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GREEN DEVELOPMENT AND ENVIRONMENTAL POLICY IN CHINA: PAST, CURRENT AND FUTURE

Evaluating China's pilot carbon Emission Trading Scheme: collaborative reduction of carbon and air pollutants

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Abstract

Collaborative reduction of carbon and air pollutants can more efficiently achieve green technological change, industrial low-carbon transition, and high-quality economic and social development. As a typical environmental policy in China, the pilot carbon Emission Trading Scheme (ETS) has obvious advantages in achieving the collaborative reduction of carbon and air pollutants. Therefore, an evaluation of China's pilot carbon ETS from the perspective of collaborative reduction of carbon and air pollutants is performed in this paper. Compared with previous studies, first, this study innovatively uses the coupled coordination degree (CCD) model to measure the collaborative reduction level of carbon and air pollutants under different scenarios based on the panel data of China's 30 provincial-level regions during 2004–2018. Second, this study uses the DID method to evaluate the impact of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants and conducts some robustness checks and regional heterogeneity regressions. Third, this study uses the synthetic control method (SCM) further to examine the policy outcomes of the pilot carbon ETS. Scenario analysis shows that attaching importance to reducing air pollution will improve the collaborative reduction effect of carbon and air pollutants. Furthermore, the implementation of China's pilot carbon ETS exerts an effect of roughly 24.7% on reducing carbon, roughly 10.1% on reducing air pollutants, and roughly 22.0% on the collaborative reduction of carbon and air pollutants, ceteris paribus. Regional heterogeneity analysis shows that the impacts of the pilot carbon ETS are significant in all regions, except that the impact on reducing air pollutants in the central region is not significant. In addition, results from SCM indicate that the impacts of the pilot carbon ETS on the collaborative reduction of carbon and air pollutants are significantly efficient in Beijing, Tianjin, Shanghai, Hubei, and Chongqing, while not much efficient in Guangdong and Fujian. The main policy implications include strengthening the top-level design of the ETS in the collaborative reduction of carbon and air pollutants, attaching importance to the governance of air pollution, making the regional governance more targeted, and improving energy efficiency.

Keywords China's pilot carbon Emission Trading Scheme (ETS) · Carbon emission reduction · Air pollutant reduction · Policy evaluation · Coupling coordination degree model · Difference-in-difference (DID) · Synthetic control method (SCM)

Introduction

As we all know, the over-exploitation and utilization of natural resources such as energy have led to climate change and air pollution crisis, especially for developing economies (Jia et al. 2022; Yang et al. 2022; Xin et al. 2022). China is a developing country with the largest economy and population in the current world and is also the largest carbon emitter. Under the background of the long-term temperature set by the Paris Agreement in 2015 (Schleussner et al. 2016), the Chinese government declared that "China will strengthen intended nationally determined contributions (INDCs), adopt more powerful policies and measures, strive to achieve carbon peaking by 2030 and carbon

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neutrality by 2060" at the 75th UN General Assembly. Besides, the long-term dependence on natural resources in China's economic development has also brought serious environmental problems such as air pollution (Wang et al. 2019). Based on these facts, combating climate change and air pollution are two problems China must face at the current stage. Scientific research shows that carbon and air pollutant emission sources are largely similar, and both are derived from fossil energy consumption (Monjardino et al. 2021; Hanaoka and Masui 2020), indicating that environmental policies may achieve the collaborative reduction of carbon and air pollutants. The collaborative reduction of carbon and air pollutants in this study means that reducing air pollutants can be achieved while reducing carbon emissions. That is, reducing carbon and air pollutants is synergistic rather than separated. A few works studied the collaborative reduction of carbon and air pollutants. The studies found that a certain correlation exists between the change of CO_2 and air pollutants (including SO_2, NO_2, O_3, and $PM_{2.5}$), and 70% of Chinese cities did not achieve the collaborative reduction of CO_2 and $PM_{2.5}$ (Song et al. 2021; Zhang et al. 2021; Lin and Jiang 2022). Theoretically, most studies only separately analyze whether carbon reduction and air pollutant reduction have a downward trend, while few studies measure the collaborative reduction level of carbon and air pollutants (Jiang et al. 2020; Lin and Jiang 2022). In recent years, the Chinese government has implemented various policies to reduce carbon emissions, such as the pilot carbon Emission Trading Scheme (ETS), the pilot low-carbon city scheme, and the work plan for the control of greenhouse gas emissions in the 14th Five-Year Plan, which have strong potentials to achieve the collaborative reduction of carbon and air pollutants. Therefore, using specific methods to measure the collaborative reduction level of carbon and air pollutants in China and studying the impact of environmental policy on the collaborative reduction of carbon and air pollutants have important theoretical and practical significance.

The pilot carbon ETS is the representative policy to reduce carbon emissions in China. Carbon emission trading originates from pollution rights trading. The practice of pollution rights trading first appeared in developed countries. In 1968, Dales (1968), an American economist, gave a more comprehensive description of "pollution rights trading." In subsequent years, a system of emissions trading has evolved. For example, the United States Environmental Protection Agency (EPA) took emissions trading from theory to practice in air and water pollution control in the 1970s. Now, it has become a centerpiece in international discussions about addressing the problem of global climate change. The Chinese government began to explore the construction of a carbon emission trading market in 2011. Unlike the traditional command-and-control environmental policy, China's pilot carbon ETS is market-based. The core idea of China's pilot carbon ETS is first to set a total carbon emission target, then allocate the carbon quotas to each enterprise. Finally, these enterprises can use their carbon quotas depending on their decisions (Zhang et al. 2022a). However, it is uncertain whether the pilot carbon ETS can achieve the collaborative reduction of carbon and air pollutants by controlling the total carbon emissions. In addition, in China, the energy sector is moving in a new direction following the call for an "energy revolution," the "fight against pollution," and the transition towards a service-based economic model (IEA 2022; Liu et al. 2022). The pilot carbon ETS places the emphasis on the evolution of electricity, clean energy, and high-efficiency digital technologies, which is in line with the call above-mentioned. As a consequence, this paper takes China's pilot carbon ETS as an example to evaluate its outcomes on the collaborative reduction of carbon and air pollutants.

The main motivations of this paper are as follows. The Chinese government has incorporated the goals of "carbon peaking" and "carbon neutrality" into the national ecological civilization construction system and has emphasized the collaborative reduction of carbon and air pollutants in the 14th Five-Year Plan for national economic and social development, which indicates that the Chinese government has a strong determination to combating with climate change and environmental pollution. On the one hand, taking China's pilot carbon ETS as an example, exploring its collaborative reduction effect on carbon and air pollutants will help the Chinese government clarify the improvement direction of relevant policy and enhance the ability to address environmental issues; on the other hand, the pilot carbon ETS is a typical market-based environmental policy proposed earlier in China. Choosing the pilot carbon ETS as the study object can not only make this study more generalizable but also verify whether the total amount control can achieve the collaborative reduction of carbon and air pollutants.

The subsequent sections of this paper are organized as follows. Some relevant literature is reviewed in the "Literature review" section. The "Study case, methods, and data" section shows the study case and the construction of relevant models, hypotheses, variables, and data and provides some corresponding formulas. The "Results and discussions" section presents the empirical results and some corresponding discussions. A further decomposition of the average effect is conducted in the "A further analysis based on synthetic control method" section. According to the analysis above, the research conclusions are drawn in the "Conclusions and policy implications" section, and some policy implications are also given based on these conclusions.

Literature review

The existing literature relevant to this study can be summarized into the following three categories: first, the effect and mechanism of carbon ETS; second, the analysis and measurement of collaboratively reducing or controlling carbon and air pollutants; third, the assessment or evaluation method for carbon ETS.

Literature on the mechanism and effect of carbon ETS

Early research on carbon emission trading mostly focused on the European Union Emission Trading Scheme (EU ETS). The EU ETS is the first mandatory regional carbon ETS in the world, and its aim is to reduce the total amount of carbon emissions in the trading sectors while minimizing the carbon reduction cost. The EU ETS was implemented on January 1, 2005, and the EU ETS would control about 46% of the EU's total carbon emissions (Watanabe and Robinson 2005). Skjaerseth and Wettestad (2008) assessed and explained the implementation of the EU ETS, and concluded that the multi-level governance approach, the decentralized nature of the EU ETS itself, and the Clean Development Mechanism under the Kyoto Protocol exerted important impacts on the policy effect of the EU ETS. In recent years, the research on the effect and mechanism of EU ETS is still abundant. Stuhlmacher et al. (2019) made a spatio-economic assessment of the EU ETS and found that there was a clustering of emissions changes at the EU and country level, which peaked at the start of the second phase but declined as the EU ETS matured. Kang et al. (2022) studied the impact of the EU ETS on aviation supply and pointed out that the EU ETS does not have a substantial impact on the average aircraft size, while it has caused a reduction of total airline seat capacity and flight frequency.

The pilot carbon ETS is an essential part of China's environmental regulations, which is conducive to achieving the goals of "carbon peaking" and "carbon neutrality" for China. The pilot carbon ETS places emphasis on the role of market forces in reducing carbon emissions. The overview, specific measures, challenges, and future of China's pilot carbon ETS have been studied by some scholars (Liu et al. 2015; Ding et al. 2019). Furthermore, various studies have evaluated the effects of China's pilot carbon ETS from different perspectives, including the main effect of carbon reduction and some other external effects. Studies related to the carbon reduction of China's pilot carbon ETS showed that the implementation of the pilot carbon ETS produces positive impacts on reducing carbon emissions (Guo et al. 2021; Chen and Lin 2021; Wang et al. 2022). The outcome variables used in these studies include carbon emission intensity and carbon emission efficiency. In addition, some studies have analyzed the impact of China's pilot carbon ETS on other factors. The conclusions drawn from those studies showed that the implementation of the pilot carbon ETS is conducive to expanding employment scales (Yang et al. 2020b), alleviating poverty (Zhang and Zhang 2020), accelerating corporate innovation (Lv and Bai 2021), improving energy efficiency (Zhang et al. 2022b), promoting green production (Huang and Du 2020; Yang et al. 2021a), improving low carbon energy investment (Mo et al. 2016), and reducing air pollutants (Cheng et al. 2015; Liu et al. 2021a).

