Research on the Impact of Carbon Markets on Inter-Provincial Carbon Equity and Spatial Spillover Effects

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Abstract. With the deepening of the "dual carbon" goals (carbon peak and carbon neutrality), ensuring inter-provincial carbon emission equity alongside improving carbon emission reduction efficiency has become crucial. This paper uses panel data from 30 provinces in China from 2006 to 2023. Employing the multi-period difference-in-differences (DID) method and the spatial Durbin model, we investigate the impact of carbon trading markets on inter-provincial carbon emission equity. The results show that the implementation of carbon trading pilot policies significantly enhances inter-provincial carbon emission equity. Mechanism analysis further reveals that carbon trading pilot policies significantly improve inter-provincial carbon emission equity through industrial structure adjustment. Furthermore, heterogeneous effects on inter-provincial carbon emission equity exist across different regions and levels of income distribution. Further analysis indicates that the impact of carbon trading pilot policies on inter-provincial carbon emission equity exhibits a positive spatial spillover effect, with a negative "siphon effect" observed among pilot regions. Finally, policy recommendations are proposed based on the research findings. This study is of significant importance for enriching research in the field of carbon emission equity and promoting the establishment of a nationwide unified carbon market.

Keywords: Carbon trading market, Carbon emission equity, Multi-period difference-in-differences method, Spatial Durbin model.

1. Introduction

Against the backdrop of accelerating global climate governance, developing countries generally face a structural contradiction between the demand for economic growth and the undertaking of climate responsibilities. China, as the world's largest carbon emitter and renewable energy investor, has achieved significant emission reduction results in advancing its "dual carbon" goals. However, significant differences among provinces in economic development levels, resource endowments, and industrial structures have led to a marked imbalance in the distribution of carbon emission responsibilities. Therefore, establishing a scientific and reasonable inter-provincial carbon emission rights allocation mechanism will lay an important institutional foundation for promoting the construction of a national unified carbon market, and will also promote benign interaction between regional equitable development and green transformation.

Carbon trading markets, with their flexibility, economic efficiency, and effectiveness in emission reduction strategies, are considered a key mechanism for effectively addressing climate change [1]. As a key policy tool, carbon emission trading markets not only provide an effective platform for achieving the “dual carbon” goals but also play a key role in promoting carbon emission equity through economic leverage.

Existing literature has systematically studied the issue of carbon emission equity from various dimensions, including definition [2-3], indicator system construction [4-5], carbon emission rights allocation mechanisms [6-7], and influencing factors [9-10], proposing multi-dimensional equity measurement frameworks and allocation methods. Simultaneously, domestic and international scholars have conducted related research on the impact of carbon trading markets on carbon emission equity. Pang and Zhang found that a carbon emission quota allocation mechanism based on producer responsibility, compared to one focusing on consumer responsibility, exhibits higher inequality in the context of inter-provincial trade, a phenomenon significantly constrained by multi-dimensional factors such as the energy structure, industrial layout, and economic strength of various provinces

[11]. The resulting allocation effect is particularly prominent in carbon trading markets, with significant differences in the allocation of carbon emission quotas in different regions. Therefore, Wang and Chen pointed out that ensuring inter-provincial carbon equity is a key consideration when constructing carbon markets and formulating provincial initial carbon emission quota allocation schemes, which is crucial for effectively advancing the "dual carbon" strategic goals [12]. Furthermore, Zhang et al., focusing on the perspective of carbon trading markets, revealed the role of restricting capital inflow into high-carbon industries and promoting improvements in green total factor productivity in promoting carbon equity [13].

This paper, from the perspective of a quasi-natural experiment, deeply investigates the impact, mechanism, heterogeneity analysis, and spatial spillover effects of carbon markets on inter-provincial carbon equity, and draws conclusions on the impact on the resilience of high-pollution enterprise supply chains under the "dual carbon" goals. However, existing literature is often limited to a single perspective of carbon emission equity or carbon trading markets, and there is still a lack of discussion on the mechanism, heterogeneity analysis, and spatial spillover effects of the impact of carbon trading markets on inter-provincial carbon emission equity.

