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Analyses of Topical Policy Issues

Assessment of the co-benefits of China's carbon trading policy on carbon emissions reduction and air pollution control in multiple sectors

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ABSTRACT

Achieving synergies in reducing carbon emissions and air pollution is the key to promoting green development in China's economy and society. However, the effectiveness and synergy of carbon reduction policies, such as the carbon trading policy in each sector, have not been assessed. This study uses the time-varying difference-in-difference model (DID) to assess the co-benefits and mechanisms of carbon trading pilot policy on the emissions of carbon and air pollutants across the country and in the power, industry, transport, and resident sectors. The results show that the policy is useful in controlling air pollution in pilot areas, and the effect is better than that of reducing carbon emissions. The carbon trading policy can also help various sectors achieve the co-benefits of reducing carbon emissions and controlling air pollution. Furthermore, the mediating role of industrial structure, technological progress, and foreign direct investment in the implementation of carbon trading policy varies across sectors. The results can provide guidance for each sector to achieve collaborative governance in reducing carbon emissions and air pollution.

1. Introduction

Since the 20th century, ecological and environmental problems have garnered widespread attention from governments and scholars all over the world. These issues not only affect the quality of people's lives but also have implications for the sustainable development of the global economy and human society (Calculli et al., 2021; Yu et al., 2022). Among these environmental issues, reducing carbon emissions and controlling air pollution have become the top priorities (Wang et al., 2022; Ismail et al., 2023; Liu et al., 2023). As one of the largest carbon emitters by far, China has the obligation to strive to achieve its carbon reduction targets (Song et al., 2020). The carbon trading policy, which utilizes market mechanisms to control greenhouse gases, is an important component of the environmental protection policy system (Yan et al., 2020). In 2013, China announced the launch of carbon trading pilot markets in Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong and Shenzhen. The National Carbon Emission Trading Market was officially launched for trading in 2021. Considering that air pollutants and greenhouse gases have the same origin and source (Rafaj et al., 2013), reducing carbon emissions and controlling air pollution are highly consistent in terms of control strategies and management measures (Chen et al., 2023). Therefore, there is an urgent need to answer the question of whether the carbon trading policy helps to reduce air

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pollutant emissions while also lowering carbon emissions. Additionally, since China's various sectors have different characteristics in terms of resource endowments, the carbon trading policy will exhibit significant variations across different sectors. Thus, assessing the co-benefits of China's carbon trading policy on carbon emissions reduction and air pollution control across multiple sectors provides a roadmap for establishing a national carbon trading market, promoting coordinated emission reduction of carbon and air pollution.

Existing studies mainly use the difference-in-difference (DID) model to assess the economic and environmental benefits of carbon trading policy. Jung and Song (2023) discovered that countries with established Emission Trading Schemes (ETS) are reducing their carbon emissions at a faster rate than those without such schemes. As the world's oldest carbon market, the EU Emissions Trading System not only incentivizes emission reductions but also boosts the trading profits of companies in the ETS (Guo et al., 2020). Liu et al. (2023) examined the effects of the pilot opening of the carbon trading market on carbon reduction strength through constructing a DID model. The results found that the carbon intensity of the power industry has significantly decreased. By incorporating the latest patenting data into the DID model, Zhu et al. (2019) found that carbon trading markets could increase the level of low-carbon innovation among ETS companies by 5–10 %, leading to reductions in carbon emissions. Additionally, the carbon trading policy can promote green technology progress (Pu and Ouyang, 2023), raise employment levels (Cong et al., 2023), attract financial investment in low-carbon energy (Mo et al., 2016). However, some scholars hold the opposite view, arguing that not all the effects of the carbon trading policy are positive. Excessive government intervention could cause carbon markets to fail, which would be detrimental to reducing carbon emissions (Li et al., 2022). This policy can even hinder the quality improvement of enterprises' export products and lead to short-term pollution transfer under the "pollution haven effect" (Zhang et al., 2023; Liu et al., 2023). In addition, several scholars have examined the pathways of this policy. Research shows that energy structure (Rojas Sánchez et al., 2019), the added value of the secondary industry (Zhang et al., 2020), technical research level (Matthias and Baumgartner, 2018; Dai et al., 2022), and companies' fixed assets investment (Wang et al., 2023) play a mediating role in it. Since the production of air pollutants such as SO_2 and $PM_{2.5}$ is highly similar to carbon emissions, there is a possibility of coordinated management (Wang et al., 2023). Scholars have also researched the collaborative reduction of greenhouse gases and air pollutants. Bain et al. (2016) study shows that while carbon emissions are reduced, the emissions of SO_2, NOx and $PM_{2.5}$ can also be reduced, confirming that improvements in air quality and the greenhouse effect can be pursued simultaneously. Coal consumption, total import and export trade, urbanization, and environmental protection investment can influence the synergistic reduction of carbon dioxide and air pollutants (Yi et al., 2022; Tang et al., 2022; Xue et al., 2023). However, some other scholars argue that the aforementioned factors are merely intermediaries in the action path of relevant environmental economic policies. The formulation and implementation of policies are the fundamental reasons for changes in the degree of synergy between pollution reduction and carbon reduction. For example, the clean energy policy (Tibrewal and Venkataraman, 2021), carbon pricing policy (Li et al., 2018), pollution control policy (Yang et al., 2022).

Although current research has discussed the effects of carbon trading policies from different perspectives, such as reducing carbon emission intensity (Liu et al., 2023), improving carbon productivity (Jung et al., 2021) and employment levels (Cong et al., 2023), and promoting a low-carbon economy (Gao, 2023), they rarely consider the co-benefits of carbon trading policies in reducing air pollutants. Additionally, the role path of carbon trading policy in various sectors is still unclear, which cannot provide targeted policy guidance for collaborative emission reduction management. Therefore, the innovation of this study mainly includes the following aspects. Firstly, we evaluate the effectiveness and synergy of the carbon trading policy on the emissions of carbon and air pollutants through a time-varying DID model, and discuss the potential co-benefits of such policy on carbon emissions reduction and air pollution control. Secondly, with the establishment of the national carbon trading market and the promotion of collaborative governance for pollution and carbon reduction, it is crucial to consider the diverse resource endowment characteristics of various sectors. We investigate the effects and action paths of the carbon trading policy in various sectors using sector-level data, and analyze the intermediate effects of industrial structure, technological progress, and foreign direct investment on policy implementation. In theory, this study can fill the research gap by exploring the mediating mechanisms and pathways of carbon trading policy across multiple sectors. Moreover, in practice, the research results can provide specific strategies for the optimization of coordinated emission reduction policies and the connection with the national carbon trading market in each sector.

