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Effect of the carbon emissions trading policy on the co-benefits of carbon emissions reduction and air pollution control

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ABSTRACT

Achieving the co-benefits of carbon emissions reduction and air pollution control is significant for pursuing a sustainable and low-carbon economy in China. This study applies the difference-in-differences method to explore the local and spillover impact of the carbon emissions trading policy (2011) on China's carbon emissions and air quality, based on city-level data. The results show that the carbon emissions trading policy significantly affects the co-benefits of the total carbon emissions reduction and air quality improvement. In addition to this direct effect, the carbon emissions trading policy could indirectly affect carbon emissions and air quality by changing the innovation ability of cities and location choice of local industries. Though the policy does not significantly affect the overall carbon emissions intensity in China, it is seen to be effective for Central China. Our further spatial analysis indicates that the policy increases the carbon emissions in neighboring cities, which supports the "pollution haven hypothesis." Thus, this study contributes to the existing climate policy literature and provides a more comprehensive picture of the policy effect by integrating the co-benefits of the carbon emissions reduction and air pollution control, estimating both local and spillover effects and exploring the underlying mechanisms.

1. Introduction

The effectiveness of climate policies and environmental regulations has received much global attention in recent decades, considering that climate change and environmental degradation are critical problems that threaten humankind. China, which has the second-largest economy in the world, has witnessed tremendous economic growth over the recent decades. However, many environmental concerns have accompanied this economic achievement; for example, the increasing greenhouse gas (GHG) emissions caused by the excessive use of fossil fuels (Chen and Chen, 2015; Fang et al., 2019; Liu et al., 2012; Xia et al., 2020; Zhang et al., 2019; Zhou et al., 2010). Not only do GHG emissions lead to climate change, but they also exert a negative effect on air quality (Bain et al., 2016; Thompson et al., 2014; West et al., 2013). Thus, the climate crisis and deteriorating air quality alongside people's increasing desire for a more sustainable society have necessitated the Chinese government to enact more climate and environmental policies that discourage the use of fossil fuels and reduce carbon emissions (Dong et al., 2020; Fang et al., 2019; Wang and Jiang, 2019; Wang et al., 2019).

In the beginning, command-and-control environmental policies were widely adopted; for example, binding environmental standard targets, punishments for pollutant emissions, and so on. In recent years, market-based policies have been introduced and have become increasingly popular in the policy framework to tackle energy consumption and carbon emissions. Unlike the command-and-control policies that set strict standards and ignore the compliance costs of control, market-based policies create economic incentives for abating emissions and allocating resources more efficiently. Therefore, market-based policies are believed to be more effective in achieving minimum cost of compliance and alleviating information asymmetry (Blackman et al., 2018; Newell and Stavins, 2003). Among the various policies, the carbon emissions trading policy is particularly important. In 2011, the central government implemented a national emissions trading scheme in some pilot areas to discourage carbon emissions and consequently alleviate global warming and climate change in a more cost-effective manner (Zhang and Hao, 2017).

However, the effectiveness of these environmental or climate policies has been debated by many scholars in terms of their potential costs. Besides their harmful effects on productivity (Cao et al., 2021; Cole, 2004; Zhang and Zhang, 2020), the policy's impacts on the environment and climate remain inconclusive. For example, the "pollution haven hypothesis" asserts that higher environmental standards induce

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energy-intensive firms to relocate to areas that have lower standards. Therefore, the carbon emissions reduction in one area will be at the cost of an increase in another area, leading to a failed reduction of energy intensity overall. In addition, the "green paradox" literature asserts that since market participants anticipate stricter regulations in the future, once a climate policy is introduced, they are likely to speed up their use of fossil fuels (Sinn, 2009). Meanwhile, another strand of literature argues that these policy interventions can benefit productivity by encouraging technologies and innovations (Dechezleprêtre and Glachant, 2014; Porter and Van der Linde, 1995; Popp and Newell, 2012; Ricci, 2007).

The carbon emissions trading policy literature has explored many topics; for example, the negative effect of the policy on carbon emissions and carbon intensity (Yan et al., 2020). Meanwhile, scholars have also discussed the economic effects of the policy on employment (Yu and Li, 2021), green production (Huang and Du., 2020; Yang et al., 2021), the stock market (Wen et al., 2020), low carbon energy investment (Mo et al., 2016), total factor productivity (Xiao et al., 2021), and so on. In addition to the policy's effect on the economy and the environment, Cao et al. (2021) further analyze how the policy could affect health by reducing carbon emissions. However, due to data limitations, most of the related studies exploring the effect of the carbon emissions trading policy have utilized provincial-level data, which cannot control for city-specific factors.

The co-benefits of air pollution abatement and GHG emissions reduction are related to the consumption of fossil fuels. Since the reduction of GHG emissions can lessen SO_2, NO_x, $PM_{2.5}$, and O_3 emissions, it can consequently contribute to an improvement in air quality (Bain et al., 2016; Thompson et al., 2014; West et al., 2013). Several studies have also proven that reducing the level of air pollutants would be beneficial for climate change mediation (Kim et al., 2020; Xie et al., 2018; Yang et al., 2018). However, there is relatively little research on the issue of how the carbon emissions trading policy is related to air quality. Its importance is evident, since the co-benefits of air pollution and GHG emissions are critical for sustainable development. A recent study conducted by Yan et al. (2020) analyzed the effect of the emissions trading system on air pollution by focusing on the policy effect in a local area. However, considering the "pollution haven hypothesis" and the effect of airflow on some particulate matter, the carbon emissions trading policy could also affect the neighboring regions. Nevertheless, these effects remain underexplored.

Accordingly, the current study applies the difference-in-differences (DID) method to explore how the carbon emissions trading policy issued in 2011 affects the carbon emissions and air pollution in China, based on city-level data. The result shows that the carbon emissions trading policy has a significant effect on the total carbon emissions reduction and improvement of air quality. Though the policy does not exert a significant impact on the overall carbon emissions intensity, it is effective in reducing the carbon emissions intensity in cities in Central China. In addition to this direct effect, this study's analysis of the underlying mechanisms reveals that the carbon emissions trading policy could indirectly affect both the carbon emissions and air quality by improving the innovation capacity of cities and the location choice of firms. A spatial analysis further proves that the carbon emissions trading policy has a positive externality on neighboring cities' carbon emissions.

