West East Gas Pipeline" on the research conclusions, this paper tests the length of natural gas pipelines and the total amount of natural gas supply in each province as control variables. The empirical results indicate that the sign and significance of the carbon emission trading coefficient have not changed, demonstrating the robustness of the research conclusions.

In addition, according to existing research, the carbon emission efficiency of regions may also be affected by the degree of population agglomeration, and there are significant differences in population density between provinces in China. Therefore, this article further controls the population density factor of provinces for testing, and the empirical results are still significant, which verifies the robustness of the research conclusions.

Table 4. Empirical Results

	0-1 adjacency weight matrix	distance weight matrix
ETS	-0.003**	-0.008***
	(-2.823)	(-6.004)
W×ETS	-0.005***	-0.004**
	(-2.188)	(-2.548)
PGDP	-0.151***	-0.008
	(-2.582)	(-0.296)
FDI	-0.474***	-0.159***
	(-5.665)	(-5.557)
EU	0.008	0.001
	(1.195)	(0.195)
UR	2.456***	0.279***
	(6.628)	(2.640)
ISU	0.040	0.309***
	(0.630)	(3.350)
ρ	0.180***	0.471***
	(2.725)	(25.133)
Individual fixed	YES	YES
Time fixed	YES	YES
N	420	420

According to Table 4, the coefficient of W × ETS is significantly negative, indicating that carbon emission trading has a negative effect on improving carbon emission efficiency when considering spatial dependence. The possible reason for this phenomenon is that the implementation of carbon emission trading may further widen the gap in carbon emission efficiency between different regions. For example, some regions may purchase more carbon emission rights, while others are unwilling to spend money on them, which may further exacerbate spatial differences and lead to negative externalities in space.

Whether carbon emission trading has a negative effect on improving carbon emission efficiency mainly depends on two aspects: first, whether the design of the trading mechanism is reasonable, and second, whether the government's supervision and management of the carbon emission market are in place. For the design of trading mechanisms, it is necessary to consider the fairness, transparency, and competitiveness of the market. If market rules are unclear, trading mechanisms are unfair, or there is monopolistic behavior in the market, it may lead to negative effects of carbon emission trading on improving carbon emission efficiency. For example, if there are a few large carbon emission rights holders in the market, they may raise prices by monopolizing the supply of carbon emission rights, thereby reducing the competitiveness of other enterprises and leading to market failure. In addition, government regulation and management of the carbon emission market are also very important. The government should establish a sound market supervision mechanism to regulate the behavior of market participants and prevent market failure. At the same time, effective management of the carbon emission market should be carried out, including verifying the authenticity of carbon emission rights, establishing a credit system for carbon emission trading, and strengthening market information disclosure and openness.

5. Conclusion

Based on the above test results, this article mainly draws the following research conclusions: (1) There is a significant spatial correlation in China's carbon emission efficiency. The carbon emission efficiency varies in different regions of our country, with the eastern region consistently higher and the central and western regions lower. There are three main clustering phenomena, one is that Gansu, Shaanxi, and Ningxia show significant low clustering; Secondly, Hebei, Guizhou, Anhui, and Jiangxi exhibit significant low high clustering; Thirdly, Zhejiang, Jiangxi, Fujian, Guangdong, Chongqing and other places have high and high concentrations in different years. (2) Carbon emission trading can improve the carbon emission efficiency of the local area, but it has negative spillover effects. This article uses the spatial Durbin model, and the results show that the coefficient of carbon emission trading is significantly positive, indicating that carbon emission trading can improve the carbon emission efficiency of the local area, thus verifying research hypothesis 1. The coefficient of the interaction term between carbon emission trading and spatial weight matrix is significantly negative, indicating that carbon emission trading will have a suppressive effect on the carbon emission efficiency of surrounding areas, thus verifying research hypothesis 2.

Based on empirical research findings, this article proposes the following policy recommendations: to increase the enthusiasm of enterprises to participate in carbon emission trading through incentive measures such as tax incentives, fiscal subsidies, green bonds, and carbon credits, and to strengthen information disclosure and supervision to safeguard the right to know and interests of enterprises and investors. Establish a comprehensive management mechanism and market mechanism for carbon total accounting, carbon monitoring, carbon capture, carbon sink, etc., and establish a sound evaluation system to regularly evaluate the carbon emission trading mechanism and carbon emission efficiency, adjust and improve policy measures in a timely manner, and ensure the smooth operation of the carbon emission trading mechanism. In response to the negative spillover effects of carbon emission trading, further exploration is needed to establish an ecological compensation mechanism. By implementing a trading spillover compensation mechanism, economic compensation can be provided to surrounding areas affected by the negative spillover effects to alleviate their economic pressure. In addition, we can increase support for the research and promotion of carbon emission reduction technologies, promote the application of clean energy and low-carbon technologies, fundamentally improve carbon emission efficiency, and provide strong support for the healthy development of the carbon emission trading market.

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