The rest of the paper is arranged as follows. Section 2 introduces the implementation background and action mechanism of carbon trading policy. Section 3 describes the methods and data used in the study in detail. Section 4 presents the results and discussions of emission reduction benefits and action paths of carbon trading policy in the country and each sector. Section 5 shows the conclusions and policy implications.

2. Theoretical hypotheses

Theoretically speaking, carbon emissions and air pollutants can achieve coordinated emission reduction to a certain extent through the implementation of carbon trading policy. "Carbon trading" involves treating carbon emission allowances as a commodity. The government assesses the maximum amount of carbon emissions within a specific area to align with the environmental capacity and then divides them into emission quotas, each representing an emission right. Then, the government will issue emission rights to the enterprises participating in the cap-and-trade, and the enterprises can emit carbon within the allocated allowances. If enterprises produce carbon emissions in excess of their quotas of carbon emission rights, they need to buy more carbon emission rights in the market. If the actual emissions of the enterprises are less than the allowance, they can earn profits by selling the quota (Shakil et al., 2019). Therefore, the carbon trading policy, as a cap-and-trade mechanism, can encourage enterprises to voluntarily reduce carbon emissions through economic leverage and clear signals (Ansari et al., 2020). Additionally, both CO_2 and air pollutants primarily result from the burning of fossil fuels in human activities and production. This common origin and process make it feasible to achieve synergistic reductions in carbon emissions and air pollutants emissions. When enterprises strive to effectively reduce carbon emissions, they will inevitably control the emission of air pollutants (Yi et al., 2022). Based on this, we propose the following hypothesis:

Hypothesis 1. The implementation of the carbon trading policy can reduce carbon emissions and control air pollution.

Currently, only enterprises in the power sector are included in the national carbon trading market and are under centralized management. Each pilot carbon trading market shares commonalities in sector coverage, but also possesses unique characteristics due to varying economic and energy consumption structures. All of the pilot markets included sectors with higher carbon emissions and greater potential to reduce emissions, such as power production and manufacturing. In particular, in provinces and cities with a large proportion of secondary industry, such as Guangdong, Hubei, Tianjin and Chongqing, the enterprises participating in their carbon trading markets are predominantly industrial enterprises. However, in provinces and cities where the tertiary industry dominates, such as Shenzhen, Beijing and Shanghai, there are fewer and limited industrial enterprises. As a result, the threshold for industrial control and emissions is set low, and public transportation and service sectors, such as commerce, hotels, and finance are included in the market. Each pilot market is situated in a region with varying emission reduction priorities, resulting in diverse emission quotas for each sector (Tang et al., 2020). Based on the theoretical analysis, the following hypothesis is proposed:

Hypothesis 2. The effect of the carbon trading policy on emissions reduction varies across sectors.

In the process of allocating carbon emissions, the carbon trading policy can play a decisive role in the market and continually optimize the distribution of production factors among industries. When the surplus income from carbon emission quotas exceeds the cost of low-carbon technology research and development, capital, labor, technology and other production factors will inevitably shift from high-polluting enterprises to low-energy and high-efficiency production sectors. This shift will promote the development of numerous environmentally friendly enterprises with advanced technical capabilities and significant growth potential. After optimizing and upgrading the industrial structure, it can facilitate the flow of production factors from traditional backward industries to emerging and efficient industries (Xiao et al., 2023). By reallocating these resources, energy efficiency can be effectively improved, leading to a reduction in carbon emissions and air pollution.

Carbon trading policy, as a form of market-based incentive regulation, can internalize the costs of carbon emissions into the production costs of enterprises, forcing enterprises to engage in more innovative activities to offset the expenses associated with environmental protection (Wei et al., 2022). Specifically, under the pressure of carbon emission restrictions, enterprises that have insufficient carbon emission quotas must increase their spending to purchase additional quotas from enterprises with excess quotas. Consequently, both enterprises with inadequate quotas and those with excess quotas are motivated to pursue technological progress by increasing their research and development (R&D) investment in order to maximize profits and promote green transformation (Matthias and Baumgartner, 2018).

Environmental policies may also impact international capital flows. According to the "pollution paradise hypothesis", certain highly polluting and energy-intensive enterprises tend to invest more in regions with fewer environmental regulations to evade environmental constraints, thereby impacting local greenhouse gas emissions and air quality (Cole, 2004). Similarly, the carbon trading policy may influence the decisions of foreign investors, who are more inclined to select non-pilot areas without emission rights restrictions, indirectly impacting the emissions from enterprises (Demena and Afesorgbor, 2020).

Thus, this study develops the following theoretical hypotheses to test the mediating effects on such policy:

Hypothesis 3a. Carbon trading policy is mediated by the industrial structure, which further affects carbon emissions and air pollution.

Hypothesis 3b. Carbon trading policy is mediated by the level of technological progress, which further affects carbon emissions and air pollution.

Hypothesis 3c. Carbon trading policy is mediated by the foreign direct investment, which further affects carbon emissions and air pollution.

3. Methods and data

3.1. Time-varying did model

Most studies assessing the effect of policy implementation have adopted the DID model (Jia et al., 2021; Zhang et al., 2019). The fundamental concept of the traditional DID method is to compare the difference between the average target value before and after the policy implementation, with the policy implementation occurring during the same period for each area.

However, the inconsistent opening date of the carbon market can lead to endogenous problems when using the traditional DID model to assess the effect, due to inaccurate year dummy variable values. In time-varying DID analysis, policy implementation nodes in each region are determined based on different policy implementation times, addressing the endogenous issues that may arise from year dummy variables (Yang et al., 2023). Therefore, this study utilizes the time-varying DID model to assess the co-benefits of carbon trading policy on carbon emissions reduction and air pollution control. The baseline model is described in detail as follows:

$$\mathrm{Y}_{it} = \alpha_0 + \alpha_1 Treated_i * Time_t + \sum \alpha_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \tag{1}$$

Table 1
Coefficient table of air pollution equivalent.

Air pollutant	Equivalent coefficient	Equivalent coefficient value
SO_2	λ_1	1/0.95
NOx	λ_2	1/0.95
CO	λ_3	1/16.7
$PM_{2.5}$	λ_4	1/2.18
NH_3	λ_5	1/9.09

Notes: the equivalent coefficient values of all air pollutants are from the Implementation Regulations of the Environmental Protection Tax Law (2017).

where *i* refers to area, and *t* refers to time. Y_{it} is the emissions-related variables (carbon emissions and air pollutants emissions) of area *i* in year *t*. $Treated_i * Time_t$ is a dummy variable, indicating whether area *i* has implemented the policy in year *t*. X_{jit} refers to control variables that may affect the explained variables. $\mu_i$is the fixed region effect, $\delta_t$is the fixed year effect, and $\varepsilon_{it}$is the random disturbance term.