Literature on the analysis and measurement of collaboratively reducing or controlling carbon and air pollutants

At present, most studies have taken China's pilot carbon ETS rather than the EU ETS as an example to analyze the collaborative reduction effect of carbon and air pollutants. Some literature theoretically analyzed the co-control of carbon and air pollutants and concluded that approaches such as reducing fossil energy consumption and green innovation have significantly improved the co-control performance of carbon and air pollutants (Wang et al. 2020; Jiang et al. 2020). A few studies evaluated the impact of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants by empirical methods. In these studies, the collaborative reduction effect of carbon and air pollutants is mainly examined by separate regression, and few studies measure the collaborative reduction level of carbon and air pollutants. For example, Dong et al. (2022) explored the effects of the pilot carbon ETS on the co-benefits of carbon emissions reduction and air pollution control at the city level by the DID model and pointed out that the implementation of the pilot carbon ETS reduced the carbon emission intensity of the city and also reduced the level of $PM_{2.5}$. Kou et al. (2022) studied whether China's pilot carbon ETS can achieve the co-benefits of SO_2 reduction, and concluded that China's pilot carbon ETS has regional heterogeneity in reducing SO_2 emissions. The existing literature mainly used the comprehensive indicator construction method or data envelopment analysis (DEA) method to measure the collaborative reduction level of carbon and air pollutants (Wang et al. 2021; Song et al. 2021). Various studies have measured the coordinated changes between two or more systems using coupled coordination degree (CCD) model. The advantage of the CCD model is that its measurement result can reflect both the development and coordination levels between systems. On the one hand, the CCD model can measure the collaborative level between multiple economic systems. Zhou et al. (2020) measured the coupling degree and path between carbon emission efficiency and industrial structure upgrading in China using the CCD model and found that there is an obvious dynamic imbalance between China's carbon emission efficiency and industrial structure upgrading; on the other hand, the CCD model can also be used to measure the collaborative level between economic systems and other systems, such as economy-environment-tourism (Fei et al. 2021) and water-energy-food (Qi et al. 2022). However, existing studies have not applied the CCD model to measure the collaborative reduction level of carbon and air pollutants.

Literature on the assessment or evaluation method for carbon ETS

The assessment or evaluation methods for carbon ETS include qualitative methods and quantitative methods. On the one hand, qualitative methods mainly include the questionnaire investigation, interview, and case study. Suk et al. (2018) estimated the expected results of ETS in South Korea in the first compliance period by questionnaire investigation and interview method and compared them with the actual operating results to evaluate the policy effects of ETS in South Korea. Wu et al. (2016) conducted a case study in Shanghai to examine the cost-effectiveness of carbon reduction in China's pilot carbon ETS; on the other hand, quantitative methods mainly include the priori method represented by the simulation forecasting model and the posteriori method represented by the DID model. Zhang et al. (2022c) constructed a dynamic CGE model to examine the carbon reduction effect of a pure carbon ETS, and then further evaluated two-hybrid systems of the carbon tax and carbon ETS based on different carbon intensity rates. Fang et al. (2021) simulated China's ETS by nonlinear programming aimed at minimizing its total emission abatement costs to estimate the difference in marginal abatement costs under different carbon peaking scenarios. Compared with the priori model, the DID model is more objective, valid, and reliable as a representative of the posterior model. The advantages of the DID model are that it can control the non-time-variant heterogeneity to alleviate the endogeneity caused by omitted variables and the policy evaluation by the DID model has few reverse causality problems. Various studies evaluated the ETS by the DID model and concluded that the implementation of the ETS promoted carbon reduction (Lin and Huang 2022), energy efficiency improvement (Hong et al. 2022), total factor productivity improvement (Pan et al. 2022), green technology innovation (Fu et al. 2022), etc. In addition, some studies also used the synthetic control method (SCM) to evaluate China's pilot carbon ETS (Kang et al. 2022). On the one hand, the SCM can solve the problem of selection bias and policy endogeneity in the DID model; on the other hand, it can provide each research object with a corresponding synthetic control object. Thus, an average evaluation can be avoided, and an objective policy effect can be obtained.

According to the analysis above, it is scientific and feasible to achieve the collaborative reduction of carbon and air pollutants. The ETS is a representative of China's environmental policy, which has great potential to achieve the collaborative reduction of carbon and air pollutants. Overall, few studies measured the collaborative reduction level of carbon and air pollutants with the consideration of both development and coordination and used this measurement result as an outcome variable to evaluate the policy effect of China's pilot carbon ETS. Therefore, based on the panel data of China's 30 provincial-level regions during 2004–2018, this study uses the CCD model, DID model, and SCM to evaluate the impact of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants. The main contributions of this paper are as follows. First, this paper applies the CCD model to measure the collaborative reduction levels of carbon and air pollutants in China's 30 provincial-level regions during 2004–2018; second, this paper innovatively conducts an evaluation of China's pilot carbon ETS from the perspective of collaborative reduction of carbon and air pollutants based on the DID model; third, this paper uses the SCM to further examine the effect of China's pilot carbon ETS on collaboratively reducing carbon and air pollutants in each region; fourth, this paper enriches the perspective of environmental policy evaluation and provides some new evidence and implications for the government to further reduce carbon emissions and air pollution. The research framework of this paper is shown in Fig. 1.

Study case, methods, and data

Study case

In October 2011, the Chinese National Development and Reform Commission (NDRC) issued the "Notice on Carrying out the Pilot Carbon Emission Trading Scheme," which approved seven provinces and cities, including Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen, as the pilots to implement the pilot carbon ETS. After several years, Fujian province established the carbon emission trading market on December 22, 2016. The spatial distribution of the study case is shown in Fig. 2. Note that Shenzhen is a city that belongs to Guangdong province; hence, it is not marked in Fig. 2. Since June 2013, the carbon emission trading market in each pilot has been gradually launched. The timeline of China's pilot carbon ETS is shown in Fig. 3.

The key points of China's pilot carbon ETS implementation include the following: first, the establishment of the carbon market and its institution; second, the clarification of the applicable industries in the pilot carbon ETS and their CO_2 quotas; third, the monitoring, reporting, and verification of carbon emission data. Based on this, Table 1 shows the overview of China's pilot carbon ETS including the data on launch dates, applicable industries for the first year, CO_2 quotas, and contract performance rate.

Fig. 1 Research framework

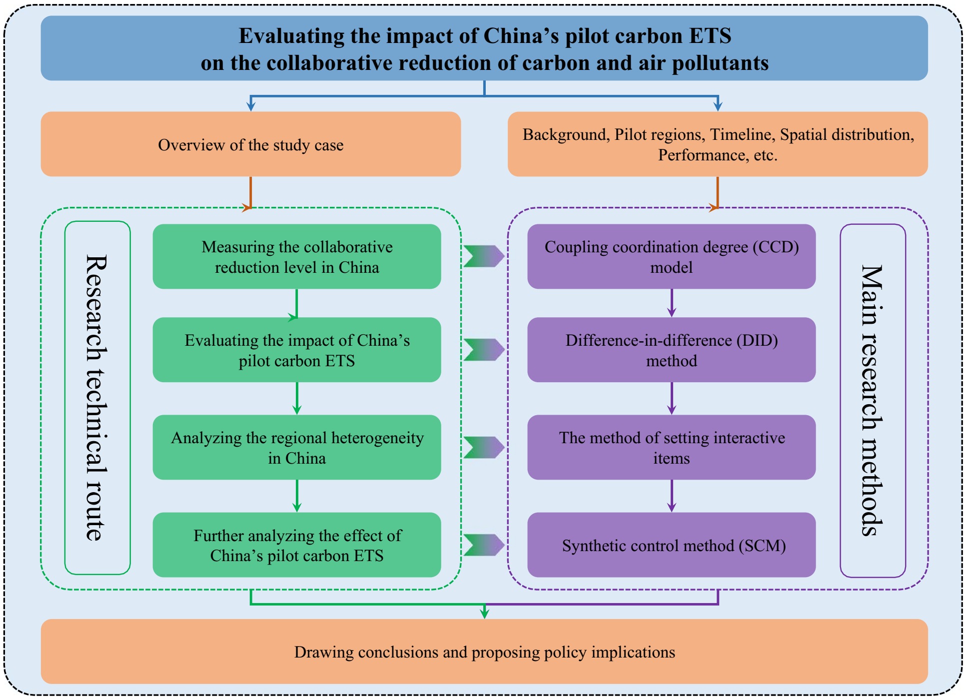
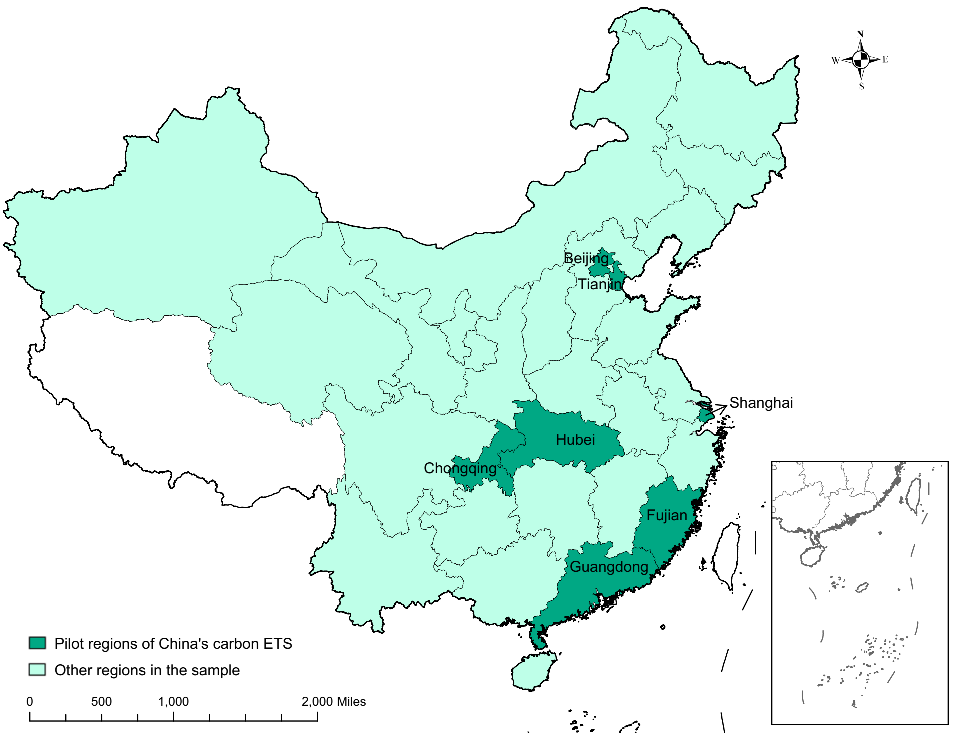