Based on existing literature, the marginal contributions of this paper are mainly reflected in: First, in terms of research perspective, it incorporates carbon markets and inter-provincial carbon emission equity into the same research framework, enriching the scope of research on the impact effects of carbon trading markets; second, in terms of research content, it empirically tests the spatial spillover effect of carbon trading markets on inter-provincial carbon emission equity, innovatively proposing the conclusion that spatial siphon and spillover effects coexist; third, in terms of heterogeneity research, existing literature mainly focuses on the heterogeneity analysis of East, Central, and West China, while this paper further introduces heterogeneity analysis of North and South regions and income distribution gaps; fourth, in terms of impact mechanisms, existing literature mainly focuses on energy structure, environmental regulation, and total factor productivity, while this paper innovatively examines the mechanism effect of industrial structure in the impact of carbon trading markets on inter-provincial carbon emission equity, enriching related research on impact pathways and effects.

2. Materials and Methods

First, this study analyzes panel data from 30 provinces in China from 2006 to 2023 (excluding Tibet, Hong Kong, Macau, and Taiwan due to data limitations). Data were collected from the China Statistical Yearbook, the CSMAR database (https://data.csmar.com), and Macrodata (https://s.macrodatas.cn). Missing data were imputed using interpolation, and outliers were handled using winsorization. Inter-Provincial Carbon Emission Equity Index: Following the research framework, a comprehensive evaluation system was constructed based on four dimensions: carbon emission responsibility, carbon emission reduction potential, carbon emission reduction capacity, and carbon emission economic efficiency [14-15]. The entropy weight method was used to calculate the inter-provincial carbon emission equity index. A higher index value indicates a higher level of equity in carbon emission allocation. (see Table 1 below).

Table 1. A fair evaluation index system for carbon emissions

	Level 1 Indicator	Level 2 Indicator	Level 3 Indicator
Carbon Emission Equity	Responsibility	Per capita carbon emissions	2.91%
	Potential	Carbon intensity	6.11%
	Capacity	Industrial output value/GDP	14.16%
	Economic Efficiency	(Provincial GDP/National GDP)/(Provincial Carbon Emissions/National Carbon Emissions)	0.14158

Second, as for explanatory variables and model specification, this study focuses on the regional governance effects of carbon trading pilot policies. A policy intervention dummy variable serves as the core explanatory variable: provinces included in the national carbon trading pilot program are assigned a value of 1 from the year of policy implementation; non-pilot provinces and pilot provinces before policy implementation are assigned a value of 0. Control and mechanism variables are described in Table 2

Table 2. Select the variables and their definitions

Variable Name	Variable Specifications	Variable Symbol	Variable Explanation
Dependent Variable	Inter-provincial Carbon Emission Equity	*equ*	equ (Inter-provincial carbon emission equity index calculated using the entropy weight method)
Explanatory Variable	Carbon Trading Market Pilot Policy	*Treat×Post*	Treat×Post (Dummy variable indicating whether a province implemented the carbon trading policy. Value is 1 if the policy was implemented in the year of launch and subsequent years; 0 otherwise)
Control Variables	Urbanization Level	*urban*	urban (Proportion of urban population to total population)
	Social Consumption Level	*sc*	sc (Total retail sales of consumer goods/Regional GDP)
	Economic Development Level	ln*(perGDP)*	ln(perGDP) (ln(Per capita GDP) = ln(Total GDP/Total Population))
	Fiscal Support	*fs*	fs (Proportion of local government general public budget expenditure)
Mechanism Variable	Urban-Rural Income Gap	*gap*	gap (Difference in income levels between urban and rural residents)
	Industrial Structure	*Is*	Is (Proportion of the tertiary industry in GDP)

The third step is to analyze the data. This study employs a quasi-natural experiment design to investigate the impact of carbon trading markets on inter-provincial carbon emission equity. The analysis proceeds as follows: descriptive statistics are presented; baseline regression analysis estimates the impact of carbon markets on carbon emission equity; robustness checks are conducted; the mechanism effect of carbon market-induced industrial structure adjustments on carbon emission equity is tested; heterogeneity analysis based on region and income distribution is performed; spatial spillover effects are analyzed; and finally, policy recommendations are aproposed.The specific calculation results are shown in Figure 1.