3.2. Mediating effect model

Theoretical analysis shows that the carbon trading policy may impact the emissions of carbon and air pollutants in pilot areas by promoting industrial structure optimization and upgrading, promoting technological progress, and influencing foreign investment. Therefore, the mediating effect model proposed by Baron and Kenny (1986) is utilized to identify the mechanism through which carbon trading policy affects emissions. Based on model (1), the mediating model is constructed as follows:

$$M_{it} = \beta_0 + \beta_1 Treated_i * Time_t + \sum \beta_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \tag{2}$$

$$Y_{it} = \gamma_0 + \gamma_1 Treated_i * Time_t + \gamma_2 M_{it} + \sum \gamma_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \tag{3}$$

where M_{it} refers to possible mediating variables. The other variables have the same meaning as in model (1). The testing steps of the mediating effect model are: firstly, model (1) is regressed to test the significance level of the coefficient α_1,when $\alpha_1$is significantly negative, showing that carbon trading policy has an obvious impact on emission reduction. Secondly, model (2) is regressed to test whether the core explanatory variable affects the mediating variable. Finally, model (3) is regressed, the direct and indirect effects of the core explanatory variable and mediating variable on the explained variable are represented by γ_1 and γ_2, respectively. When $\beta_1\gamma_2 \neq 0$ and both are significant, indicating that there is a possible mediating effect of the policy on emissions. When γ_1 is significant, it refers to there being a partial mediating effect, otherwise, there is a complete mediating effect.

3.3. Variable selection and data description

3.3.1. Explained variables

Carbon emission (CE) and air pollutants emission (PE). The emissions of CO_2 and air pollutants from China's 30 provinces from 2006 to 2020 were estimated using the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC) (Li et al., 2017; Zheng et al., 2018). In this study, we select five typical air pollutants: SO_2, NO_x, CO, $PM_{2.5}$, and NH_3. The emissions of CO_2 and major air pollutants from fossil fuel combustion and cement production processes can be estimated separately for provinces as follows:

$$E = \sum_{i}^{n} A_i \times EF_i \tag{4}$$

where *i* refers to emission sources. *E* refers to CO_2 or five air pollutants emissions. *A* denotes fuel consumption and industrial production. *EF* denotes CO_2 and air pollutants emission factors obtained from Liu et al. (2015). To facilitate a comprehensive comparison of the co-effects of the policy on carbon emission reduction and air pollution control in various regions, this study uses the equivalent coefficient of air pollutants to standardize the emissions of each air pollutant (Liu et al., 2023). The calculation method is as follows:

$$PE = \lambda_1 E_{SO_2} + \lambda_2 E_{NOx} + \lambda_3 E_{CO} + \lambda_4 E_{PM_{2.5}} + \lambda_5 E_{NH_3} \tag{5}$$

where λ refers to air pollution equivalent, the specific coefficients are shown in Table 1.

3.3.2. Core explanatory variable

$Treated_i * Time_t$, as the interaction term of the dummy variable, is the core explanatory variable in this study. Where $Treated_i$ is the regional virtual variable, and the value of the region where the pilot market is located is 1, otherwise 0; $Time_t$ is the year dummy variable, where $Time_t$=0 represents the non-pilot period before the implementation of the policy, and $Time_t$=1 represents the pilot period after the official implementation of the policy. Beijing, Tianjin, Shanghai, Chongqing, Hubei, Guangdong, Shenzhen and Fujian

Table 2
The results of baseline regression.

	CE		PE	
Variables	(1)	(2)	(3)	(4)
Treat ∗*Time*	−0.1560***	−0.1572***	−0.2183***	−0.1644***
	(0.0231)	(0.0235)	(0.0210)	(0.0228)
ES		−0.1128**		−0.0541
		(0.0371)		(0.0360)
EI		0.1867***		0.1178***
		(0.0259)		(0.0251)
PGDP		0.2961***		0.0634
		(0.0438)		(0.0425)
POP		0.5379***		−0.2612**
		(0.1155)		(0.1121)
T		0.0003		0.0005
		(0.0005)		(0.0005)
R		0.0247		−0.0027
		(0.0255)		(0.0247)
-cons	9.9028***	2.9565**	5.2351***	6.9698***
	(0.0190)	(1.1092)	(0.0173)	(1.0770)
Province FE	yes	yes	yes	yes
Year FE	yes	yes	yes	yes
Obs.	480	480	480	480
R-squared	0.6797	0.7519	0.8702	0.8852
F-statistic	709.47***	40.96***	956.15***	82.57***

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; robust standard errors in parentheses.

successively launched pilot carbon trading markets from 2013 to 2016. Considering that the study will utilize provincial data, the information from Shenzhen will be included as part of Guangdong Province. Due to the inconsistency in the formal establishment and trading hours of the trading market in the seven pilots, for Beijing, Tianjin, Shanghai and Guangdong, $Time_t$ is 1 in 2013 and subsequent years, 1; for Chongqing and Hubei, $Time_t$ is 1 in 2014 and subsequent years; for Fujian, $Time_t$ is 1 in 2016 and subsequent years; the remaining years have a $Time_t$ value of 0.

3.3.3. Mediating variables

Industrial structure (IS). Existing studies often use the proportion of the secondary or tertiary industry in the gross domestic product (GDP) to represent the industrial structure (Zhu et al., 2019; Dai et al., 2023). Considering that enterprises are the main participants in the carbon trading market, we refer to the study by Zhang et al. (2022) and select the proportion of heavily polluting enterprises among all enterprises as the indicator of industrial structure. This indicator can more accurately describe the industrial structure and demonstrate the correlation between industrial structure and the effectiveness of emission reduction.

Technological progress (TP). Since the level of technological progress cannot be measured directly, we choose research and development (R&D) funding as a proxy variable for technological progress (Matthias and Baumgartner, 2018). The more funding is invested in R&D, the greater the opportunities for achieving technological innovation and promoting technological progress.

Foreign direct investment (FDI). According to the study by Dong et al. (2022), FDI data is utilized to identify whether environmental policies may indirectly affect carbon emissions and air pollution generated by firms through influencing international capital flows.

3.3.4. Control variables

According to Kaya identity, CO_2 emissions can be decomposed as follows (Yang et al., 2020):

$$CO_2 = \frac{CO_2}{Energy} \times \frac{Energy}{GDP} \times \frac{GDP}{Population} \times Population \tag{6}$$

Therefore, CO_2 emissions are affected by four variables: energy consumption structure, energy consumption per unit of GDP (i.e., energy intensity), per capita GDP and population. In addition, CO_2 is also influenced by environmental factors such as temperature (Gurriaran et al., 2023) and rainfall (Wang et al., 2015). Due to air pollutants and CO_2 being homologous, the emissions of air pollutants are also affected by the factors mentioned above. Therefore, we identify the following control variables: energy consumption structure (ES), energy intensity (EI), per capita GDP (PGDP), population (POP), temperature (T) and rainfall (R).