Fig. 2 Spatial distribution of the study case



Coupling coordination degree model

The CCD model is commonly used to quantitatively measure the coordinated development index between two or more systems. Here, coupling is a concept from electronics physics, which is widely used to describe the degree of interaction between systems (Ruehli 1974). The index measured by coupled coordination model can reflect not only the closeness between systems but also the development of multiple systems. Li et al. (2012) first used the CCD model to measure

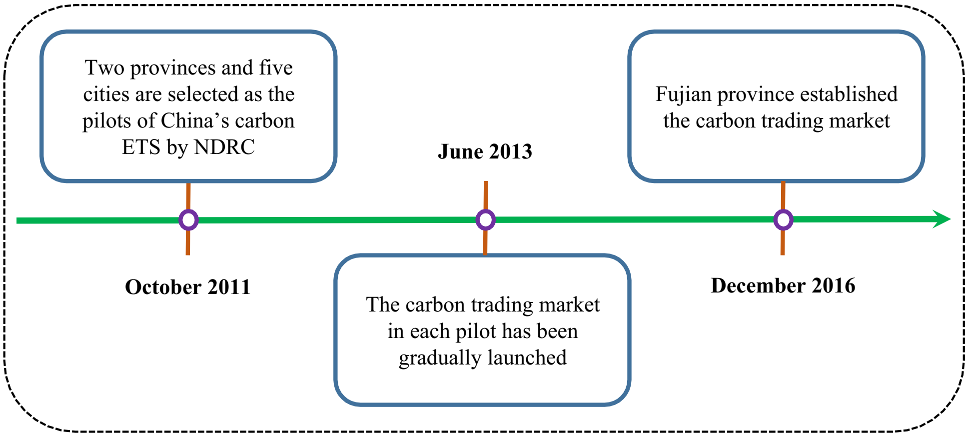


Fig. 3 Timeline of China's pilot carbon ETS

Table 1 Overview of China's pilot carbon ETS

Regions	Launch dates	Applicable industries for the first year	CO_2 quotas	Contract performance rate
Shenzhen	June 18, 2013	635 industrial enterprises and 197 construction enterprises	107 million t in 2013–2015; 30 million t in 2020	2013: 99.2%; 2014: 99.7%; 2020: 100%
Shanghai	November 26, 2013	191 enterprises in steel, petrochemical, chemical, nonferrous metals, electricity industries, etc	160 million t in 2013; 105 million t in 2020	2013: 100%; 2014: 100%; 2020: 100%
Beijing	November 28, 2013	415 enterprises in steel, cement, petrochemical industries, etc	60 million t in 2013; 50 million t in 2020	2013: 97.1%; 2014: 100%; 2017: 99.6%
Guangdong	December 19, 2013	About 200 enterprises in the electricity, cement, petrochemical, and steel industries	388 million t in 2013; 465 million t in 2020	2013: 98.9%; 2014: 100%; 2020: 100%
Tianjin	December 26, 2013	114 enterprises in the industry of steel, chemical, electricity, thermal, petrochemical, oil and gas exploration industries, etc	160 million t in 2013; 160 million t in 2020	2013: 96.5%; 2014: 99.1%; 2020: 100%
Hubei	April 2, 2014	138 enterprises in 12 industries, including steel, chemical, and cement	324 million t in 2014; 166 million t in 2020	2014: 100%; 2017: 100%
Chongqing	June 19, 2014	242 enterprises in metallurgy, electricity, chemical, building materials, machinery, and light industries	125 million t in 2014; 130 million t in 2020	2014: 70%
Fujian	December 22, 2016	277 enterprises in electricity, steel, chemical, petrochemical, nonferrous metals, civil aviation, building materials, paper-making, and ceramics industries	Undeclared	2016: 98.6%; 2020: 100%

The data are manually collected from related official websites by the authors

the coordinated development level between systems. Therefore, to evaluate the collaborative emission reduction effect of carbon and air pollutants, this study uses the CCD model to measure their coordinated development index. The evaluating systems in this study are carbon reduction (*CR*) and air pollutant reduction (*APR*), which will be measured by CO_2 emissions (million t) and industrial SO_2 emissions (thousand t), respectively. The detailed data processing steps are as follows.

First, construct an original data matrix **X** of *i* regions and *j* periods as shown in Eq. (1):

$$\mathbf{X} = (x_{ij})_{m\times n} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \tag{1}$$

where i is the region code, j is the period code, m is the number of regions, n is the number of periods, and x indicates the original data of indicators. To facilitate the dynamic comparison of the data over different periods, this study normalizes the original data matrix $\mathbf{X}$ using the dynamic mean range method, thereby obtaining a normalized data matrix $\mathbf{X}'$. Referring to the study of Yang et al. (2020a), the raw data processing method is shown in Eqs. (2) and (3):

$$x'_{ij} = \frac{x_{ij} - \min(x_{i1}, x_{i2}, \cdots, x_{in})}{\max(x_{i1}, x_{i2}, \cdots, x_{in}) - \min(x_{i1}, x_{i2}, \cdots, x_{in})} \tag{2}$$

$$x'_{ij} = \frac{\max(x_{i1}, x_{i2}, \cdots, x_{in}) - x_{ij}}{\max(x_{i1}, x_{i2}, \cdots, x_{in}) - \min(x_{i1}, x_{i2}, \cdots, x_{in})} \tag{3}$$

where x' indicates the normalized value of indicators, and $x' \in [0, 1]$. Here, Eq. (2) is applicable to the variables with a positive effect, while Eq. (3) is applicable to the variables with a negative effect. In this study, CO_2 and industrial SO_2 emissions negatively impact the variables of *CR* and *APR*, respectively, and hence Eq. (3) is applicable to processing them. The greater the normalized variables, the higher the corresponding emission intensity. Therefore, the normalized data matrix $\mathbf{X}'$ obtained is shown as Eq. (4):

$$\mathbf{X}' = (x'_{ij})_{m\times n} = \begin{pmatrix} x'_{11} & x'_{12} & \cdots & x'_{1n} \\ x'_{21} & x'_{22} & \cdots & x'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x'_{m1} & x'_{m2} & \cdots & x'_{mn} \end{pmatrix} \tag{4}$$

Next, referring to the work of Li et al. (2012), the coupling coordination degree model of *CR* and *APR* is constructed as follows:

$$C_{ij} = \left\{ \frac{CR'_{ij} \times APR'_{ij}}{[(CR'_{ij} + APR'_{ij})/2]^2} \right\}^{\frac{1}{2}} \tag{5}$$

$$T_{ij} = \alpha \times CR'_{ij} + \beta \times APR'_{ij} \tag{6}$$

$$D_{ij} = (C_{ij} \times T_{ij})^{\frac{1}{2}} \tag{7}$$

where i is the region code, j is the period code, CR' and APR' are from matrix $\mathbf{X}'$ indicating the normalized value of *CR* and *APR*, respectively, and C, T, and D indicate the coupling degree, coordination degree, and coupling coordination degree of reducing carbon and air pollutants, respectively. Here, α and β are the contribution coefficients of reducing carbon and air pollutants, respectively, and meet $\alpha + \beta = 1$. This study assumes three scenarios as follows: carbon and air pollutant reductions have equal status ($\alpha = 0.5$, $\beta = 0.5$), carbon reduction has a slightly higher status ($\alpha = 0.6$, $\beta = 0.4$), and carbon reduction has a much higher status ($\alpha = 0.7$, $\beta = 0.3$). It is noted that C, T, and $D \in [0, 1]$.

Finally, D is positively correlated with the collaborative reduction level of carbon and air pollutants. Referring to some recent works (Fei et al. 2021; Qi et al. 2022), the classification criteria of coupling coordination degree are determined as shown in Table 2.

Hypotheses and DID model

The main goal of the pilot carbon ETS is to control the total emissions of carbon by market forces and achieve a low-carbon transition of the economy (Dong et al. 2022; Hong et al. 2022). Specifically, some economic activities can produce negative externalities such as carbon emissions (Cong and Wei 2010). Pigou (1951) proposed that the government could internalize the negative externalities of economic activities through tax intervention. Contrary to Pigou's theory, Coase (1960) believed that a market and property rights determination method is conducive to solving external problems. The Coase theorem states that if public goods are given clear boundaries of property rights, market forces will work on regulating related corporate behaviors. Dales (1968) introduced the concept of property rights in the Coase theorem into environmental pollution control and proposed that pollution is a type of property right to enterprises granted by the government, and pollution rights can be traded through the market. This has become a theoretical foundation for studying the ETS. In the pilot carbon ETS, the carbon emissions that have been given property rights are allowed to be freely traded in the market, which indicates that it has been changed from a public good to a commodity, thereby controlling the excessive carbon emission behaviors of enterprises (Kou et al. 2022; Wang et al. 2022). For high carbon emission enterprises, carbon emissions exceeding the carbon quota produce additional production costs, while the carbon reduction by green production brings additional economic benefits (Duan et al. 2014). It means that the pilot carbon ETS may help enterprises better consider economic benefits and corporate social responsibility for reducing

Table 2 Classification of coupling coordination degree

Range of *D*	$D \in [0.0, 0.2)$	$D \in [0.2, 0.4)$	$D \in [0.4, 0.6)$	$D \in [0.6, 0.8)$	$D \in [0.8, 1.0)$
Collaborative level	Extreme antagonism	Slight antagonism	Primary synergy	Moderate synergy	High synergy

carbon emissions (Guo et al. 2021). In short, China's pilot carbon ETS may achieve carbon reduction effectively.