This study contributes to the existing literature as follows. First, unlike previous studies, it integrates air pollution and carbon emissions into one framework to examine whether the carbon emissions trading policy is beneficial for the co-benefits of air pollution control and climate change mitigation. In addition, by combining the "Porter hypothesis" and the "pollution haven hypothesis," this study attempts to examine the mechanism through which the carbon emissions trading policy comes into effect, which, despite its significance in the climate policy realm, has not been empirically explored sufficiently. Understanding the underlying mechanisms is also beneficial to explore to the scope for improving the efficiency of the policy.

Second, in addition to the traditional DID method that has been widely used to examine the effect of policy, this study further employs spatial analysis to examine the spillover effects of the carbon emissions trading policy on the neighboring cities; thus, it moves beyond the previous literature that has focused on local policy effects by providing a more comprehensive picture about the effect of the emission trading policy and shedding light on a more efficient and collaborative policy system design.

Third, in contrast to most of the related studies based on provincial-level data or simulation analysis, this study focuses on the carbon emissions at the city-level. Considering that prefecture-level cities are a vital part of China's local government apparatus, our city-level analysis provides a good balance between an appropriate unit of study and a stable boundary for heterogeneity analysis over time.

The remainder of this paper is organized as follows. Section 2 introduces the data and model specification. Section 3 presents and discusses the empirical results, and Section 4 provides the conclusion and policy implications.

2. Method

2.1. Data and variable definitions

2.1.1. Carbon emissions

Our independent carbon emissions-related variables include total carbon emissions and carbon emissions intensity (total carbon emissions/GDP) in an attempt to explore the heterogeneous effects of the carbon emissions trading policy on carbon emissions from various perspectives. The carbon emissions data were from Chen et al. (2020).

2.1.2. Air quality

Ambient fine particulate matter ($PM_{2.5}$) was used to measure air quality. Since 2013, China has initiated a nationwide air quality monitoring and disclosure program that requires cities to monitor and report the levels of $PM_{2.5}$. However, the data are only available after 2013. Therefore, the city-level $PM_{2.5}$ data applied in this study are derived from the "Global Annual $PM_{2.5}$ Grids from MODIS, MISR, and SeaWiFS Aerosol Optical Depth (AOD) with GWR."[1] The original data are based on AOD retrievals from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS), Multi-Angle Imaging Spectro Radiometer (MISR), and the Sea-Viewing Wide Field-of-View Sensor (SeaWiFS), and have been widely used in the literature (e.g., Anenberg et al., 2017; Heft-Neal et al., 2018). Van Donkelaar et al.'s (2016) study provides a detailed description of the methodology.

2.1.3. Carbon emissions trading policy

In October 2011, the National Development and Reform Commission issued the "Notice on Carrying out Pilot Carbon Emissions Trading" and approved Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen as pilot areas to prepare carbon emissions trade work. These areas were allocated carbon emissions allowances/permits according to each firm's output, with specific benchmarks for fuel and technology. Following Chen et al. (2021), we defined the policy-shock dummy variable *Post* as equaling one after 2012 and zero before 2012.

Considering the time taken to conduct the preparation work, there are different starting times for each carbon trading pilot area. Shenzhen initiated trading in June 2013; Shanghai and Beijing followed in November 2013; and Chongqing, Guangdong, Hubei, and Tianjin started by June 2014. Therefore, in our robustness check, we further defined *Post2* as equaling one after 2014 and zero before 2014 (Yu et al., 2021).

[1] Van Donkelaar et al., 2016. Global Annual $PM_{2.5}$ Grids from MODIS, MISR and SeaWiFS Aerosol Optical Depth (AOD) with GWR, 1998–2016. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4ZK5DQS. Accessed DAY MONTH YEAR.

We defined the dummy variable *Treat* as equaling one if a city belonged to a pilot area and zero if otherwise to distinguish the treated and control groups in the DID regression model.

2.2. Control variables

Scholars have discussed the other factors that affect carbon emissions from multiple perspectives. For example, population is an essential factor that affects carbon emissions (Fan et al., 2021) and air quality (Song et al., 2022) and further contributes to a city's aggregated carbon emissions. Thus, we added a city's total population (*Population*) as a control variable.

Different industries have varying contributions toward carbon emissions and air pollutants (Li et al., 2021; Zhang et al., 2014; Zhang et al., 2022a). For example, Xiao et al. (2019) find that the service industry produces fewer carbon emissions than the secondary industry. Thus, we applied the ratio of the second industry's employers to the total number of employers as the proxy for industrial structure (*Ind*).

Considering the critical role of economic development in carbon emissions (Al-Mulali et al., 2015; Zaman and Abd-el Moemen, 2017) and air quality (Brajer et al., 2011), we used the *GDP* and its squared term to control for the effect of economic development. Except for the industrial structure, all controls were from the city statistical yearbook and were taken in the logarithm form. After considering the overlap of the three main data sources, this study's period of analysis was 2008–2016. Table 1 shows the variable definitions and summary statistics.

Fig. 1 shows the geographical distribution of the average carbon emissions of Chinese cities in 2006, 2008, 2011, and 2015. The carbon emissions decrease from the East to West areas and from the North to South areas. The cities with the highest carbon emissions level are mainly concentrated in northern China. Generally, we can see that the pilot cities are located in areas that have higher carbon emissions.

2.3. Model specification

We applied a DID model to estimate the causal effect of the carbon emissions trading policy on carbon emissions, carbon emissions intensity, and air quality. This method is widely applied in the studies estimating the casual effect of policies or events (For example, ; Jia et al., 2021). By comparing the difference between the non-pilot areas and the pilot areas both before and after the policy's implementation, we can eliminate the difference between the different areas before the policy's implementation and then the causal effect of the policy.