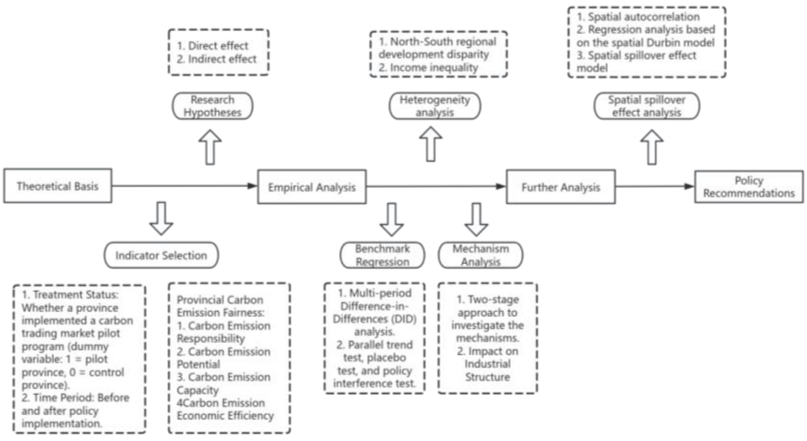

Figure 1. Frame diagram

This paper treats the phased implementation of carbon trading market pilot policies in China as a quasi-natural experiment. A multi-period difference-in-differences (DID) model is employed to evaluate the policy's impact on inter-provincial carbon emission equity. Considering the temporal differences in policy implementation across pilot regions, the following multi-period DID model is constructed:

$$equit=\alpha 0+\alpha 1Treatedi\times Postt+\alpha 2Xit+\mu i+\delta t+\varepsilon it \quad (1)$$

To further investigate the potential indirect effects of the carbon trading market pilot program on inter-provincial carbon emission equity, industrial structure (Is) is selected as a mediating variable. A mediation analysis model (2) is constructed for analysis.

$$Isit=\delta 0+\delta 1Treatedi\times Postt+\delta 2Xit+\mu i+\delta t+\varepsilon it \quad (2)$$

To examine the impact of carbon trading pilot provinces on carbon emission equity in neighboring provinces, a spatial difference-in-differences (DID) model is further constructed as follows:

$$equit=\rho Wijequit+\beta 1Treatedi\times Postt+\beta 2Xit+\gamma 1\ WijTreatedi\times postt+\gamma 2\ WijXit+\mu i+\delta t+\varepsilon it \quad (3)$$

3. Results

3.1. Descriptive Statistics

Descriptive statistics are shown in the table 3 below:

Table 3. Descriptive statistics

Variable	Sample Size	Mean	Min	Max
equ	540	0.194	0.0923	0.623
Treated×Post	540	0.133	0	1
lnperGDP	540	10.64	9.180	12.07
fs	540	0.242	0.0976	0.758
sc	540	0.381	0.221	0.550
urban	540	0.575	0.275	0.893
gap	540	2.636	1.842	4.061
Is	540	1.271	0.527	5.690

3.2. Main Findings

3.2.1 Baseline Regression

A multiple time-point difference-in-differences analysis was conducted based on Model (1) to investigate the impact of the carbon trading market pilot program on inter-provincial carbon emission equity. The results are shown in Table 4. The regression results show that the coefficient of the DID term is significantly positive at the 1% level regardless of whether control variables are included or whether regional and year fixed effects are controlled. Furthermore, the R^2 significantly increases after including fixed effects, indicating that regional and time factors have a significant impact on the dependent variable edu. This suggests that the carbon trading market pilot program has a long-term positive impact on inter-provincial carbon emission equity, supporting Hypothesis 1. (see Table 4 below).