> Hypothesis 1. China's pilot carbon ETS significantly reduces carbon emissions.

Based on the above analysis and Hypothesis 1, the first estimation function in this study is shown as Eq. (8) conforming to the principle of the DID model:

$$CR'_{it} = \alpha_0 + \alpha_1 ETS_{it} + \boldsymbol{\alpha}_2 \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{8}$$

where CR'_{it} indicates the outcome variable of the region i in period t; ETS_{it} is an indicator variable of China's pilot carbon ETS, equal to one if the region i implemented the pilot carbon ETS in period t, and zero otherwise; $\mathbf{X}_{it}$ is a vector of control variables including a series of individual characteristics of each region, such as economy (*Eco*), population (*Pop*), technology (*Tec*), industrial structure (*IS*), and energy structure (*ES*). Referring to the works of Zhao et al. (2022), Liu et al. (2021b), Yang et al. (2021b), and Xu et al. (2022), this study chooses regional GDP (billion Chinese Yuan, CNY) to measure *Eco*, chooses year-end resident population (million people) to measure *Pop*, chooses granted patents (number) to measure *Tec*, chooses proportion of secondary industry in GDP (%) to measure *IS*, and chooses proportion of primary energy (%) to measure *ES*; α_0, α_1 and $\boldsymbol{\alpha}_2$ are the parameters to be estimated; μ_i is the region fixed effects; λ_t is the period fixed effects; and ε_{it} is the stochastic disturbance.

At the beginning of the 14th Five-Year Plan, China entered a new stage of "Collaborative reduction of carbon and air pollutants" (Song et al. 2021). In September 2020, the Chinese government declared the major national strategic goals of "carbon peaking" in 2030 and "carbon neutrality" in 2060 (Chen and Lin 2021; Zhang et al. 2022b). In essence, contrary to the negative externalities mentioned above, the collaborative reduction of carbon and air pollutants belongs to the positive externalities of policy effects. In other words, ETS can reduce emissions of air pollutants while reducing carbon emissions (Kou et al. 2022). The possible causes of positive externalities are as follows. On the one hand, although carbon pollution and traditional air pollution are different, they largely arise from the excessive consumption of fossil fuels. The same pollution source determines that the collaborative reduction of carbon and air pollutants is theoretically scientific and logically feasible (Wang et al. 2020; Jiang et al. 2020); on the other hand, forests, grasslands, wetlands, and other ecosystems can not only effectively achieve carbon fixation, but also reduce air pollutants such as SO_2, nitrogen oxides, and inhalable particles (Lin et al. 2020; Li and Huang 2020). This evidence shows a superior synergy between combating climate change and air pollution.

> Hypothesis 2. China's pilot carbon ETS significantly reduces air pollutant emissions.
> Hypothesis 3. China's pilot carbon ETS significantly achieves the collaborative reduction of carbon and air pollutants.

For investigating the impact of China's pilot carbon ETS on air pollutant reduction and its synergy with carbon reduction based on Hypotheses 2 and 3, some further DID models are obtained by replacing the outcome variable *CR*. Specifically, model (9) is obtained by a replacement with variable *APR*, and model (10) is with variable *D*, which are shown as follows:

$$APR'_{it} = \alpha_0 + \alpha_1 ETS_{it} + \boldsymbol{\alpha}_2 \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{9}$$

$$D_{it} = \alpha_0 + \alpha_1 ETS_{it} + \boldsymbol{\alpha}_2 \mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{10}$$

where i is the region code, j is the period code, APR' indicates air pollutant reduction, D indicates the collaborative reduction level of carbon and air pollutants, and the meaning of other variables are the same as those in model (8). Based on the above, the specific definitions and indicators of all variables are shown in Table 3.

Data

The study sample in this paper includes China's 30 provincial-level regions during 2004–2018. Some regions are not included due to the limitation of data, such as Tibet, Hong Kong, Macao, and Taiwan. The data mentioned above are all from the China Statistical Yearbook (2005–2019), the Statistical Yearbook of each region (2005–2019), the China Statistical Yearbook on Environment (2005–2019), the China Energy Statistical Yearbook (2005–2019), the Economy Prediction System (EPS) database, and the "Notice on Carrying out the Pilot Carbon Emission Trading Scheme" proclaimed by the NDRC. The monetary indicators above are deflated at the constant price of 2004. The descriptive statistics of data and its detailed sources are presented in Table 4.

Results and discussions

Measurements of coupling coordination degree under different scenarios

Based on the panel data of China's 30 provincial-level regions during 2004–2018, the CCD model is used in this study to measure the coupled coordination degree of reducing carbon and air pollutants under three different scenarios, including equal status of carbon and air pollutant reductions (scenario 1), slightly higher status of carbon reduction (scenario 2), and much higher status of carbon

Table 3 Specific definitions of variables

Variables	Definitions	Indicators	Units
CR	Carbon reduction	CO_2 emissions	Million t
APR	Air pollutant reduction	Industrial SO_2 emissions	Thousand t
ETS	The pilot carbon ETS	An indicator variable of China's pilot carbon ETS, equal to one if the region *i* implemented the pilot carbon ETS in period *t*, and zero otherwise	-
Eco	Economy	Regional GDP	Billion CNY
Pop	Population	Year-end resident population	Million people
Tec	Technology	Granted patents	Number
IS	Industrial structure	Proportion of secondary industry in GDP	%
ES	Energy structure	Proportion of primary energy	%

Table 4 Descriptive statistics of data and their detailed sources

Variables (units)	Total sample		Pilot regions		Non-pilot regions		Data sources
	Obs.	Mean	Obs.	Mean	Obs.	Mean	
CR (million t)	450	305.61	105	189.49	345	340.96	EPS database
APR (thousand t)	450	595.30	105	383.79	345	659.67	China Statistical Yearbook on Environment (2005–2019)
ETS	450	0.08	105	0.35	345	0.00	"Notice on Carrying out the Pilot Carbon Emission Trading Scheme" from the official website of the NDRC
Eco (billion CNY)	450	1641.98	105	2142.83	345	1489.55	China Statistical Yearbook (2005–2019) and Statistical Yearbook of each region (2005–2019)
Pop (million people)	450	44.70	105	41.00	345	45.83	
Tec (number)	450	30991.42	105	49,846.15	345	25,253.02	
IS (%)	450	43.53	105	41.80	345	44.06	
ES (%)	450	43.98	105	47.03	345	43.05	China Energy Statistical Yearbook (2005–2019)

Obs. stands for observations

reduction (scenario 3). The mean values of coupling coordination degree results and their trends in three different scenarios are illustrated in Table 5 and Fig. 4, respectively.

As shown in Table 5, before the proclamation of the pilot carbon ETS in 2011, the collaborative reduction level of carbon and air pollutants has a downward trend by and large. However, the coupling coordination degree becomes increasing after 2011, and the growth was even more pronounced after each pilot carbon emission trading market was gradually established in 2013. In terms of the classification in Table 2, the collaborative levels are moderate synergy in 2004 under three different scenarios, while they become slight antagonism in 2011. In 2017 and 2018, the collaborative levels rebound back to primary synergy. Figure 4 shows the trends of coupling coordination degree results in different regions. The growth rates of coupling coordination degree in the pilot regions are significantly greater than those in the non-pilot regions. In addition, scenarios 1 and 2 have better effects than scenario 3. For emphasizing the main status of carbon reduction, variable *D* in scenario 2 is set as the outcome variable in baseline regression, while that in scenarios 1 and 3 is

Table 5 Mean values of coupling coordination degree results under different scenarios

Year	Scenario 1	Scenario 2	Scenario 3
2004	0.695	0.729	0.761
2005	0.490	0.517	0.543
2006	0.480	0.510	0.538
2007	0.559	0.592	0.622
2008	0.604	0.628	0.652
2009	0.611	0.626	0.640
2010	0.544	0.550	0.556
2011	0.239	0.241	0.243
2012	0.329	0.331	0.332
2013	0.355	0.355	0.355
2014	0.394	0.391	0.388
2015	0.466	0.462	0.458
2016	0.572	0.544	0.513
2017	0.581	0.547	0.509
2018	0.473	0.445	0.413
Mean	0.493	0.498	0.502