The baseline model specification is as follows:

$$Y_{\mathrm{it}} = \beta_0 + \beta_1 * \mathrm{Post_t} * T\mathrm{reat_i} + \alpha * X_{\mathrm{it}} + \mathrm{City\ \ FE} + \mathrm{Year\ \ FE} + \varepsilon_{\mathrm{it}} \tag{1}$$

where t indexes the year and i indexes the city. Y_{it} is the carbon emissions-related variables (total carbon emissions, carbon emissions intensity, and $PM_{2.5}$) of city i in year t. $Post_t$ equals one for every year after the policy. $Treat_i$ is a dummy variable that equals one if a city belongs to a pilot area and zero otherwise. β_1 on the cross term $Post_t*Treat_i$ captures the causal effect of the carbon emissions trading policy.

Table 1
Summary statistic.

Variable	Obs	Mean	Std. Dev.	Min	Max
Carbon emission	3141	24.740	23.862	0.340	230.712
Carbon emission intensity	2511	0.021	0.016	0.002	0.511
PM2.5	3114	43.484	21.336	2.181	112.340
Treat	3141	0.120	0.325	0.000	1.000
Post	3141	0.556	0.497	0.000	1.000
*Treat*post*	3141	0.040	0.196	0.000	1.000
GDP	2490	1793.025	2456.646	65.965	25123.450
Population	2490	443.823	311.084	19.500	3375.200
Ind	2511	50.222	10.336	15.170	90.970

X_{it} is a set of control variables, which include the *GDP* and its squared term, population (*Population*), and the industrial structure (*ind)*. We added the city fixed effect (*City FE*) to control for unobserved factors that changed across cities but remained the same as time progresses, and the year fixed effect (*Year FE*) to control for unexpected events over time. ε_{it} is the error term.

As previously discussed, the "pollution haven hypothesis" indicates that polluting firms may choose to move to areas that have lower environmental standards. Therefore, the carbon emissions trading policy could also have a spillover effect on the neighboring cities, which would lead to a deterioration of the neighboring cities' air quality as well as higher carbon emissions. In this case, the spillover effect on air quality could be negative. However, particulate matter such as $PM_{2.5}$ can travel long distances via wind and airflows. When the local air quality is improved because of the carbon emissions trading policy, the neighboring cities could also benefit. Consequently, the spillover effect on air quality could be positive.

Considering this potential spillover effect, we applied the spatial Durbin model with an inverse-distance matrix to control for this potential. We added spatial lags of the dependent and explanatory variables *Post*Treat* to the model.

3. Results and discussion

3.1. Baseline results

Table 2 shows the estimated baseline results of the impact of the carbon emissions trading policy on cities' carbon emissions, according to Equation (1). The interaction term *Treat*Post* is significantly negative at the 1% level in column (1), indicating that the average total carbon emissions in the pilot areas have experienced a larger decline during the policy period compared to the non-pilot areas. This result is relatively stable after adding the city fixed effect and the year fixed effect in column (4). Regarding the carbon emissions intensity, the interaction term *Treat*Post* is significantly negative at the 1% level in column (2) but loses its significance after controlling for the fixed effect, which suggests that the carbon emissions trading policy may not exert a significant impact on the carbon emissions intensity. These results assert that the carbon emissions trading policy is effective in terms of reducing the total carbon emissions. However, the policy does not lower the carbon emissions per unit of production In columns (3) and (6), the interaction term *Treat*Post* is significantly negative, suggesting that the carbon emissions trading policy could have a negative effect on $PM_{2.5}$. This result indicates that the carbon emissions trading policy is beneficial for improving air quality. This provides evidence that the climate policy is effective in achieving the co-benefits of carbon emissions reduction and air pollution control.

3.2. Robustness check

We conducted a series of additional analyses to ensure that the results were robust.

3.2.1. Parallel trend test

To remove the potential for the pre-existing factors in the carbon emissions trends to obtain results on the distinct changes between the pilot and non-pilot areas. We used a parallel trend test to visualize the trend evolving over time between the two groups. Fig. 2(a)–(c) exhibit the total carbon emissions, carbon emissions intensity, and $PM_{2.5}$ trends, respectively.

In Fig. 2(a), before 2010, the gap between the treated and control groups virtually remains the same, though the total carbon emissions of the non-pilot areas are lower than that of the pilot areas. The total carbon emissions of the pilot areas increase more slowly after 2010 and experience a sudden decrease in 2012. The slower increase rate of the pilot areas indicates an expected effect for the policy before 2012. Unlike