3.4. Data sources

Given the lag in policy implementation and data availability, this study primarily utilizes panel data from 30 provinces in China, spanning the period from 2006 to 2020. The emissions of CO_2 and five air pollutants from each province are obtained from MEIC, and any missing data is calculated using fuel consumption information from the China Energy Statistical Yearbook. Other data is provided by the China Statistical Yearbook, China Environmental Statistical Yearbook and China Climate Bulletin. The missing data in various

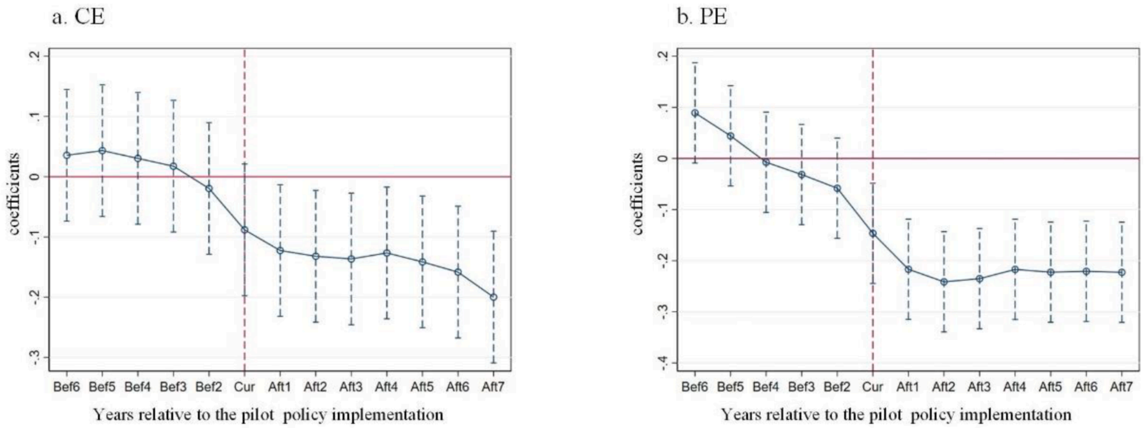

Fig. 1. The results of parallel trend test.

yearbooks is filled using the linear interpolation method.

4. Empirical results and discussion

4.1. Analysis of baseline results

According to model (1), the results of the co-benefits of China's carbon trading policy on carbon emissions and air pollutants are shown in Table 2. As shown in columns (1) and (2), with or without adding control variables, *Treat* ∗ *Time* are significantly negative, with almost identical values. The results clearly demonstrate that the carbon trading policy can curb the excessive carbon emissions from enterprises in pilot regions, in comparison to regions without policy regulations. Similarly, the interaction terms *Treat* ∗*Time* in columns (3) and (4) are significantly negative, and their absolute value exceeds that of the interaction terms of CE. This shows that the carbon trading policy can effectively control air pollution, with a greater impact than simply reducing carbon emissions. The possible reason is that the Chinese government has long paid attention to air pollution. Since the 11th Five-Year Plan listed the reduction of total pollutants as a mandatory target, a range of pollution prevention and treatment measures have been issued and deployed. These measures include the Air Pollution Prevention and Control Action Plan, which is coordinated with carbon trading policy to control air pollution. In summary, based on the baseline regression results, we cannot reject Hypothesis 1., in other words, the carbon trading policy can raise the co-benefits of carbon emissions reduction and air pollution control.

4.2. Robustness test

To ensure the robustness of the baseline regression results, we carry out a series of robustness tests.

4.2.1. Parallel trend test

Parallel trends refer to the requirement that the treatment group and the control group must exhibit comparable characteristics before the policy implementation, such as following the same development trend. This is a prerequisite for using the time-varying DID model. Therefore, the event analysis method is used to test whether there are parallel trends in the impact of the carbon trading policy on emissions. In reference to Beck et al. (2010), we conducted the test model as shown below:

$$\begin{aligned} CE(orPE) \quad = \quad & \eta_0 + \eta_1 (Treat_i * Time_t)^{-6} + \eta_2 (Treat_i * Time_t)^{-5} + \cdots \\ & + \eta_{13} (Treat_i * Time_t)^{7} + \sum \eta_j X_{jit} + \mu_i + \delta_t + \varepsilon_{it} \end{aligned} \tag{7}$$

where $(Treated_i{*}Time_t)^k$ refers to the k year of the pilot policy implementation. We took the first year before the policy implementation as the baseline group and selected the six years preceding the policy pilot, the pilot year, and the following seven years for estimation. The test results are shown in Fig. 1.

In Fig. 1a, before the pilot regions are impacted by the carbon trading policy, the non-statistically significant coefficients indicate that there are no marked differences in carbon emission trajectories between the treatment group and the control group, satisfying the parallel trend hypothesis. Due to the time lag of the policy, η becomes significantly negative one year after the pilot, showing that the policy is effective in curbing the increase of carbon emissions. Similarly, the results of the PE trajectory also pass the parallel trend test. The difference is that the coefficient η of PE is significantly negative in the current period of policy implementation, which is consistent with the analysis above.

Table 3
The results of PSM-DID test.

	CE			PE		
Variables	Nearest neighbor matching	Radius matching	Kernel matching	Nearest neighbor matching	Radius matching	Kernel matching
Treat ∗Time	−0.1280***	−0.1248***	−0.1252***	−0.1553***	−0.1527***	−0.1588***
	(0.0201)	(0.0228)	(0.0237)	(0.0297)	(0.0295)	(0.0231)
-cons.	2.9371*	3.1643*	2.5099*	6.9346***	6.5182***	7.2359***
	(1.0819)	(1.5046)	(1.0790)	(1.3776)	(1.4189)	(1.0519)
Control variables	yes	yes	yes	yes	yes	yes
Province FE	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes
Obs.	370	383	432	370	383	432
R-squared	0.6367	0.6784	0.7846	0.9448	0.9401	0.8865
F-statistic	32.78***	32.25***	35.52***	69.58***	70.61***	77.96***

Notes: The nearest neighbor matching is 1:3 matching with $K = 3$. The radius matching is performed with the radius of 0.01. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; robust standard errors in parentheses.