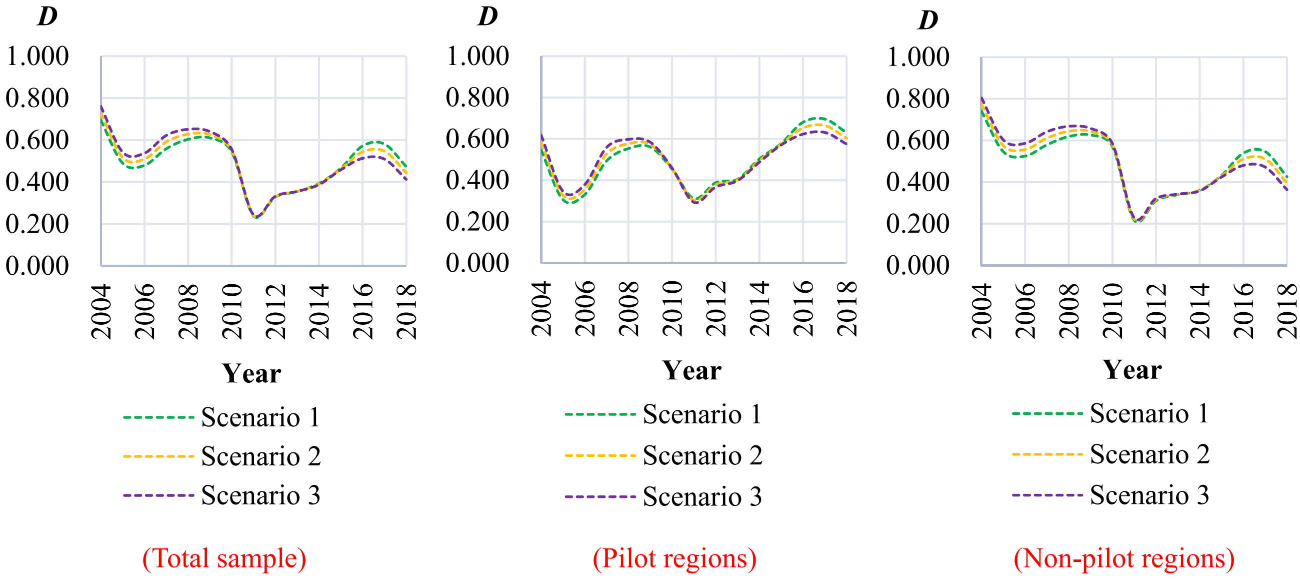


Fig. 4 Trends of coupling coordination degree results in different regions. **a** Total sample. **b** Pilot regions. **c** Non-pilot regions

used in robustness checks. Furthermore, Fig. 5 shows the spatial distribution results of variable *D* in China under scenario 2, taking 2004, 2006, 2009, 2012, 2015, and 2018 as examples. It can be seen that the collaborative reduction level of carbon and air pollutants presents a downward trend as a whole from 2004 to 2012. From 2012 to 2018, the overall collaborative reduction level rebounds upward, especially in the pilot regions of the pilot carbon ETS except for Guangdong and Fujian.

Verification of the parallel trend assumption

Using the DID model needs to meet the presumption of parallel trends in the development of the treatment and control group; otherwise, estimation bias may exist. In this regard, it is necessary to verify the parallel trend assumption in this paper to ensure significant systematic differences between the two groups before and after the implementation of the pilot carbon ETS. In this study, the time window covers 5 years that follow the implementation of the pilot carbon ETS and 12 years that precede it. The estimated coefficients can be obtained from the regression formulas (11), (12), and (13):

$$CR'_{it} = \alpha_0 + \alpha_1(d\_12)_{it} + \alpha_2(d\_11)_{it} + \cdots + \alpha_{16}(d4)_{it} + \alpha_{17}(d5)_{it} + \gamma\mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{11}$$

$$APR'_{it} = \alpha_0 + \alpha_1(d\_12)_{it} + \alpha_2(d\_11)_{it} + \cdots + \alpha_{16}(d4)_{it} + \alpha_{17}(d5)_{it} + \gamma\mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{12}$$

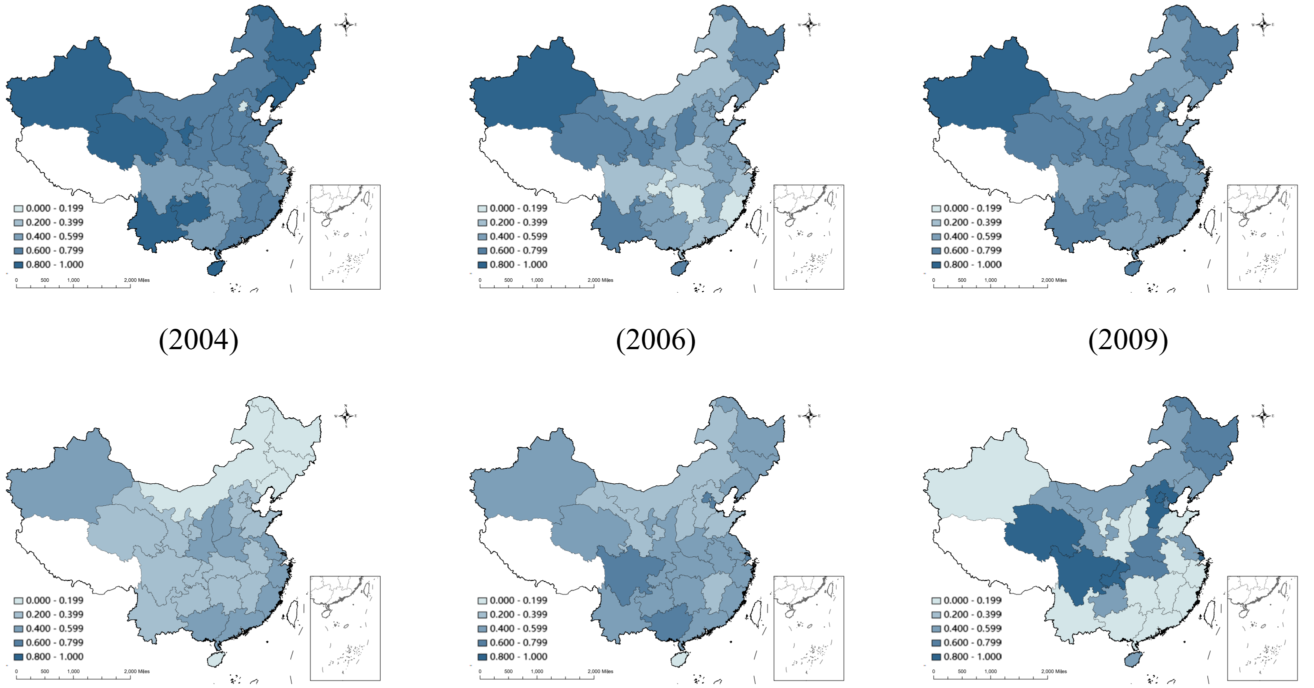
$$D_{it} = \alpha_0 + \alpha_1(d\_12)_{it} + \alpha_2(d\_11)_{it} + \cdots + \alpha_{16}(d4)_{it} + \alpha_{17}(d5)_{it} + \gamma\mathbf{X}_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{13}$$

where $(d\_m)_{it}$'s and $(dm)_{it}$'s are dummy variables, $(d\_m)_{it}=1$ if period *t* for the region *i* is the *m*th period prior to the implementation of the pilot carbon ETS and zero otherwise, and $(dm)_{it}=1$ if period *t* for the region *i* is the *m*th period following the implementation of the pilot carbon ETS and zero otherwise; $\mathbf{X}_{it}$ is the vector of control variables in model (8).

The test results of the parallel trend are presented in Fig. 6. For ease of reading, only the results within the previous 7 years and the following 5 years of the pilot carbon ETS are shown. In these three models, the coefficients of dummy variables have no significant deviation from zero in the periods prior to the implementation of the pilot carbon ETS, meaning that the parallel trend assumption cannot be rejected. In the periods following the implementation of the pilot carbon ETS, a significant positive deviation from zero exists in the coefficients of dummy variables, indicating that the pilot carbon ETS supports the improvement of *CR*′, *APR*′, and *D*.

Regression results and analysis

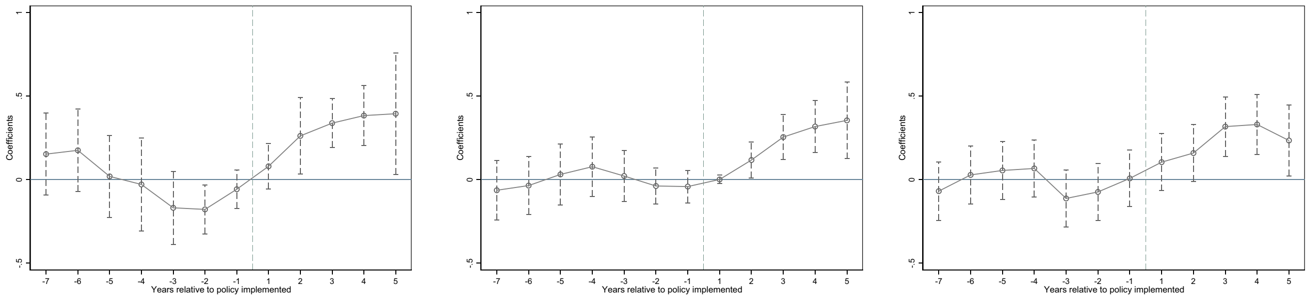
The impacts of the implementation of the pilot carbon ETS on *CR*′, *APR*′, and *D* in China are examined by the



(2004) (2006) (2009)

(2012) (2015) (2018)

Fig. 5 Spatial distribution results of *D* under scenario 2 in China. **a** 2004. **b** 2006. **c** 2009. **d** 2012. **e** 2015. **f** 2018



(CR') (APR') (D)

Fig. 6 Results of parallel trend tests. **a** CR'. **b** APR'. **c** D

DID method in this study. Based on the DID models constructed in the previous section, the baseline regressions are conducted and their results are reported in Table 6. It should be noted in particular that the outcome variables CR' and APR' used in this paper are from the variables CR and APR processed by Eq. (3), and the processed outcome variables CR' and APR' are positive indicators.