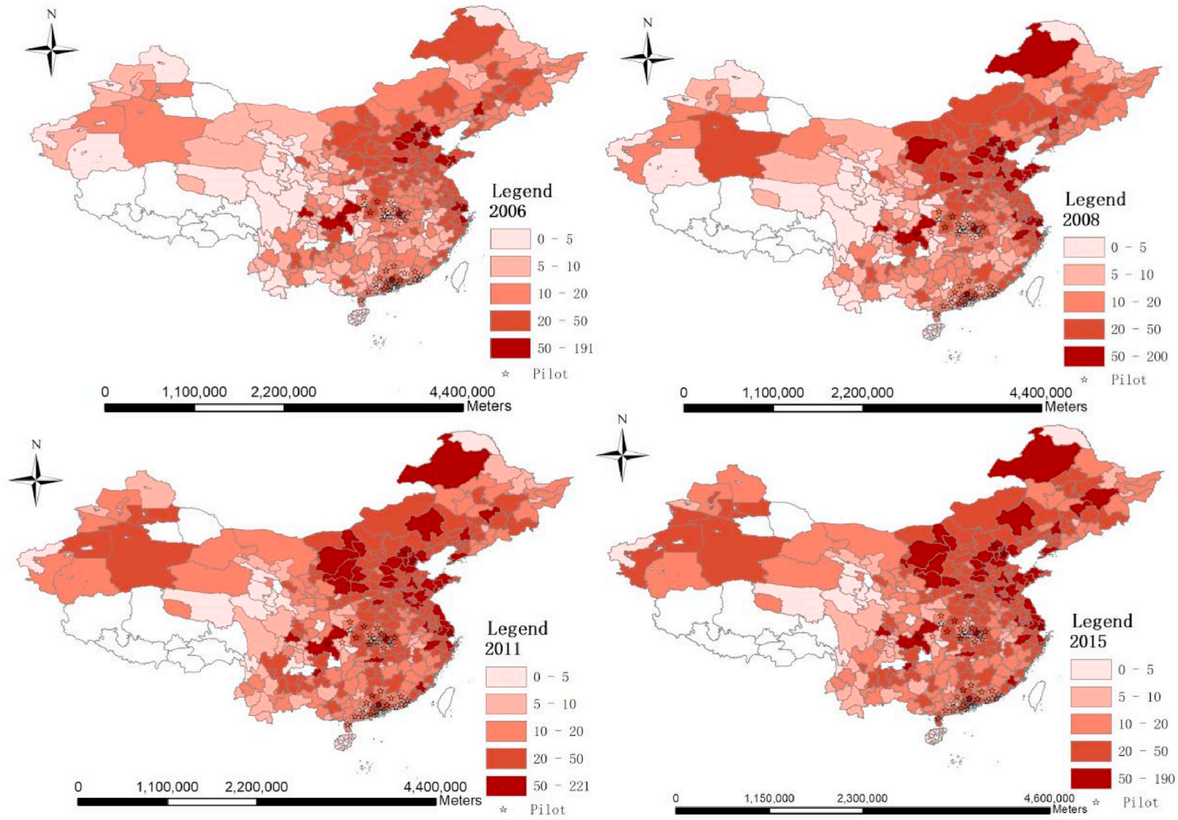


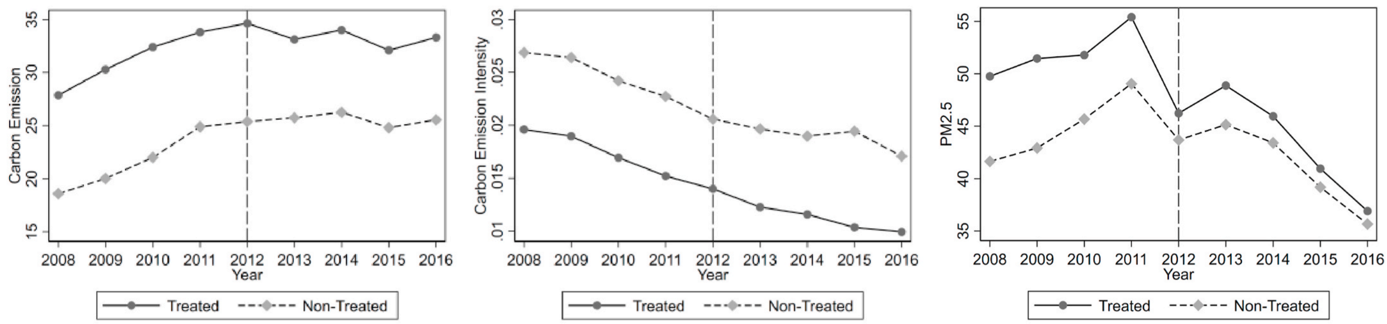
Fig. 1. Carbon emission of Chinese cities in 2006, 2008, 2011 and 2015.

Table 2
Baseline regression.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Carbon emission	Carbon emission intensity	PM2.5	Carbon emission	Carbon emission intensity	PM2.5
*Treat*Post*	-0.149***	-0.066***	-0.283***	-0.041***	-0.030	-0.121***
	(0.019)	(0.025)	(0.039)	(0.011)	(0.043)	(0.034)
Treat	-0.168***	-0.254***	-0.021			
	(0.046)	(0.048)	(0.152)			
Post	-0.197***	-0.113***	-0.193***			
	(0.027)	(0.036)	(0.039)			
L.Log(GDP)	0.347	-1.387***	-0.235	0.332***	-0.584*	0.359**
	(0.304)	(0.449)	(0.431)	(0.093)	(0.303)	(0.163)
L.Log(GDP)_sq	0.292	1.002**	0.150	-0.278***	0.740**	-0.436***
	(0.275)	(0.389)	(0.402)	(0.085)	(0.306)	(0.159)
L.Log(Pop)	0.085**	0.033	0.523***	0.109*	-0.134	-0.137
	(0.039)	(0.045)	(0.057)	(0.057)	(0.227)	(0.138)
L.Ind	0.035	0.024	0.343***	0.019*	-0.157*	-0.094***
	(0.030)	(0.041)	(0.053)	(0.011)	(0.090)	(0.025)
Constant	0.611***	-0.063	0.402***	0.634***	-0.308***	0.321***
	(0.026)	(0.042)	(0.051)	(0.012)	(0.108)	(0.017)
Observations	2490	2465	2481	2490	2465	2481
R-squared	0.696	0.185	0.295	0.994	0.674	0.941
Year FE	NO	NO	NO	YES	YES	YES
City FE	NO	NO	NO	YES	YES	YES
Adjusted R-squared	0.695	0.182	0.293	0.993	0.629	0.933

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

the total carbon emissions, Fig. 2(b) shows that the carbon emissions intensity of the non-pilot areas is higher than that of the pilot areas. The difference between the treated and control groups remains the same in terms of the carbon emissions intensity over the entire analysis period, which suggests that the carbon emissions trading policy may exert no effect on carbon intensity. Regarding the trend of the $PM_{2.5}$ level in Fig. 2(c), the gap between the treated and control groups is observed to remain the same from 2007 to 2010. The $PM_{2.5}$ level of the pilot areas experiences a sudden decrease in 2011, while both areas rebound in 2012. After the air quality information disclosure requirement was issued at the end of 2013, the air quality in both areas witnesses a moderate improvement. Overall, the parallel trend test holds for all figures.



(a) Carbon emission (b) Carbon emission intensity (c) PM2.5

Fig. 2. Parallel trend test.

3.2.2. Different settings of the policy time

This section follows Yu et al. (2021) and uses *Post2* as equaling one after 2014 and zero before 2014 to perform an additional robustness check. Table 3 shows that *Treat*Post2* is significantly negative at the 1% level in columns (1) and (3), but is not significant in column (2). This result is consistent with the results in Table 2.