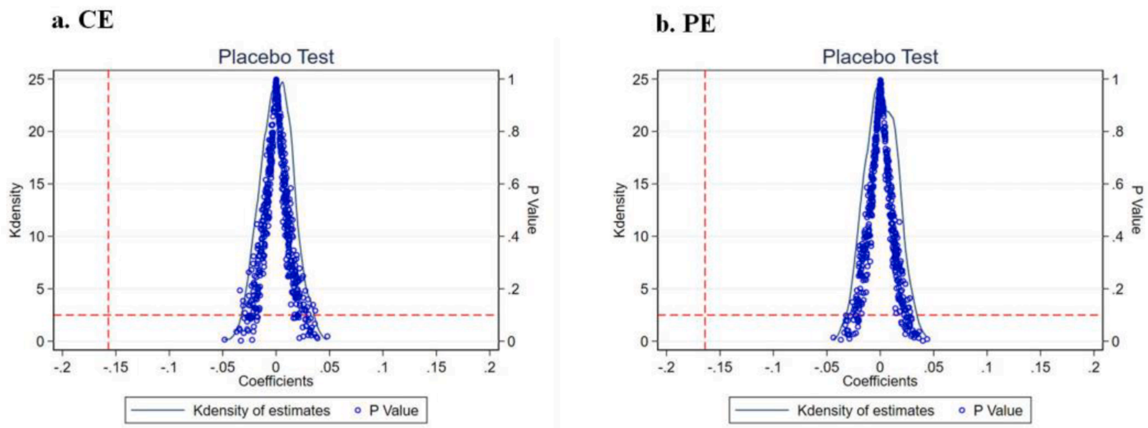

Fig. 2. Interaction term coefficient distribution of placebo test.

4.2.2. PSM-DID test

The carbon trading policy may have a self-selection effect on the pilot sample, resulting in the non-randomness of the policy implementation. To mitigate "selectivity bias" between the treatment group and the control group, a robustness test was conducted using the PSM-DID method. During the sample period, the pilot region was designated as the treatment group. Control variables were then used to represent the covariates for re-matching the treatment group using nearest neighbor matching, radius matching, and kernel matching, respectively. The balance test results after matching showed that the standard deviation of most covariates was below 5 %. We removed the samples from the control group that could not be successfully matched and then estimated the CE and PE respectively according to model (1). The regression results for the new samples after matching show that the estimated coefficients of *Treat ∗ Time* change very little and remain significantly negative at the 1 % level (Table 3). This is largely consistent with the baseline regression's conclusion, demonstrating the robustness of the results.

4.2.3. Placebo test

To further investigate whether the impact of carbon trading policy on carbon emissions and air pollution in pilot regions is influenced by random factors or other policies, this study randomly selects a dummy treatment group and a control group to conduct a placebo test. The specific method involves randomly selecting 7 provinces from 30 provinces to form a new treatment group and generating dummy policy years at random. On this basis, the new sample group is used for regression Eq. (1). The above steps are repeated 500 times to obtain estimated coefficients for 500 interaction terms *Treat ∗ Time*, which are then compared with the actual coefficients. The resulting distribution is shown in Fig. 2. The estimated values of pseudo-policy dummy variables are centrally distributed around 0, deviating from the actual coefficients (−0.1572 and −0.1644) respectively. Most of them fail to be significant at the 10 % level, indicating that the baseline regression results are relatively robust, and other unobservable factors will not interfere with carbon trading policy to affect emissions.

4.2.4. Replace the explained variable

We employ the substitution of explained variables to further test the robustness of the baseline regression results, in order to prevent any deviation from the empirical truth. Given the potential relationship between emissions growth and economic growth, this

Table 4
The results of different explained variables.

Variables	Carbon emission intensity	Air pollutants emission intensity
Treat ∗ Time	−0.1572***	−0.1644***
	(0.0235)	(0.0228)
-cons.	12.1669***	16.1802***
	(1.1092)	(1.0771)
Control variables	yes	yes
Province FE	yes	yes
Year FE	yes	yes
Obs.	450	450
R-squared	0.9428	0.9847
F-statistic	40.96***	82.57***

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; robust standard errors in parentheses.

Table 5
The results of each sector.

	CE				PE			
Variables	Power	Industry	Transport	Resident	Power	Industry	Transport	Resident
Treat ∗Time	−0.0698*	−0.0626*	−0.0677***	−0.0643*	−0.0881*	−0.2185***	−0.1161***	−0.1378***
	(0.0432)	(0.0310)	(0.0172)	(0.0344)	(0.0576)	(0.0376)	(0.0190)	(0.0363)
ES	−0.0221	−0.0359**	−0.0033	0.0403***	0.0216	−0.0026	0.0048	0.0547***
	(0.0449)	(0.0135)	(0.0044)	(0.0107)	(0.0600)	(0.0164)	(0.0049)	(0.0112)
EI	0.1864***	0.0884***	−0.0020	0.0267**	0.0638*	0.0280	0.0002	0.0535***
	(0.0217)	(0.0155)	(0.0059)	(0.0087)	(0.0289)	(0.0188)	(0.0066)	(0.0092)
PGDP	0.2143**	0.2892***	0.2768***	−0.1207	−0.0596	−0.0577	0.2954***	−0.0664
	(0.0817)	(0.0523)	(0.0341)	(0.0676)	(0.1091)	(0.0635)	(0.0378)	(0.0713)
POP	0.2679***	0.0304	0.0112	−0.1472	0.0232	−0.2667***	0.0122	−0.3209**
	(0.0591)	(0.0630)	(0.0263)	(0.1043)	(0.0789)	(0.0766)	(0.0291)	(0.1101)
T	0.0002	0.0007	0.0001	0.0001	0.0008	0.0011	−0.0001	0.0006
	(0.0009)	(0.0006)	(0.0004)	(0.0007)	(0.0012)	(0.0007)	(0.0004)	(0.0008)
R	−0.0623	−0.0303	0.0231	0.0698	−0.1132	−0.0829*	0.0117	0.0307
	(0.0473)	(0.0305)	(0.0205)	(0.0373)	(0.0632)	(0.0371)	(0.0226)	(0.0393)
-cons	5.5323***	6.3705***	4.3026***	9.5854***	4.9332***	7.3371***	0.3168	5.7993***
	(0.8628)	(0.5746)	(0.3973)	(1.2084)	(1.1519)	(0.6980)	(0.4395)	(1.2752)
Province FE	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	450	450	450	450	450	450	450	450
R-squared	0.5541	0.6962	0.8946	0.2233	0.8386	0.7813	0.4237	0.6922
F-statistic	86.88***	55.04***	181.53***	132.52***	57.55***	83.61***	163.81***	214.28***

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; robust standard errors in parentheses.

study takes emission intensity as a proxy variable for emissions in the robustness analysis. The replacement results are shown in Table 4. Both the coefficients of the core explanatory variables are consistent with the baseline results, indicating strong robustness of the results, which will not change with different explained variables.