Table 4. Baseline regression results

Variable	(1)	(2)	(3)	(4)
	edu	edu	edu	edu
_cons	0.1756***	0.1849***	-0.6608***	-1.3888***
	(0.0029)	(0.0015)	(0.0742)	(0.1801)
Treated×Post	0.1390***	0.0687***	0.0592***	0.0294***
	(0.0081)	(0.0061)	(0.0076)	(0.0058)
lnperGDP		0.0634***		0.1790***
		(0.007)		(0.0168)
fs		-0.2313***		-0.1364***
		(0.0215)		(0.0410)
sc		0.0741**		0.1393***
		(0.0340)		(0.0266)
urban		0.1090***		-0.8538***
		(0.0318)		(0.0723)
gap		0.0519***		0.0547***
		(0.0069)		(0.0125)
Region FE	No	Yes	No	Yes
Year FE	No	Yes	No	Yes
obs	540	540	540	540
R-squared	0.3553	0.8717	0.6262	0.9151
F	296.52	128.38	148.81	73.50

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are standard deviation

3.2.2 Mechanism Analysis

Following Jiang Ting's discussion on channel testing [16], we first verify the impact of the carbon trading market on industrial structure adjustment. Then, to compensate for the shortcomings of industrial structure adjustment in the theoretical argument of the causal effect of carbon emission equity, we further investigate the impact of industrial structure adjustment on carbon emission equity to provide additional supporting evidence.

The study of the impact of the carbon trading market on industrial structure adjustment is based on the synergistic effect of the demand-side pollution haven hypothesis and the supply-side Porter hypothesis [17]. The carbon quota trading mechanism incentivizes enterprises to increase investment in green technology R&D, while value chain restructuring prompts the reallocation of production factors to low-carbon provinces, accelerating the transformation and upgrading of the industrial structure [18]. Research by Zhang Youzhi et al [19]. also supports this conclusion.

The adjustment of the industrial structure by the carbon trading market forces high-carbon industries to implement green transformation, while low-carbon industries use this opportunity to expand their scale and obtain economic benefits, thus narrowing the difference in carbon emission intensity between provinces and breaking the market monopoly dominated by pollution. In addition, the regional emission reduction responsibility sharing mechanism can effectively curb carbon leakage and pollution transfer, reducing the transfer of environmental governance costs between provinces. Simultaneously, strategic adjustments to the industrial structure alleviate dependence on fossil fuels, optimize the intertemporal allocation of green capital, mitigate the discount bias problem in intergenerational environmental governance among provinces, and thus promote inter-provincial carbon emission equity.

Table 5 shows the results. Column (1) shows the test results with industrial structure adjustment as the explained variable and the carbon trading market as the explanatory variable. The impact of the carbon trading market on industrial structure adjustment is significantly positive at the 1% level, indicating that the carbon trading market significantly promotes industrial structure adjustment.

Column (2) regresses the impact of industrial structure on carbon emission equity. The estimated coefficient of industrial structure is significantly positive at the 1% level, providing additional correlational evidence supporting the positive impact of industrial structure adjustment on carbon emission equity. These results support the previous speculation, indicating that industrial structure adjustment is a potential channel through which the carbon trading market promotes inter-provincial carbon emission equity.

Table 5. Regression Results on the Impact of Industrial Structure Adjustment on Carbon Emission Equity

Variable	(1)	(2)
	Is	edu
Treated × Post	0.291***	
	(3.42)	
Is		0.049***
		(14.12)
_cons	-3.271***	-0.625***
	(-3.93)	(-9.52)
Controls	Yes	Yes
Obs	540	540
R-squared	0.40	0.70
F-statistic	58.25	204.2

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are t-statistics. No multicollinearity was detected based on Variance Inflation Factor (VIF).