As shown in Table 6, the results of the impacts on CR' are shown in columns (1) and (2), the impacts on APR' are shown in columns (3) and (4), and the impacts on D are shown in columns (5) and (6). Compared with columns (1), (3), and (5), we found that the R^2 in columns (2), (4), and (6) have improved because of the addition of control variables, indicating the regression effects after adding control variables is better. The baseline regression results show that, under the addition of control variables, region fixed effects, and period fixed effects, the coefficient of variable ETS impacting on CR' is significantly positive at the 5% significance level (0.247), on APR' is significantly positive at the 5% significance level (0.101), and on D is significantly

Table 6 Baseline regression results

Variables	*CR′*		*APR′*		*D*	
	(1)	(2)	(3)	(4)	(5)	(6)
ETS	0.222^{**} (0.108)	0.247^{**} (0.104)	0.136^{***} (0.045)	0.101^{**} (0.046)	0.217^{***} (0.065)	0.220^{***} (0.069)
Control variables	No	Yes	No	Yes	No	Yes
Region fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	450	450	450	450	450	450
R^2	0.8024	0.8050	0.7929	0.8203	0.4406	0.4558

Robust standard errors are in parentheses. Significance levels are $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

positive at the 1% significance level (0.220). The results mean that implementing China's pilot carbon ETS not only produces significantly positive impacts on reducing carbon and air pollutants, respectively, but also produces significantly positive impacts on the collaborative reduction of carbon and air pollutants. These results also have corresponding economic meanings. Specifically, the implementation of China's pilot carbon ETS produces growth of roughly 24.7% in *CR′*, roughly 10.1% in *APR′*, and roughly 22.0% in *D*, ceteris paribus. The lag window in this paper is 5 years, and thus the average annual growth effects of the pilot carbon ETS are roughly 4.94% in *CR′*, roughly 2.02% in *APR′*, and roughly 4.40% in *D*, ceteris paribus. To sum up, these results basically support Hypotheses 1, 2, and 3 and provide direct evidence that the implementation of the pilot carbon ETS makes an outstanding contribution to achieving the collaborative reduction of carbon and air pollutants in China. The results of the baseline regressions in this paper are similar to those of Dong et al. (2022), while they are somewhat different from those of Kou et al. (2022). Kou et al. (2022) concluded that the effect of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants has different effects in different regions, indicating that a further economic regional heterogeneity analysis is necessary.

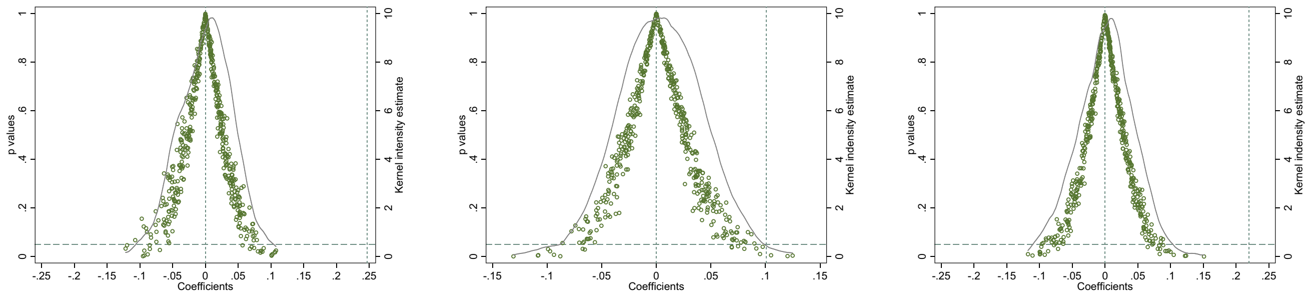
Robustness checks

In this part, some necessary robustness checks are conducted to avoid estimation bias. First, a placebo test is exerted to check whether the effects of omitted or unobserved factors exist. The estimated coefficients $\hat{\alpha}_1$ of *ETS* can be expressed as Eq. (14):

$$\hat{\alpha}_1 = \alpha_1 + \delta \frac{\mathrm{cov}(ETS_{it}, \varepsilon_{it}|\mathbf{X}_{it})}{\mathrm{var}(ETS_{it}|\mathbf{X}_{it})} \tag{14}$$

where δ is a parameter indicating the estimated bias. If $\delta = 0$, the estimation of $\hat{\alpha}_1$ is unbiased and biased otherwise. For testing the parameter δ equal zero or not, the impacts on a specific region produced by the pilot carbon ETS are randomized by computer, and this random process is replicated 500 times. If the $\hat{\alpha}_1$ is estimated to be zero, the δ can be treated as zero.

The distribution results of estimates and their *p* values in the randomization test are shown in Fig. 7. The mean values produced by a random process are close to zero compared with the benchmark regression results and not significant. Thus, the improvements in *CR′*, *APR′*, and *D* are unlikely to be caused by omitted or unobserved factors, inferring that the DID regression results above are robust.



(*CR′*) (*APR′*) (*D*)

Fig. 7 Results of placebo tests. **a** *CR′*. **b** *APR′*. **c** *D*

Second, some other robustness regressions are carried out. The selection of the pilot regions listed in the pilot carbon ETS is not completely random, which may be the most significant endogenous problem in this study. Other factors determining China's pilot carbon ETS regions list include economic development, resource endowment, social environment, openness, and geographical location. Therefore, the propensity score matching (PSM) strategy is employed in this paper, as articulated by Rosenbaum and Rubin (1983), to reduce these potential selection biases. The PSM-DID results are reported in columns (1) to (3) of Table 7; the data prior to the implementation of the pilot carbon ETS are used to exert a DID regression in this part for checking the existence of the policy outcomes further. If the regression coefficients are not significant, proving that there are no significant differences between the treatment and control group before the implementation of the pilot carbon ETS. By advancing the impact periods of the pilot carbon ETS by 3 years (advancing to the period before the pilot carbon ETS was proclaimed), we conduct some robustness DID regressions. The results of impact periods advance are reported in columns (4) to (6) of Table 7; the outcome variable *D* in scenario 2 is replaced by that in scenarios 1 and 3 to further check the robustness of baseline regression results under different scenarios. The results of outcome variable replacement are reported in columns (7) and (8) of Table 7. In Table 7, the coefficients of *ETS* in columns (1) to (3) are significantly positive, in columns (4) to (6) are not significant, and in columns (7) and (8) are significantly positive. The results indicate that the estimations in this paper are reliable and robust.

Economic regional heterogeneity

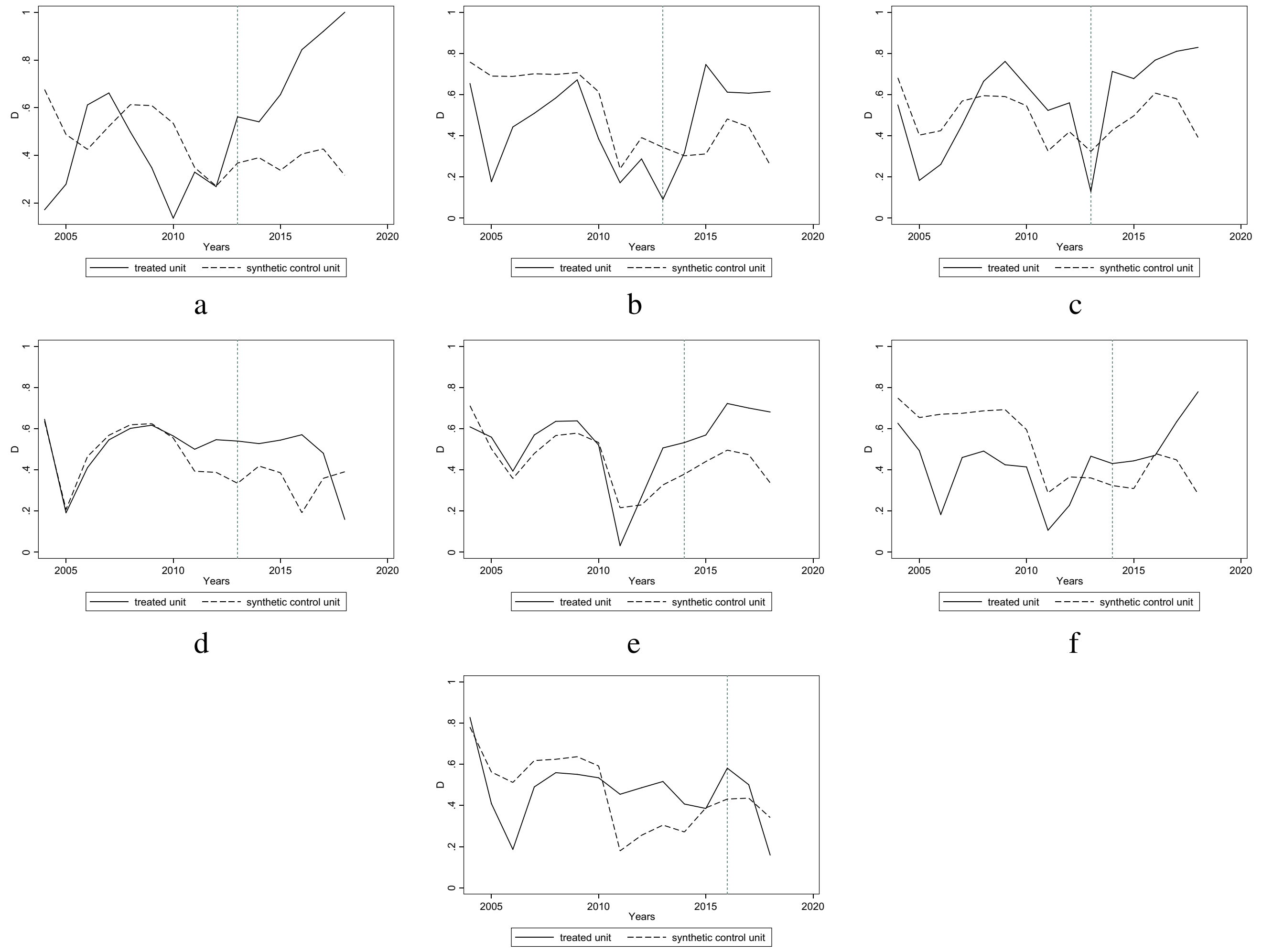
China is a vast country with unequal regional economic development. China's economic development presents a situation of "high in the east and low in the west" (Kou et al. 2022; Shi and Xu 2022). Specific differences are shown in that the eastern region has obvious advantages in terms of economic size, infrastructure, labor quality, transportation conditions, and innovation level, while the central and western regions have fragile environmental resources and relatively backward production technology, and their economic growth mainly depends on resource-intensive and labor-intensive industries (Cheng et al. 2018; Nie et al. 2021). It can be inferred that an economic regional heterogeneity may exist in impacting the collaborative reduction of carbon and air pollutants. Therefore, referring to the division of China's economic regions by the National Bureau of Statistics of China (NBSC) (Fig. 8) and the method in the study made by Shi and Xu (2022), economic regional heterogeneity regressions are performed. Three dummy variables, $East_{it}$, $Center_{it}$, and $West_{it}$, are introduced into the baseline model to examine regional heterogeneity effects caused by the pilot carbon ETS. The dummy variable $East_{it}$ equals 1 if the city *i* is in the eastern region and zero otherwise. Similarly, the dummy variable $Center_{it}$ equals 1 if the city *i* is in the central region and zero otherwise; the dummy variable $West_{it}$ equals 1 if the city *i* is in the western region and zero otherwise. The regional heterogeneity regression results are shown in Table 8.