3.2.3. Exclusion of the effects of other policies

In addition to the carbon emissions trading policy, many environmental regulations and climate policies were introduced during the analysis period, which may have led to biased estimates. To ensure that our results were robust, we conducted a series of regressions to exclude the potential co-benefit effect of the following policies:

(1) The pollutant emissions trading policy in 2007. Before the carbon emissions trading policy was introduced, China implemented another emissions trading system (i.e., pollution rights trading) to discourage pollutant emissions in 2007. This policy approved 11 regions as pilots of pollution rights trading. Therefore, we removed these areas from the data and re-analyzed Equation (1). The results are shown in columns (1)–(3) of Table 4.

(2) The low-carbon city policy in 2010. The low-carbon city pilot scheme was first introduced in 2010 in China. It listed 36 cities and 6 provinces as pilots to deal with energy consumption and climate change issues. We excluded the piloted cities and provinces and re-performed the analysis.

(3) The air quality monitoring and disclosure program in 2013. China initiated a nationwide air quality monitoring and disclosure program in 2013. The first stage included 74 cities that were required to monitor and report air quality information. To eliminate the effect of the air quality monitoring and disclosure program, we excluded the 74 cities and re-performed the analysis. The results are shown in columns (4)–(6) of Table 4.

Table 3
The different settings of the policy time.

	(1)	(2)	(3)
VARIABLES	Carbon emission	Carbon emission intensity	PM2.5
*Treat*Post2*	-0.060***	-0.018	-0.190***
	(0.011)	(0.034)	(0.029)
L.Log(GDP)	0.318***	-0.578*	0.308*
	(0.091)	(0.305)	(0.164)
*L.Log(GDP)*Log (GDP)*	-0.263***	0.733**	-0.383**
	(0.084)	(0.300)	(0.159)
L.Log(Pop)	0.108*	-0.135	-0.142
	(0.058)	(0.229)	(0.135)
L.Log(Ind)	0.018	-0.158*	-0.096***
	(0.011)	(0.091)	(0.024)
Constant	0.637***	-0.308***	0.330***
	(0.011)	(0.107)	(0.018)
Observations	2490	2465	2481
R-squared	0.994	0.674	0.941
Year FE	YES	YES	YES
City FE	YES	YES	YES
Adjusted R-squared	0.994	0.629	0.933

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

The results are robust when compared with the results shown in Table 2, which indicates that the carbon emissions trading policy is effective in reducing the total carbon emissions and $PM_{2.5}$.

3.2.4. Placebo test

Since we could not exclude every related policy that may have affected carbon emissions and air quality, we conducted a placebo test based on randomly generated "false" treated pilot areas. As the policy was significantly effective in reducing the total carbon emissions and $PM_{2.5}$, we conducted the placebo test on the total carbon emissions and $PM_{2.5}$ in all cities.

If the carbon emission changes in our research were due to the "true" carbon emissions trading policy, then the coefficients of the falsified *Treat*Post* were expected to be insignificant for the "false" treated groups. We started by randomly generating pilot areas of the carbon emissions trading policy during the analysis period. We then re-ran the DID analysis 1000 times based on the "false" pilot areas. Then, we plotted the distributions of the estimated coefficients and *t*-values of the falsified *Treat*Post* based on the estimated results. The results are shown in Figs. 3 and 4.

Fig. 3(a) shows that most of the estimated coefficients based on the "false" pilot areas are centered around zero and are different from the "true" coefficients (-0.041*** in Table 2). Fig. 3(b) shows that the "false" *t*-values of *Treat*Post* range from -2 to 2, which means that most of the estimated coefficients for falsified *Treat*Post* are statistically insignificant. A similar distribution can also be seen in Fig. 4. In sum, the placebo test provides further evidence that our DID results are robust, and that the carbon emissions trading policy is beneficial for carbon emissions reduction and air pollution control.

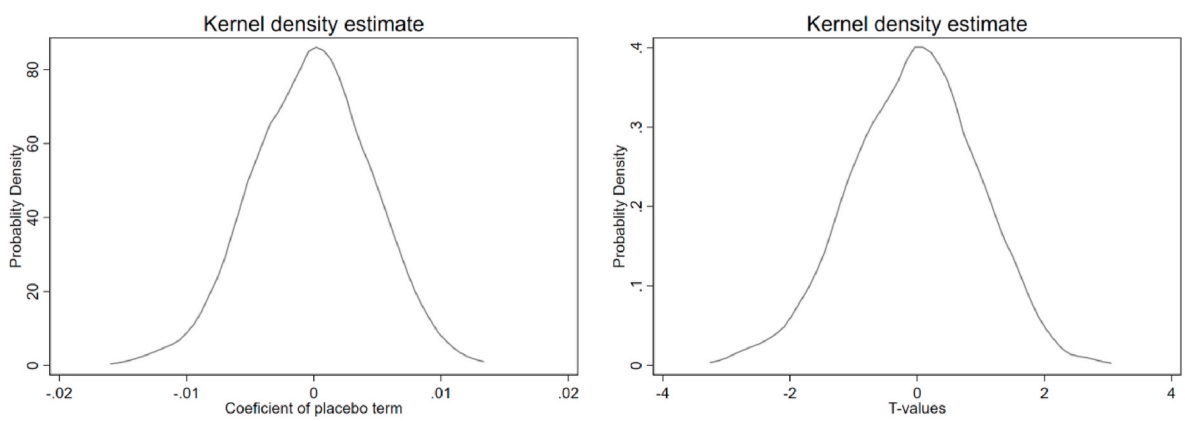
3.3. Mechanism analysis

In addition to the direct effect on carbon emissions, there are existing indirect mechanisms that may accelerate the efficiency of the carbon emissions trading policy. This section explores two such potential mechanisms. First, the carbon emissions trading policy stimulates firms to innovate in order to achieve long-term competitiveness (Popp and