3.2.3 Heterogeneity Analysis

(1) Regional Heterogeneity (North and South)

Due to unbalanced regional development in China, policy effects often vary. Based on geographical characteristics and referencing the study by Zhang S et al. [20], the sample is divided into northern and southern China, using the Qinling-Huaihe line as the boundary. Pilot provinces Beijing and Tianjin belong to the north, while Shanghai, Guangdong, Hubei, Chongqing, and Fujian belong to the south. This section explores the impact of carbon trading markets on carbon emission equity in both regions (Table 6 – *missing from the prompt*). The key explanatory variable is significant at the 1% level in the south (column 1) but not significant in the north (column 2). A Fisher test, significant at the 1% level, confirms a significant difference in the marginal effects of carbon trading markets on carbon emission equity between the north and south. Specifically, the effect is significantly more pronounced in the south.

(2) Income Distribution Heterogeneity

Given that income inequality can lead to heterogeneous policy effects, this study focuses on the differentiated impact of income distribution on carbon emission equity. Provincial-level average carbon emission Gini coefficients for 2020-2022, calculated using Tian Weimin's method [20], are used to measure income distribution. The sample is divided based on the international warning line of 0.4, with values below 0.4 representing income equality. As shown in Table 6 (*missing from the prompt*), the coefficient is negatively significant at the 10% level for high Gini coefficients (column 3) and positively significant at the 1% level for low Gini coefficients (column 4). Since both income distribution groups are significant, a Fisher test was conducted to enhance robustness. The Fisher test p-value is significant at the 1% level, indicating heterogeneity between the two groups. Income equality significantly promotes carbon emission equity, while income inequality significantly suppresses it.

Table 6. Heterogeneity Analysis

Variable	North and South		Income Distribution	
	(1)	(2)	(1)	(2)
	South	North	A high Gini coefficient	A low Gini coefficient
Treated× *Post*	0.070***	0.005	-0.016*	0.044***
	(6.33)	(1. 19)	(-1.75)	(5.74)
_cons	-1.687***	0.291	-2.788***	-1.588***
	(-5.65)	(1.56)	(-7.60)	(-6.74)
Control	YES	YES	YES	YES
Obs	288	252	144	396
R-squared	0.94	0.96	0.93	0.92
F	77.85	11.02	26.51	61.93
P-value of system difference		0.000		0.000

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively Values in parentheses are t-statistics

3.2.4 Spatial Spillover Effects Analysis

(1) Spatial Autocorrelation

To test for spatial autocorrelation in provincial carbon emissions, this paper uses an inverse distance matrix to calculate Moran's I. The results show that the Moran's I for carbon emissions from 2006 to 2021 ranges from 0.066 to 0.141, with some exhibiting strong positive significance (see Table 7). This indicates significant spatial clustering of provincial carbon emissions, justifying the use of spatial econometrics.

Table 7. Moran's I Values for Carbon Emission Equity (equ) (2006-2021)

Year	Moran'sasds I (equ)	Year	Moran's I (equ)
2006	0.121**	2014	0.133**
2007	0.141**	2015	0.131**
2008	0.112**	2016	0.116**
2009	0.096*	2017	0.109**
2010	0.092*	2018	0.091*
2011	0.089*	2019	0.079*
2012	0.104**	2020	0.070
2013	0.136**	2021	0.066

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively

(2) Spatial Econometric Model Selection and Results

Spatial error (SEM-DID) and spatial lag (SAR-DID) models were tested using Wald and LR tests (Table 8 – *missing from the prompt*). Both tests indicate that the spatial Durbin DID model (SDM-DID) should be chosen.

Table 8. Spatial Econometric Model Selection

Model	Wald Test	LR Test
SEM-DID	68.73***	64.65***
SAR-DID	37.99***	71.2***

Note: *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 9 presents the spatial effects regression results. The spatial Durbin model regression results show that the coefficient of Treated × Post is significant at the 1% level regardless of whether the spatial weight matrix is included (see Table 9). This indicates a positive spatial spillover effect of

Treated × Post on equ, suggesting that the implementation of carbon emission pilot policies in other provinces promotes carbon emission equity in the focal province.