In Table 8, the regression result with CR' as the outcome variable is shown in column (1), the regression result with APR' as the outcome variable is shown in column (2), and the regression result with *D* as the outcome variable is shown in column (3). The coefficients of each interaction term are significantly positive (0.273, 0.210, and 0.179) in column (1), meaning that the impacts of the pilot carbon ETS on reducing carbon are significant in all regions, and the pilot carbon ETS produces around 27.3%, 21.0%, and 17.9% impacts on CR', respectively,

Table 7 Robustness regression results

Variables	PSM-DID			Impact periods advance			Outcome variable replacement	
	CR'	APR'	D	CR'	APR'	D	D (scenario 1)	D (scenario 3)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ETS	0.245^{**} (0.105)	0.091^{*} (0.047)	0.210^{***} (0.070)	0.161 (0.104)	0.071 (0.067)	0.095 (0.058)	0.212^{***} (0.064)	0.228^{***} (0.074)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Period fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	439	439	439	450	450	450	450	450
R^2	0.7946	0.8207	0.4756	0.7928	0.8289	0.4739	0.4336	0.4834

Robust standard errors are in parentheses. Significance levels are $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$



a

b

c

d

e

f

g

Fig. 8 Division of China's economic regions

Table 8 Economic regional heterogeneity regression results

Variables	CR' (1)	APR' (2)	D (3)
$ETS \times East$	0.273^{*} (0.150)	0.119^{*} (0.059)	0.216^{**} (0.099)
$ETS \times Center$	0.210^{***} (0.038)	0.007 (0.046)	0.203^{***} (0.056)
$ETS \times West$	0.179^{***} (0.032)	0.130^{***} (0.031)	0.255^{***} (0.028)
Control variables	Yes	Yes	Yes
Region fixed effects	Yes	Yes	Yes
Period fixed effects	Yes	Yes	Yes
Observations	450	450	450
R^2	0.8057	0.8211	0.4561

Robust standard errors are in parentheses. Significance levels are $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.1$

ceteris paribus. The lag window is 5 years, and thus the average annual effects on CR' are around 5.46%, 4.20%, and 3.58%, respectively, ceteris paribus; the coefficients of $ETS \times East$ and $ETS \times West$ are significantly positive (0.119 and 0.130) in column (2), indicating that the impacts of the pilot carbon ETS on reducing air pollutants are significant in eastern and western regions, and the pilot carbon ETS produces about 11.9% and 13.0% impacts on APR', respectively, ceteris paribus. The lag window is 5 years, and thus the average annual effects on APR' are around 2.38% and 2.60%, respectively, ceteris paribus; The coefficients of each interaction term are significantly positive (0.216, 0.203, and 0.255) in column (3), showing that the impacts of the pilot carbon ETS on achieving the collaborative reduction of carbon and air pollutants are significant in all regions, and the pilot carbon ETS produces around 21.6%, 20.3%, and 25.5% impacts on D, respectively, ceteris paribus. The lag window is 5 years, and thus the average annual effects on *D* are around 4.32%, 4.06%, and 5.10%, respectively, ceteris paribus. Based on the results of economic regional heterogeneity analysis, it can be seen that in the eastern, central, and western regions of China, the carbon reduction effects and the collaborative reduction effects of carbon and air pollutants from the implementation of the pilot carbon ETS are significant. The effect of the pilot carbon ETS on reducing air pollutants only in the central region is not significant. The possible reason is that the economic development in the central region is inferior to those in the eastern region, and also lacks additional policy support in pollution reduction like those in the western region. The results of this study are different from those of Kou et al. (2022). The reason for the difference may be that the results of the regional economic heterogeneity regressions in this paper are average effects. Therefore, this paper will use the SCM for further analysis of each pilot region to decompose the average effect of the DID model in multiple regions.

A further analysis based on synthetic control method

To further decompose the average effect of collaboratively reducing carbon and air pollutants obtained from the DID model, this paper conducts a further analysis for each pilot region based on the SCM. The SCM is proposed by Abadie and Gardeazabal (2003), which can not only evaluate the effect of each pilot but also overcome some inherent deviations between the treatment group and the control group in the DID method to a certain extent. The SCM takes the entities not impacted by the pilot carbon ETS as the synthetic entity, determines the weight of each synthetic entity in a data-driven way, and then constructs a control group that is similar to the treatment group through the approach of weighting. The construction of SCM in this paper is as follows.

First, assume that for $K+1$ regions and T time periods, the data of outcome variable D can be used to predict the effect of the pilot carbon ETS on collaboratively reducing carbon and air pollutants in China. Let the $(K+1)$th region be the only one that has been intervened by the pilot carbon ETS in period T_0+1, meaning that there are T_0 pre-intervention periods, and $T_0 \in [1, T)$. The remaining K regions do not be intervened by the pilot carbon ETS during the impacting period. Second, let Y_{kt} be the value of the outcome variable D in region k ($k=1, 2, \cdots, K, K+1$) at time t ($t=1, 2, \cdots, T_0, T_0+1, \cdots, T$), Y^I_{kt} be the value of Y_{kt} when region k is exposed to the intervention of the pilot carbon ETS, and Y^N_{kt} be the value of Y_{kt} when the intervention is absence, implying that $Y_{kt} = \begin{cases} Y^I_{kt}, k = K+1 \text{ and } t > T_0 \\ Y^N_{kt}, \text{ otherwise} \end{cases}$. Third, referring to the work of Abadie et al. (2010), the effect of the pilot carbon ETS can be estimated by formula (15):

$$\alpha_{K+1,t} = Y^I_{K+1,t} - Y^N_{K+1,t} = Y_{K+1,t} - Y^N_{K+1,t} = Y_{K+1,t} - \sum_{k=1}^{K} w^*_k Y_{kt} \tag{15}$$

where w^*_k is a time-invariant weight assigned to the region k, $w^*_k \geq 0$, and $\sum_{k=1}^{K} w^*_k = 1$. The aim of SCM is to find the weights that can replicate its behavior during the pre-intervention period most closely by generating a synthetic control combination for a given treatment region. The optimal weights w^*_k can be obtained in two steps. The first step is to find the vector $\mathbf{W}^* = (w^*_1, \cdots .w^*_K)^{\mathrm{T}}$ that minimizes function (16):

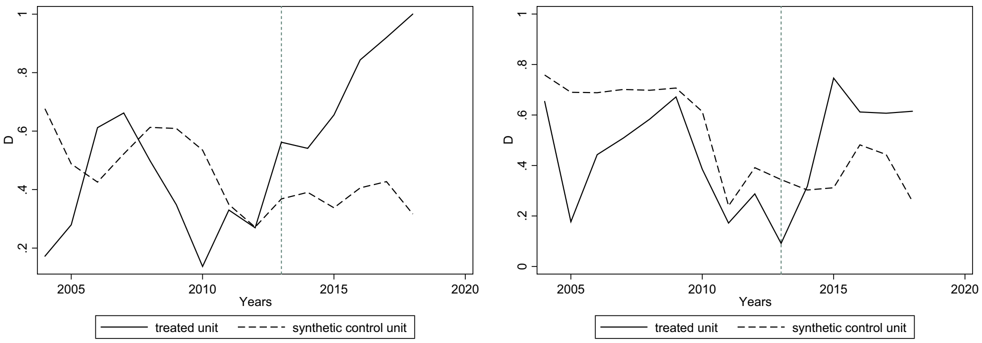
$$\left(\mathbf{X}_1 - \mathbf{X}_0\mathbf{W}\right)^{\mathrm{T}}\mathbf{V}(\mathbf{X}_1 - \mathbf{X}_0\mathbf{W}) \tag{16}$$

where $\mathbf{X}_1$ is an $(M \times 1)$ vector of the pre-intervention values of predictors for the treatment region; $\mathbf{X}_0$ is a $(M \times K)$ matrix containing the values of the same predictors for the K possible control regions; K is the number of predictors for the outcome variable D; $\mathbf{V}$ is a $(K \times K)$ diagonal matrix containing non-negative components. The second step is to select the $\mathbf{V}^*$ that minimizes the deviation of the outcome variable path of the synthetic control combination defined by $\mathbf{W}^*(\mathbf{V})$ from the counterpart of the treatment region during the pre-intervention period. The $\mathbf{V}^*$ can be obtained by formula (17):

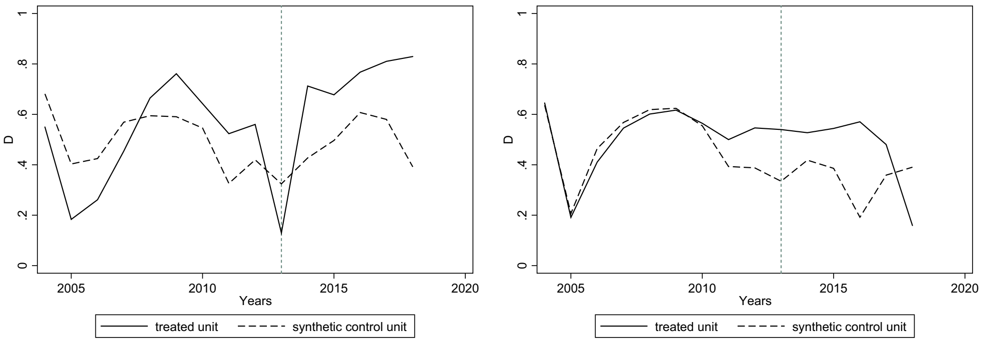
$$\mathbf{V}^* = \underset{V \in \nu}{\arg\min} [Y_1 - Y_0 W^*(V)]^{\mathrm{T}} [Y_1 - Y_0 W^*(V)] \tag{17}$$

where $\mathbf{Y}_1$ is a $(T_0 \times 1)$ vector containing the values of the outcome variable D during the pre-intervention period for the treatment region; $\mathbf{Y}_0$ is a $(T_0 \times K)$ matrix containing the values of the same variable D for the synthetic control combination.