4.3. Sectoral heterogeneity analysis

Table 5 displays the various performance of the carbon trading policy across multiple sectors. The coefficients of *Treat ∗Time* are significantly negative in all sectors, and the values vary, so Hypothesis 2. cannot be rejected. This indicates that the policy can reduce the emissions of carbon and air pollutants in multiple sectors to different extents. In addition, the carbon trading policy is more effective in controlling air pollution than carbon reduction in all sectors, which is consistent with sector-wide empirical results. Specifically, carbon trading policy can reduce 6.98 % of carbon emissions and 8.81 % of air pollutant emissions in the power sector, with little difference between the two. The possible explanation for this phenomenon is that all carbon trading pilot areas initially focused on the power production industry as the primary source of emission control enterprises when the market opened. Additionally, the national carbon trading market initially only covered the power sector. Such emphasis will strongly encourage enterprises in the power sector to enhance their awareness of carbon emissions, promote the progress of low-carbon technology, and ultimately reduce carbon emissions during the production activities of power enterprises. In the industry sector, the policy has shown the best performance in controlling air pollution, effectively reducing air pollutant emissions by 21.85 %. China has always ranked first all over the world in the production of industrial sources such as iron, steel, cement plants, metal smelters, which are major sources of anthropogenic air pollutants. High emissions mean large emission reduction space. Since the 20th century, the Chinese government has become increasingly concerned about industrial air pollution and issued a series of targeted policies. For example, the Boiler Emission Standards for Air Pollutants (2001) and the 11th Five-Year Plan for National Environmental Protection (2007). The implementation of

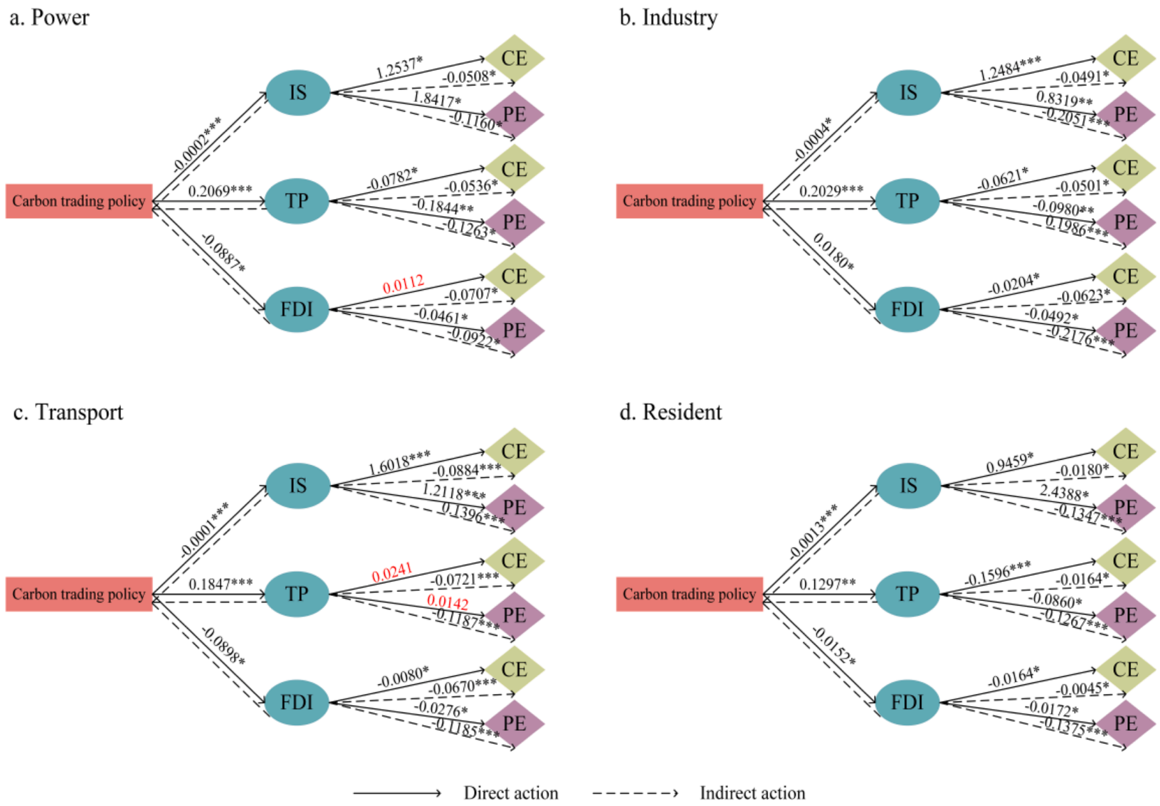

Fig. 3. Mediating mechanism in four sectors. Notes: $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

these policies has effectively controlled air pollution in the industry sector, resulting in a reversal of air pollutant emissions. Since 2013, the carbon trading policy has been piloted, aiming to enhance the emission reduction policy system and facilitate the green transformation of the industry sector. In the transport and resident sectors, the carbon trading policy has shown moderate performance, reducing carbon emissions by 6.77 % and 8.81 %, and air pollutant emissions by 11.61 % and 13.78 %, respectively. This is inseparable from the government's great attention and full implementation in controlling vehicle exhaust emissions, retiring yellow-label and old vehicles, promoting of clean fuels in the resident sector and collaborating with the existing emission reduction policy system.

4.4. Mediating effect analysis

Furthermore, we used the mediating model to verify Hypotheses 3a to 3c. The results of the effect assessment for the three mediating variables and the action mechanism of the carbon trading policy to reduce emissions in four sectors are shown in Fig. 3. The numbers on the arrows in the figure represent the coefficient β_1 of the interaction $Treated_i{*}Time_t$ in Eq. (2), the coefficient γ_2 of the mediating variable M_{it}, and the coefficient γ_1 of the interaction coefficients $Treated_i{*}Time_t$ in Eq. (3), respectively. The results of mediating mechanism are shown in Appendix. Table A1 is the empirical results of model (2), illustrating the first stage of the mediating mechanism. Supplementary Table A2 is the empirical results of model (3), illustrating the second stage of the mediating mechanism. Fig. 3 provides a more intuitive and graphical representation of the impact of each mediating variable on emissions in each sector, as well as the action path of carbon trading policy in each sector.