Table 4
Exclusion of the effect of other policies.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Pollution rights trading			Low carbon city			Air quality monitoring		
VARIABLES	Carbon emission	Carbon emission intensity	PM2.5	Carbon emission	Carbon emission intensity	PM2.5	Carbon emission	Carbon emission intensity	PM2.5
*Treat*Post*	-0.024*	-0.020	-0.097**	-0.088***	-0.268**	-0.205***	-0.034***	-0.006	-0.095***
	(0.013)	(0.021)	(0.043)	(0.017)	(0.120)	(0.049)	(0.010)	(0.021)	(0.036)
L.Log(GDP)	0.632***	-1.757***	0.102	0.266**	-0.778*	0.291	0.359***	-1.811***	0.443*
	(0.132)	(0.374)	(0.252)	(0.118)	(0.402)	(0.217)	(0.135)	(0.408)	(0.228)
*L.Log(GDP)*Log (GDP)*	-0.513***	0.542**	-0.184	-0.227*	1.158*	-0.368*	-0.275*	0.719**	-0.579***
	(0.117)	(0.250)	(0.238)	(0.125)	(0.637)	(0.220)	(0.143)	(0.318)	(0.218)
L.Log(Pop)	0.102	0.349***	-0.338***	0.085	-0.358	-0.119	0.104	0.361***	-0.338***
	(0.067)	(0.103)	(0.109)	(0.058)	(0.277)	(0.156)	(0.075)	(0.118)	(0.120)
L.Log(Ind)	-0.006	0.051	-0.082**	0.024*	-0.153*	-0.142***	0.007	0.068	-0.112***
	(0.013)	(0.050)	(0.035)	(0.013)	(0.088)	(0.031)	(0.011)	(0.043)	(0.034)
Constant	0.458***	-0.082*	0.011	0.605***	-0.262***	0.450***	0.431***	-0.149***	0.158***
	(0.016)	(0.044)	(0.029)	(0.007)	(0.051)	(0.014)	(0.013)	(0.019)	(0.020)
Observations	1527	1507	1518	1655	1635	1646	1842	1817	1833
R-squared	0.992	0.957	0.934	0.993	0.611	0.942	0.992	0.959	0.943
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Adjusted R-squared	0.991	0.950	0.924	0.992	0.555	0.934	0.991	0.953	0.935

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.



(a) Estimated coefficients (b) T-values

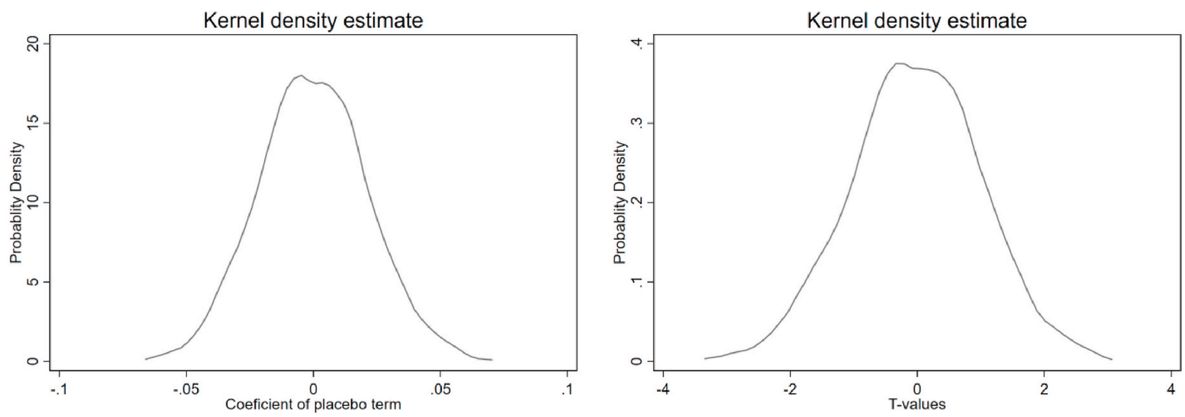
Fig. 3. Density plots of on total carbon emission.

Newell, 2012; Porter and Van der Linde, 1995), which, in turn, induces more environment-friendly innovations and leads to less carbon emission. Second, the "pollution haven hypothesis" suggests that environmental policy may affect international capital flows and firms' location choice, since some polluting and energy-intensive firms tend to invest more in regions that have less environmental regulations (Cole, 2004;). Since foreign investments and local industrial firms determine the local carbon emissions and air quality (Demena and Afesorgbor, 2020; Ren et al., 2014; Zhang and Zhang, 2018), we propose that the carbon emissions trading policy could exert an indirect effect on the carbon emissions and air pollutants by changing foreign investments and local industrial firms' location choice.

Accordingly, we used the innovation ability index from the "China Urban and Industrial Innovation Ability Report 2017." as the proxy for innovation, the foreign direct investment (FDI) from the city's statistical yearbook as the proxy for foreign investment, and the number of local industrial firms (firm location) as the proxy for firms' location choice to investigate the above mechanisms. We began by testing whether the carbon emissions trading policy could affect the innovation ability of cities, foreign investment, and firms' location (see Table 5), and then estimated how the carbon emissions trading policy played a role (see Table 6).

Table 5 shows that the coefficients of *Treat*Post* are significantly positive in column (1) and significantly negative in columns (2)–(3), which indicates that the carbon trading emissions policy could induce more innovation but would lead to lesser FDI and firms. This result is consistent with the "Porter hypothesis," which suggests that environmental regulations could encourage more innovations (Porter and Van der Linde, 1995), and the "pollution haven hypothesis," which demonstrates that foreign capital and firms prefer to invest in areas that have less stringent environmental standards (Greenstone, 2002).

Table 6 shows that the significantly positive coefficient of *Innovation* on carbon emissions combined with the result in Table 5 column (1) means that carbon emissions trading policy could reduce the total carbon emissions by encouraging more innovations. The insignificant *Innovation* coefficient on the carbon emissions intensity and $PM_{2.5}$ means that the carbon emissions trading policy is unable to achieve the co-benefits of carbon emissions and air quality by enhancing cities'



(a) Estimated coefficients (b) T-values

Fig. 4. Density plots of PM 2.5.

Table 5
Mechanism analysis: First stage.