Under the inverse distance matrix, the spatial autoregressive coefficient (ρ) is significantly negative, indicating a negative spatial interaction effect of the carbon trading market policy on surrounding regions, which can be interpreted as a siphon effect. The implementation of policies in pilot provinces has a reverse radiation effect on neighboring regions and regions with close economic ties through spatial dependence mechanisms**.** The spatial autoregressive coefficient is significant at the 1% level, indicating a significant siphon effect on carbon emission equity among provinces.

Table 9. Spatial Effects Regression Results

Variable	(1) Without Spatial Weight Matrix	(2) With Spatial Weight Matrix
Treated × Post	0.0354*** (6.5336)	0.1017*** (6.0987)
ρ	-0.2301*** (-2.7138)	-0.2301*** (-2.7138)
Controls	Yes	Yes
Individual FE	Yes	Yes
Time FE	Yes	Yes
Obs	540	540
R-squared	0.057	0.057

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are t-statistics

(3) Further Analysis

Directly using the spatial regression coefficient cannot accurately measure the spatial spillover effect. Therefore, it is decomposed into direct, indirect, and total effects [22]. From the direct effect perspective, Treated × Post is significantly positive at the 1% significance level, indicating that the carbon market promotes carbon emission fairness. From the indirect effect perspective, the regression coefficient of Treated × Post on carbon emission fairness is significantly positive at the 1% significance level, suggesting that the carbon trading market not only promotes carbon emission fairness in the region itself but also in neighboring regions (see Table 10).

From the total effect perspective, the regression coefficient of Treated × Post on carbon emission fairness is positive and significant at the 1% significance level, indicating that whether a carbon trading market pilot policy is implemented in a province significantly impacts carbon emission fairness in both the province itself and neighboring provinces. That is, policy implementation can promote carbon emission fairness and has a significant positive spatial spillover effect. Overall, the direct, indirect, and total effects of Treated × Post are all significantly positive at the 1% significance level. The regression coefficient of the indirect effect is larger than that of the direct effect, indicating that the impact of implementing a provincial carbon trading pilot policy on the carbon emission fairness of neighboring provinces is greater than its impact on the province itself. Hypothesis 3 is thus supported.

Tabel 10. The result of spatial effect decomposition

Variable	(1) Direct Effect	(2) Indirect Effect	(3) Total Effect
Treated × Post	0.0324*** (5.8064)	0.0440*** (4.2345)	0.0764*** (6.1763)
Controls	Yes	Yes	Yes
Individual FE	Yes	Yes	Yes
Time FE	Yes	Yes	Yes
Obs	540	540	540
R-squared	0.384	0.384	0.384

Note: *cons* represents the constant term. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively Values in parentheses are t-statistics

4. Statistical Analysis

4.1. Parallel Trend Test

This paper conducts a parallel trend test following Figure 2. Considering the data volume and time span, the data are truncated, merging data before period 4 and after period 7. To avoid collinearity issues, referring to the parallel trend test research of Liu Zhihua and Xu Junwei, the first period before the pilot program is used as the baseline year, i.e., the dummy variable for this year is removed from the model [23]. As shown in Figure 3, the regression coefficients are insignificant in each observation period before the implementation of the carbon trading market pilot policy, indicating that there is no significant difference in the development of pilot and non-pilot regions before the policy implementation, satisfying the parallel trend test requirements. After the policy implementation, the coefficient estimates for each period are significantly positive and show an increasing trend, indicating that the impact of the carbon trading market pilot policy on inter-provincial carbon emission fairness has a clear time-varying trend.