Obviously, when the mediating variable is IS, the coefficients β_1 are significantly negative in each sector. This indicates that carbon trading policy can intervene in the proportion of heavy-polluting enterprises and subsequently affect the industrial structure in each sector. In other words, following the trading market pilot, the number of heavy-polluting enterprises in pilot regions decreased significantly. In the power sector, as shown in Fig. 3a, the coefficients γ_1 in the regression results of model (3) are -0.0508 and -0.1160, respectively, and both are significant at the 10 % level. Thus, the carbon trading policy can reduce CO_2 emissions by 5.08 % and air pollutants by 11.60 % by optimizing the industrial structure. This represents a transmission mechanism with a partial mediating effect. Due to the limited emission allowances, the heavy-polluting enterprises in the pilot region will have to incur higher expenses to acquire additional emission quotas. To avoid such high costs, enterprises will likely alter their development approach, by transitioning to clean energy in place of coal consumption, phasing out outdated industrial capacities, and implementing other measures to reduce carbon emissions. As a result, the number of high-polluting enterprises is decreasing, the industrial structure is being optimized, and overall emissions of carbon and air pollutants within the sector are declining. The policy transmission path based on industrial structure is consistent across other sectors, and its effect on controlling air pollution is more pronounced. Carbon trading policy can distinctly improve the co-benefits of reducing carbon emissions and air pollutants by optimizing the industrial structure. This can reduce carbon emissions by 4.91 % and air pollutants emissions by 20.51 % in the industry sector, emissions by 8.84 % and air pollutants emissions by 13.96 % in the transport sector, and emissions by 1.80 % and air pollutants emissions by 13.47 % in the resident sector. The mediating role of industrial structure can be supported by the above analysis, so **Hypothesis 3a.** cannot be rejected.

On the contrary, when the mediating variable is TP, the coefficients β_1 in model (2) are significantly positive in each sector. This indicates that the carbon trading policy can attract more R&D investment, thereby promoting technological progress. In the power, industry, and resident sectors, the coefficients of both the dummy variables $Treat * Time$ and mediating variables TP in model (3) are significantly negative. This shows that the impacts of carbon trading policy on the emissions of carbon and air pollutants are mediated by technological progress. The most important reason is that the policy can send a clear signal to enterprises, that is, emission reduction can lower costs and increase profits, thereby encouraging enterprises to reduce production costs by adopting advanced technology to maximize profits. This process can not only effectively control carbon emissions and air pollution but also realize the coordinated development of economic progress and environmental friendliness in the pilot areas. However, in the transport sector, as shown in Fig. 3c, while the policy can mitigate carbon emissions and air pollutants, the coefficients of the mediating variables (0.0241 and 0.0142 respectively) in model (3) are positive but not statistically significant, indicating that technological progress does not act as an intermediary in this process. One possible reason is that the transport sector lacks sufficient basic research and applied basic research, leading to inadequate research reserves for key core technologies in some fields. Additionally, the scientific and technological innovation system still needs improvement. As a result, the extra scientific research funds generated by the carbon trading policy have not been converted into practical technologies in time and have not play a mediating role in environmental effects. Thus, the mediating effect of technological progress can only be proven in partial sectors and **Hypothesis 3b.** cannot be rejected in the power, industry, and resident sectors.

The role of foreign direct investment in the environmental impact mechanism of carbon trading policy varies across different sectors and is more complex. In the power sector, the coefficient of $Treat * Time$ in model (2) is significantly negative, which shows that the carbon trading policy has driven away foreign investors. In theory, FDI can lower operating costs and be utilized for the green transformation of enterprises, thus reducing emissions. Since the coefficients of $Treat * Time$ and the mediating variable FDI in model (3) are all significantly negative (−0.0461 and −0.0922, respectively), carbon trading policy can control air pollution through the intermediary role of FDI. However, because of the potential for time lag, this mediating mechanism is not effective for reducing carbon emissions. In the industry sector, as shown in Fig. 3b, the coefficient of $Treat * Time$ in model (2) is significantly positive, indicating that the carbon trading policy can attract more foreign investment to industrial enterprises located in the pilot regions. On the one hand, China's industry sector has been the main source of foreign investment, and the pilot carbon trading policy has not reversed this situation. On the other hand, the government provides financial support for environmentally friendly projects and emerging industries with positive environmental benefits through its policies. This can attract high-quality foreign direct investment. Furthermore, the policy can signally reduce emissions by attracting foreign investment, which is the most ideal mediating mechanism for the environmental effect. In the transport and resident sectors, as shown in Fig. 3c and 3d, the coefficients of $Treat * Time$ in model (2) are significantly negative. This suggests that the establishment of a carbon trading market restricts the influx of pollution-intensive FDI. Since the coefficients of $Treat * Time$ and the mediating variables in model (3) are all significant, this indicates that FDI can act as an intermediary to influence the policy on emission reduction. The primary reason is that stringent environmental regulations can effectively deter pollution-intensive enterprises from investing in the pilot regions, leading to the gradual optimization of the structure and quality of FDI. This, combined with the technology spillover effect and industrial correlation effect of foreign investment, will further reduce the emissions of the host country and improve environmental quality, thereby creating the "pollution halo effect" of FDI (Wang et al., 2019). Generally speaking, **Hypothesis 3c.** cannot be rejected in the industry, transport, and resident sectors, and the transmission mechanism of FDI as a mediating variable differs in these sectors.

5. Conclusions and policy implications

According to the panel data of the emissions of CO_2 and air pollutants in 30 provinces of China, this study explores whether the carbon trading policy can promote co-benefits of carbon emissions reduction and air pollution control in multiple sectors, using the time-varying DID method. Additionally, we test the robustness of the baseline results and establish mediating effect models for the industrial structure, technological progress, and foreign direct investment to further identify the impact pathway of the policy on emission reduction benefits in each sector. The results reveal that the carbon trading policy plays a significant role in reducing carbon emissions and controlling air pollution. And the effectiveness of air pollution reduction is better due to a comprehensive pollution reduction policy system. The policy's co-benefits exhibit distinct sectoral variations, with the emissions of air pollutants in the industry sector being particularly sensitive to the policy. Furthermore, the results of the mediating model show that the policy can upgrade the industrial structure, playing a significant role in the process of carbon emission reduction and air pollution control in each sector. The carbon trading policy can also promote technological progress, then improve enterprise energy efficiency and effectively inhibit the emissions of carbon and air pollutants, without the transport sector. In addition, foreign direct investment also plays a mediating role in emission reduction, but the response of various sectors to this policy is contradictory.

The above results provide implications for addressing the challenges presented at the beginning. Firstly, the carbon trading policy can achieve the coordinated reduction of carbon emissions and air pollutants in pilot regions. Thus, the government should strengthen the top-level planning, accelerate the improvement of the carbon trading market system, and enhance the scope and operational

Table A1
Mediating mechanism: First stage.