	(1)	(2)	(3)
VARIABLES	Innovation	FDI	Firm location
*Treat*Post*	0.266***	-0.076*	-0.146*
	(0.070)	(0.046)	(0.067)
L.Log(GDP)	-2.534***	1.918***	-0.417
	(0.311)	(0.290)	(0.415)
*L.Log(GDP)*Log(GDP)*	2.684***	-1.907***	0.583
	(0.313)	(0.255)	(0.449)
L.Log(Pop)	0.480**	0.548***	0.303
	(0.241)	(0.089)	(0.179)
L.Ind	-0.034**	0.148***	0.153***
	(0.015)	(0.028)	(0.044)
Constant	0.030*	0.048	0.177***
	(0.017)	(0.037)	(0.031)
Observations	2465	2465	2354
R-squared	0.802	0.948	0.874
Year FE	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Adjusted R-squared	0.775	0.941	0.856

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

innovation ability, which echoes the previous literature about the positive effect of innovation on energy consumption (Xu et al., 2021; Yang et al., 2021). *FDI* is significantly negative in column (5), but is not significant in columns (4) and (6). This result seems to contradict some of the literature suggesting that higher FDI induces more carbon emissions (Zhang and Zhang, 2018). However, considering the productivity, the result makes senses. Higher FDI could increase productivity and improve energy use efficiency (Wang and Zhang, 2021), which would lead to less carbon emissions per productivity. The results suggest that though the policy does not have a direct effect on the carbon emissions intensity, it could lead to an increase in emissions intensity by squeezing out the FDI.

In addition, the *Firm* coefficient is significantly positive in columns (7) and (8), suggesting that more industrial firms could push up the total carbon emissions and produce more air pollutants, which is consistent with the findings of earlier studies (Xiao et al., 2019). This provides evidence that the carbon emissions trading policy could exert a negative indirect effect on carbon emissions and $PM_{2.5}$ by reducing the number of local industrial firms. The insignificant *Firm* coefficient in column (8) means that having more industrial firms will have no effect on the carbon emissions intensity. This result makes sense, since more firms means more products and more carbon emissions; however, the carbon emissions intensity remains unchanged.

Table 6
Mechanism analysis: Second stage.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	Carbon emission	Carbon emission intensity	PM2.5	Carbon emission	Carbon emission intensity	PM2.5	Carbon emission	Carbon emission intensity	PM2.5
*Treat*Post*	-0.029***	-0.031	-0.132***	-0.041***	-0.046	-0.126***	-0.038***	-0.033	-0.117***
	(0.009)	(0.042)	(0.031)	(0.011)	(0.045)	(0.034)	(0.010)	(0.042)	(0.035)
Innovation	-0.045***	0.004	0.048						
	(0.008)	(0.017)	(0.032)						
FDI				-0.005	-0.086***	-0.021			
				(0.006)	(0.023)	(0.020)			
Firm							0.040***	-0.037	0.040**
							(0.007)	(0.023)	(0.019)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2465	2465	2456	2354	2354	2345	2465	2465	2456
R-squared	0.994	0.674	0.940	0.995	0.623	0.940	0.994	0.674	0.940
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.994	0.629	0.932	0.994	0.570	0.932	0.994	0.629	0.932

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

3.4. Additional analysis

3.4.1. Regional heterogeneity analysis

Since there are huge regional differences in China (Zhang et al., 2022b), the impact of the carbon emissions trading policy is expected to be different in different parts of the country. We re-performed the DID analysis based on a sub-sample of different areas in China; namely, the East, Central, and West areas. Table 7 shows the results.

For the total carbon emissions results (columns (1)–(3)), the *Post*Treat* coefficient is only significant in column (2), which indicates that the effect of the carbon emissions trading policy is mainly due to its effectiveness in Central China. The carbon emissions intensity result is summarized in columns (4)–(6). The *Post*Treat* coefficient is only significant in Central China. This means that though the carbon emissions trading policy is ineffective in reducing the carbon emissions intensity across the whole country, it is effective in Central China. Columns (7)–(9) demonstrate the effect of the carbon emissions trading policy on $PM_{2.5}$. The magnitude of *Post*Treat* is -0.179 and -0.169 in columns (7) and (8), respectively, which indicates that there is no significant difference between the East and Central areas in terms of the effect of the carbon emissions trading policy on air pollution control. The magnitude of *Post*Treat* is -0.403 in the West area, which is about 2.3 times higher than that in the East and Central areas. This result suggests that the carbon emissions trading policy reduces the air pollution in the West area the most.

3.4.2. Spatial DID analysis

As previously discussed, the "pollution haven hypothesis" indicates that polluting firms may choose to move to areas that have lax environmental regulations. Therefore, the carbon emissions trading policy could also have a third-party effect on the neighboring cities, resulting in the degradation of their air quality. In this case, the spillover effect on air quality could be negative. However, particulate matter such as $PM_{2.5}$ can travel long distances via wind and airflows. An improvement in local air quality attributed to the carbon emissions trading policy could also benefit the neighboring cities. In this case, the spillover effect on air quality could be positive.

Considering this potential spillover effect, we applied the spatial Durbin model with an inverse-distance matrix to control for this potential. We added spatial lags of the dependent and explanatory variables *Post*Treat* to the model. Table 8 shows the results: local *Post*Treat* is significantly negative in columns (1) and (5) and insignificant in column (3), which is consistent with our previous results.

The spatial lagged *Post*Treat* in column (2) is significantly positive, which suggests that local carbon emissions would increase if a neighboring city implemented a carbon emissions trading policy. This result proves that the pollution haven effect does play a significant role. Interestingly, the spatial lagged *Post*Treat* in column (6) is insignificantly positive. Regarding air quality, the neighboring cities could be affected by both the pollution haven effect (negative) and the atmospheric motion effect (positive). Regarding carbon emissions, the neighboring cities could be affected by the pollution haven effect (negative). Therefore, there are different effects of the carbon emissions trading policy on air quality and carbon emissions. The spatially lagged *Carbon emissions, Carbon emissions intensity,* and $PM_{2.5}$ are significantly positive in columns (2), (4), and (6), which indicates that the neighboring cities' carbon emissions and air quality are positively related to local carbon emissions and air quality.

4. Conclusions and policy implications

The Chinese government has implemented several policies to reduce carbon emissions and initiate a low-carbon economy. However, the effectiveness of these policies remains contested due to their potentially harmful impacts on the economy and the inconclusive effects on carbon emissions. Therefore, this study explores the effect of the carbon emissions trading policy issued in 2011 on the co-benefits of carbon emissions reduction and air quality improvement in China, based on city-level data. Our findings are as follows.