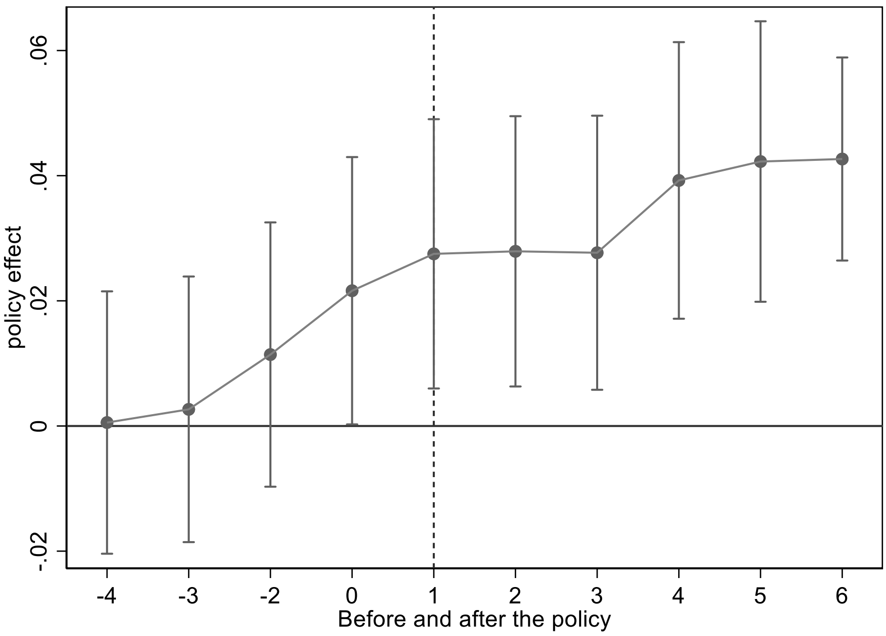

Figure 2. Parallel trend test

4.2. Placebo Test

To ensure the robustness of the baseline regression results and avoid bias caused by potential interference from omitted variables and random factors, a placebo test was conducted, as shown in Figure 3. Following the proportion of treatment and control groups in the original sample, this paper randomly selected treatment provinces and randomly constructed policy time points to generate a dummy variable, PseudoTreat×Post, which replaced the original variable for 500 baseline regressions [24-25]**[25]**. In Figure 3, the vertical dashed line represents the real coefficient estimated by the baseline regression, and the horizontal dashed line represents P=0.1. If the scatter points are below this horizontal dashed line, it indicates that the coefficient is significant at least at the 10% level; otherwise, it is not significant. The kernel density of the 500 regression coefficients and the distribution of the corresponding P-values are shown in the figure. It can be seen that the virtual regression coefficients basically show a normal distribution centered on 0 and are clearly different from the baseline regression coefficients. On the other hand, the vast majority of P-values are greater than 0.1, indicating that the carbon trading market, when affecting carbon emission fairness, is not affected by other unobservable interference factors.