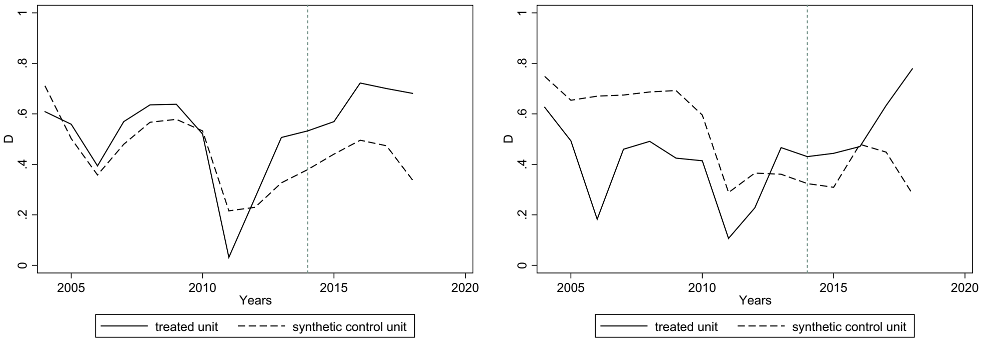
Based on the SCM above, the impact of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants is further examined. The evaluation results during 2004–2018 are shown in Fig. 9. In Fig. 9, the dotted line is the evolution path of the regions synthesized by SCM, the solid line is the evolution path of the pilot regions, and the vertical dotted line is the impact period of the pilot carbon ETS. From Fig. 9, the pilot carbon ETS in different regions has different effects on collaboratively reducing carbon and air pollutants. For Beijing, Tianjin, Shanghai, Hubei, and Chongqing, the collaborative reduction levels of the pilot regions and the synthetic control regions during the pre-intervention period are much similar, while during the post-intervention period are significantly deviated. The deviations indicate that the collaborative reduction levels in these regions are higher than in other non-pilot regions, implying that the impact of the pilot carbon ETS is efficient. Moreover, the effect size of the pilot carbon ETS can



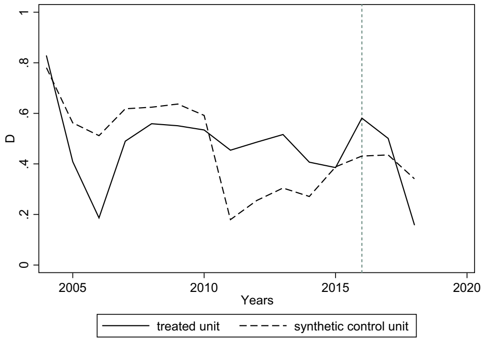
(Beijing) (Tianjin)



(Shanghai) (Guangdong)



(Hubei) (Chongqing)



(Fujian)

Fig. 9 Evaluation results based on SCM. **a** Beijing. **b** Tianjin. **c** Shanghai. **d** Guangdong. **e** Hubei. **f** Chongqing. **g** Fujian be measured using the difference of outcome variable D between the treatment regions and synthetic control regions. Therefore, the deviations in these areas also show gradually expanding trends, which means that the pilot carbon ETS in these regions is continuously playing its role. Specifically, the effect of the pilot carbon ETS is the most significant in Beijing, and the long-term effect in Chongqing is better than the short-term effect.

However, the pilot carbon ETS in Guangdong and Fujian have not produced satisfactory effects, which is consistent with the results of the spatial distribution analysis mentioned above (Fig. 5). For Guangdong, the deviation in Guangdong first occurred around 2011, which may benefit from the first batch of pilot low carbon city program. The deviation in Guangdong increased slightly after 2013, indicating that the pilot carbon ETS worked. Subsequently, the deviation in Guangdong begins to decrease after 2017, meaning that the effect of the pilot carbon ETS in Guangdong on the collaborative reduction of carbon and air pollutants is diminishing. For Fujian, the reason for the unsatisfactory effect in Fujian includes the following: first, the local government may have insufficient experience in implementing relevant policies due to the late implementation of the pilot carbon ETS; second, the implementation date of the pilot carbon ETS in Fujian is December 22, 2016 (Table 1). Given the lag effect of the policy, it is likely that the policy effect will gradually emerge after 2018. This limitation needs to be considered in future research; third, the CO_2 quotas of the pilot carbon ETS in Fujian were not declared (Table 1). Untimely and unclear public disclosure may have a negative impact on the effect of the pilot carbon ETS implementation. Overall, the effect of the pilot carbon ETS on the collaborative reduction of carbon and air pollutants is notable, and the conclusions drawn from the statistical analysis, DID method, and regional heterogeneity analysis have been further verified.

Conclusions and policy implications

In recent years, the reduction of carbon and air pollutants has made an important contribution to combating environmental problems in China. Using the CCD model, DID model, and SCM, the panel data of 30 provincial-level regions in China during 2004–2018 are used in this study to evaluate the impact of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants. Some conclusions are drawn as follows. First, attaching importance to reducing air pollution can improve the collaborative reduction effect of carbon and air pollutants; second, the implementation of China's pilot carbon ETS produces an effect of roughly 24.7% on reducing carbon, roughly 10.1% on reducing air pollutants, and roughly 22.0% on the collaborative reduction of carbon and air pollutants, ceteris paribus; third, the impacts of the pilot carbon ETS are significant in all regions, except that the impact on reducing air pollutants in the central region is not significant; fourth, the impacts of the pilot carbon ETS on the collaborative reduction of carbon and air pollutants are significantly efficient in Beijing, Tianjin, Shanghai, Hubei, and Chongqing while not much efficient in Guangdong and Fujian. The conclusions show that it is feasible for environmental policies to promote the collaborative reduction of carbon and air pollutants. Further studies on the collaborative reduction effect of carbon and air pollution based on individual cases may reveal new findings.

The findings in this paper clarify China's collaborative reduction level of carbon and air pollutants and its economic regional differences and provide essential evidence for further developing the pilot carbon ETS and achieving the collaborative reduction of carbon and air pollutants. Our findings have clear policy implications. First, considering that the pilot carbon ETS is conducive to collaboratively reducing carbon and air pollutants, Chinese policymakers should continue the implementation of the pilot carbon ETS, expand the pilot of the pilot carbon ETS, double the scope of the pilot at least within 3 years, and strengthen top-level design to ensure the effectiveness of the pilot carbon ETS. Compared with developed economies, there is greater pressure on reducing carbon and air pollutants in developing economies all over the world at the current stage. Therefore, other developing economies also should implement the pilot carbon ETS as soon as possible, construct the supporting facilities of the pilot carbon ETS, and promote the application and innovation of green technologies. Local government should improve the supervision level in the process of implementing the pilot carbon ETS and provide some rational guidance and financial subsidies for the applicable industries, so as to ensure the feasibility of the pilot carbon ETS; second, considering that attaching importance to reducing air pollution can improve the collaborative reduction effect of carbon and air pollutants, the government should establish and improve the management system of the collaborative control of air pollutants and greenhouse gas emissions as soon as possible, accelerate the integration of laws and regulations in climate governance and ecological environmental protection, and establish a special research department for the collaborative reduction of carbon and air pollutants to provide timely and effective decision-making supports; third, the results of the regional heterogeneity analysis in this paper suggest that there are some regional differences in the effect of China's pilot carbon ETS. For China, the government of the central region should clarify the specific policy differences with other regions, including applicable industries, regulatory means, and CO_2 quota, and strengthen the control of air pollutants. Policymakers in Guangdong and Fujian should actively adjust specific policies to ensure the continuous effectiveness of the pilot carbon ETS. For any economy, there may be a crowding-out effect between regions in the emission of carbon and air pollutants based on the "pollution haven" hypothesis. Therefore, policymakers should take into account the impact of carbon and air pollutant emissions on other regions and strengthen interregional cooperation, which is crucial for achieving the global goal of carbon and pollution reduction; fourth, for these pilot regions, local policymakers, especially in developing economies, should strengthen the role of market forces in improving energy efficiency, insist on reducing carbon and air pollutant emissions from the source, and balance reduction goals between carbon emissions and air pollutant emissions. In addition, it is necessary to encourage the enterprises in the pilot regions to become green innovators, optimize the industrial structure in the pilot regions, and promote the application balance of the pilot carbon ETS among industries, so as to construct a resource-saving and environment-friendly society.

This study has examined the effect of China's pilot carbon ETS on the collaborative reduction of carbon and air pollutants, and it still has some limitations. First, the long-term effect of some regions cannot be examined in this study due to data limitations; second, this paper lacks detailed mechanism analysis due to the limited space of this paper. Future research also can focus on evaluating the effect of China's pilot carbon ETS from different perspectives and continue to focus on how China can achieve the goal of carbon neutrality and air pollution reduction.

Author contribution Xiuyi Shi: writing—original draft, conceptualization, methodology, data curation, software, visualization, validation, funding acquisition; Yingzhi Xu: resources, project administration, funding acquisition, writing – review and editing, supervision; Wenyuan Sun: funding acquisition, supervision.

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Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

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