	Power			Industry			Transport			Resident		
Variables	IS	TP	FDI	IS	TP	FDI	IS	TP	FDI	IS	TP	FDI
*Treat *Time*	−0.0002***	0.2069***	−0.0887*	−0.0004*	0.2029***	0.0180*	−0.0001***	0.1847***	−0.0898*	−0.0013***	0.1297**	0.0152*
	(0.0000)	(0.0486)	(0.0710)	(0.0002)	(0.0524)	(0.0097)	(0.0000)	(0.0446)	(0.0653)	(0.0001)	(0.0494)	(0.0116)
ES	0.0001	−0.0948*	0.0579	0.0002**	−0.0784***	−0.0118	0.0001	−0.0107	0.0150	−0.0002***	0.0329*	0.0175
	(0.0000)	(0.0506)	(0.0739)	(0.0000)	(0.0228)	(0.0346)	(0.0000)	(0.0115)	(0.0168)	(0.0000)	(0.0153)	(0.0222)
EI	−0.0001***	0.0381*	−0.0076	0.0002*	0.0819**	0.0971*	−0.0001***	0.0447**	−0.0464*	−0.0001***	−0.0327*	0.0507**
	(0.0000)	(0.0244)	(0.0356)	(0.0001)	(0.0261)	(0.0398)	(0.0000)	(0.0154)	(0.0225)	(0.0000)	(0.0125)	(0.0181)
PGDP	0.0003***	0.6494***	0.7674***	0.0036***	0.5107***	0.6846***	0.0003***	0.7366***	0.6984***	0.0016***	0.7275***	0.6275***
	(0.0000)	(0.0920)	(0.1344)	(0.0003)	(0.0884)	(0.1344)	(0.0000)	(0.0885)	(0.1296)	(0.0002)	(0.0972)	(0.1409)
POP	0.0003***	1.1571***	0.9380***	−0.0001	1.6551***	1.1008***	0.0002***	1.1500***	0.9327***	0.0023***	1.0566***	0.6740**
	(0.0000)	(0.0665)	(0.0972)	(0.0004)	(0.1065)	(0.1620)	(0.0000)	(0.0683)	(0.0110)	(0.0004)	(0.1500)	(0.2174)
T	−0.0001	−0.0001	0.0022*	−0.0001	−0.0003	0.0022*	−0.0001	−0.0004	0.0025*	−0.0001	−0.0001	0.0022*
	(0.0000)	(0.0010)	(0.0015)	(0.0000)	(0.0010)	(0.0015)	(0.0000)	(0.0010)	(0.0015)	(0.0000)	(0.0010)	(0.0015)
R	0.0001	−0.0916*	−0.2058**	−0.0001	−0.0889*	−0.1954*	0.0001	−0.0841*	−0.2159*	0.0001	−0.1097*	−0.1792*
	(0.0000)	(0.0533)	(0.0779)	(0.0002)	(0.0515)	(0.0784)	(0.0000)	(0.0531)	(0.0777)	(0.0001)	(0.0536)	(0.0777)
-cons	−0.0039***	−1.2218*	−8.7015***	−0.0304***	−3.9805***	−8.7931***	−0.0042***	−2.2897*	−7.8777***	−0.0291***	−1.8758	−5.3555*
	(0.0003)	(0.9712)	(1.4191)	(0.0035)	(0.9709)	(1.4771)	(0.0003)	(1.0306)	(1.5083)	(0.0042)	(1.7378)	(2.5180)
Province FE	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Year FE	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Obs.	450	450	450	450	450	450	450	450	450	450	450	450
R-squared	0.5587	0.9195	0.8623	0.6197	0.8769	0.7715	0.6586	0.8765	0.8072	0.4149	0.9309	0.8877
F-statistic	48.26***	45.85***	27.54***	65.83***	42.79***	25.68***	48.65***	45.88***	25.84***	89.66***	48.64***	24.17***

Notes: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; robust standard errors in parentheses.

efficiency of the carbon trading market. Promote the full launch of the national carbon trading market, including steel, chemical, construction, and other high-polluting industries into the trading system, and facilitate the integration of the national carbon trading market with existing pilot trading markets. It is necessary to consider a more effective and coordinated policy system, fully utilize the guiding role of carbon trading markets in reducing emissions of carbon and air pollutants, and accelerate coordinated management of carbon emissions reduction and air pollution control. In addition, developing countries should learn from this experience, gradually improve the carbon emission trading mechanism, and promote the coordinated management model.

Secondly, the carbon trading policy is conducive to reducing air pollution and carbon emissions, but its impact varies from sector to sector. The government should accurately classify enterprises in different sectors and establish a fair and equitable carbon trading system. Fully understanding the rationale behind setting the total amount of carbon emission rights and the allocation of quotas, improving the mechanism for disclosing carbon emission information, and guarding against "carbon transfer" and "carbon leakage" between sectors is crucial. At the same time, the government should promote the practical experience of the initially covered sectors and fully leverage the demonstration effect of sectors with good emission reduction benefits. For instance, the power sector should set a good example of demonstration and provide theoretical guidance and low-carbon technical support for emission reduction efforts in other sectors, and encourage green enterprises to share emission reduction technologies and management models. In the transport and resident sectors, regulators should implement additional environmental and economic policies, particularly carbon reduction policies, to supplement the existing emission reduction system and attain more co-benefits.

Thirdly, the carbon trading policy can influence the emissions of carbon and air pollutants through three intermediaries: industrial structure, technological progress, and foreign investment. Therefore, on the one hand, managers should actively mobilize the economic incentives of the policy to optimize industrial structure and promote the flow of production factors to low-emission and high-productivity sectors by optimizing the allocation of resource factors. On the other hand, the government should prioritize technological innovation, especially low-carbon technologies. It should also focus on improving and expanding the conversion rate and application scope of innovation achievements to achieve resource conservation and sustainable development from the source. In addition, governments at all levels need to provide reasonable guidance and monitoring of foreign direct investment, reduce or eliminate preferential environmental policies for foreign direct investment, and strictly control the transfer of pollution-intensive industries to China. The action paths of carbon trading policy vary across different sectors, and as a result, the policy implications of this study also vary across sectors. For example, the transport sector should prioritize research and development as well as the promotion of low-carbon technologies. It should also actively introduce advanced technologies and innovative systems. As the carbon trading policy drive away foreign investment support for the power sector, domestic investors should be encouraged to pay attention to power enterprises and enhance preferential power investment. However, there is a "pollution halo" effect in the resident sector. Therefore, managers should continue to introduce FDI to exert an inhibitory effect on environmental pollution. Additionally, governments at all levels should establish a coordination mechanism to demonstrate the role of this sector.

The method employed in this study can quantitatively assess the impact of carbon trading policy on the emissions of carbon and air pollutants, and identify the action path of the policy through theoretical analysis and econometric models. However, our study contained some uncertainties and limitations. Firstly, a control group is required when using the DID model. Since the policy in this study has been implemented nationwide since 2021, the data used are only updated to 2020. Secondly, the mediating effect model can only provide a rough test of the relationship between explanatory variables and explained variables, disregarding the complex interplay between variables. Thirdly, because of the unavailability of small-scale data, this study can only be conducted at the provincial level and cannot provide a detailed representation of its internal structure. We will continue to enhance it in future studies.

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Appendix

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