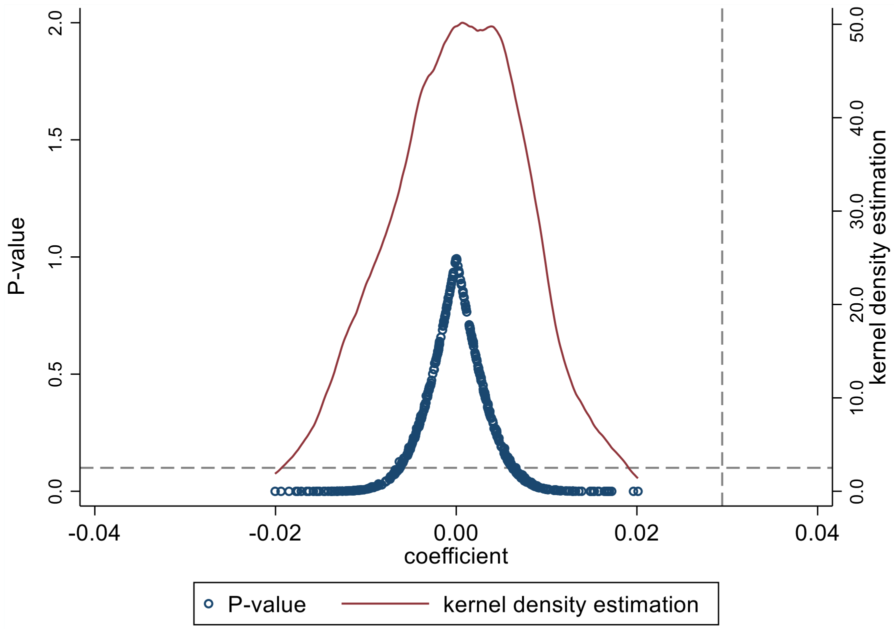

Figure 3. Placebo Test

5. Disscussion

This paper investigates the impact of the carbon trading market on inter-provincial carbon emission fairness from the perspective of a quasi-natural experiment of carbon emission trading pilot programs, employing a multi-period difference-in-differences method. The research results show that: (1) The implementation of the carbon trading market pilot policy has a significant impact on inter-provincial carbon emission fairness, and this impact remains robust after multiple robustness checks. (2) Analysis of the impact mechanism reveals that the carbon trading pilot policy significantly enhances inter-provincial carbon emission fairness through the channel of industrial structure adjustment. (3) Heterogeneity analysis reveals that carbon emission fairness is more prominent in the south compared to the north, and in regions with income equality compared to regions with income inequality. (4) The carbon trading pilot policy exhibits a positive spatial spillover effect on inter-provincial carbon emission fairness, with a significant positive promoting effect on neighboring provinces. (5) There is a negative "siphoning effect" among provinces regarding the carbon trading pilot policy.

Based on the above conclusions, the following policy recommendations are proposed:

(1) Strengthen the effectiveness of the carbon trading market in promoting inter-provincial carbon emission fairness. Further improve the top-level design of the carbon trading market, using price mechanisms to force high-pollution enterprises to undergo green transformation and encourage the development of clean industries. Improve the total carbon emission control and quota allocation, and establish a unified carbon emission quota allocation mechanism. Increase the transparency and standardization of the carbon trading market, improve the verifiability of emission reduction effects, and thus have a long-term positive impact on inter-provincial carbon emission fairness.

(2) Optimize the industrial structure adjustment mechanism and promote low-carbon transformation. For high-carbon emission industries such as steel, cement, and chemicals, formulate differentiated carbon quota allocation schemes and, through adjusting carbon prices, force high-pollution enterprises to reduce carbon emission intensity through technological transformation and energy substitution. Support the development of emerging industries and increase support for low-carbon industries such as clean energy and energy conservation and environmental protection. Use carbon market revenue to support green technological innovation, forming a virtuous cycle of "emission reduction-revenue-reinvestment."

(3) Establish an inter-regional carbon revenue redistribution mechanism, allocating carbon market revenue proportionally to subsidize low-income groups, green skills training, and support low-carbon

industries in underdeveloped provinces. Simultaneously, improve the initial allocation rules for carbon emission rights, appropriately tilting quotas towards small and medium-sized enterprises and low-income provinces to alleviate the "Matthew effect" under the market mechanism and promote the synergistic increase of economic growth and equitable distribution. Northern provinces should strengthen the construction of supporting market mechanisms: first, optimize the quota allocation standards for high-energy-consuming industries in the north and introduce dynamic adjustment mechanisms to enhance enterprise emission reduction motivation; second, increase financial support for industries in the north, promote low-carbon technological transformation of traditional industries in the north, and cultivate renewable energy industrial clusters.

(4) Give full play to the spatial spillover effect of the carbon trading market on inter-provincial carbon emission fairness. Encourage geographically close or economically interconnected provinces to establish regional carbon market alliances to magnify the spatial spillover effect; promote cross-regional carbon compensation mechanisms and establish a linkage mechanism of "carbon emission trading + ecological compensation," encouraging developed provinces with high carbon emissions to support ecological protection and green transformation in underdeveloped regions by purchasing low-carbon carbon sinks.

(5) Strengthen institutional construction and mechanism adjustments to weaken the "siphoning effect." Formulate carbon trading systems suitable for local conditions based on the specific circumstances of different provinces and enterprises, strengthen regional and industry coordination, and design differentiated quota allocation schemes. By optimizing quota allocation, strengthening regional coordination, and enriching market participants, it is possible to improve emission reduction efficiency while ensuring fairness. In the future, it is necessary to further balance the pilot experience with the institutional connection of the national unified market to avoid exacerbating unfair distribution of carbon emission responsibilities due to regional or industry differences.

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