First, the carbon emissions trading policy has a significant effect on the reduction of the co-benefits of the total carbon emissions and $PM_{2.5}$, while it does not exert a significant impact on the carbon emissions intensity on average. In addition to this direct effect, the carbon emissions trading policy could exert an indirect effect on carbon emissions and air quality by changing cities' innovation ability and local industrial firms' location choice.

Second, the co-benefit effect shows a significant regional difference and spillover effect. For example, the effect on air quality diminishes from West to East China, and the policy effectively reduces the carbon emissions intensity in Central China. Our spatial analysis concludes that the implementation of the carbon emissions trading policy has a different spillover impact on neighboring cities' carbon emissions and air quality. This shows that both the pollution haven effect and atmospheric motion effect play a role.

Based on these results, our study fills the research gap as follows. First, compared with the previous studies that have focused on climate

Table 7
Heterogeneity analysis.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	Carbon emission			Carbon emission intensity			Pm25		
	East	Middle	West	East	Middle	West	East	Middle	West
*Treat*Post*	-0.013	-0.068***	-0.063	-0.014	-0.066**	-0.016	-0.179***	-0.169***	-0.403***
	(0.018)	(0.013)	(0.038)	(0.083)	(0.028)	(0.094)	(0.038)	(0.050)	(0.082)
L.Log(GDP)	0.266	-0.184	0.347**	-0.163	-1.802***	-2.121***	0.266	-0.662	1.334***
	(0.167)	(0.115)	(0.165)	(0.408)	(0.366)	(0.588)	(0.244)	(0.441)	(0.326)
L.Log(GDP)_sq	-0.220	0.202*	-0.257	0.711	1.147***	0.652	-0.274	0.163	-0.813***
	(0.166)	(0.107)	(0.161)	(0.614)	(0.261)	(0.434)	(0.262)	(0.374)	(0.266)
L.Log(Pop)	0.156	0.028	0.173	-0.771	0.158**	0.434	-0.357	-0.228	0.051
	(0.151)	(0.044)	(0.148)	(0.867)	(0.061)	(0.355)	(0.230)	(0.182)	(0.325)
L.Ind	0.045***	0.008	-0.025	-0.263***	0.003	0.130	0.058*	-0.139***	-0.231***
	(0.017)	(0.013)	(0.019)	(0.079)	(0.043)	(0.082)	(0.030)	(0.052)	(0.051)
Constant	0.913***	0.560***	0.429***	-0.712***	-0.131***	-0.156	0.410***	0.671***	0.027
	(0.043)	(0.008)	(0.054)	(0.099)	(0.026)	(0.122)	(0.047)	(0.025)	(0.120)
Observations	905	880	705	905	871	689	896	880	705
R-squared	0.995	0.993	0.995	0.345	0.959	0.963	0.966	0.940	0.930
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
City FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Adjusted R-squared	0.995	0.992	0.994	0.250	0.953	0.956	0.961	0.931	0.919

Robust standard errors in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.

Table 8
Spatial analysis.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	Carbon emission		Carbon emission intensity		Pm25	
	Local	Spatial	Local	Spatial	Local	Spatial
*Treat*Post*	-0.103***	0.337***	-0.044	-0.024	-0.056**	0.047
	(0.011)	(0.059)	(0.079)	(0.199)	(0.026)	(0.040)
Spatial lagged DV		0.908***		0.600***		1.026***
		(0.032)		(0.109)		(0.006)
L.Log(GDP)	0.298***		-0.886***		-0.044	
	(0.033)		(0.293)		(0.080)	
L.Log(GDP)_sq	-0.138***		0.667**		0.052	
	(0.033)		(0.294)		(0.080)	
L.Log(Pop)	0.053**		-0.044		0.005	
	(0.025)		(0.220)		(0.063)	
L.Ind	-0.002		-0.037		-0.023**	
	(0.005)		(0.037)		(0.009)	
Constant	0.055***		0.506***		0.136***	
	(0.001)		(0.008)		(0.002)	
Observations	1944	1944	1944	1944	1944	1944
Number of groups	216	216	216	216	216	216
City FE	YES	YES	YES	YES	YES	YES

Standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

policies' effectiveness on carbon emissions, we further integrate the co-benefits of air quality and carbon emissions and explore the policy efficiency that have been underexplored by the previous literature. By connecting the "Porter hypothesis" and the "pollution haven hypothesis," we further attempt to reveal the underlying mechanisms. Second, unlike traditional OLS and DID regression, we apply spatial analysis to enrich the literature by considering the spillover effect instead of simply exploring the policy's local effect, which provides a relatively more comprehensive understanding about the effect of the policy and contributes to the climate policy literature. Third, we analyze the effect of the carbon emissions trading policy on carbon emissions and air quality at the city-level, which ensures a good balance between a the unit of study, while providing a stable boundary for heterogeneity analysis over time in comparison to the provincial-level data that have been widely used in the previous studies.

Our findings have clear policy implications. The carbon emissions trading policy could indeed decrease the total carbon emissions; however, it could also harm the neighboring cities when considering the "pollution haven" effect. Therefore, when implementing the policy, it is necessary to consider its potential effect on the other regions. How to reduce the negative spillover effect is vital to achieve environmental justice and reduce the inefficiency of the policy. Moreover, we reveal that climate policy is beneficial for air pollution, while its effect differs across regions. Therefore, it is worth considering a more effective, collaborative policy system depending on the levels and regions for the co-benefits of carbon emissions reduction and air pollution control. This would, in turn help achieve a greener and more sustainable society. In addition, when attempting to reduce carbon emissions, it will be beneficial for the government to provide guidance or subsidies to stimulate green innovation. This could simultaneously ensure productivity, reduce carbon emissions, and improve air quality, which would help achieve a win-win situation between the economy and the environment in the long-term (Xu et al., 2021; Yang et al., 2021).

This study has attempted to examine the causal effect of carbon emissions trading policy issued in 2011 on the co-benefits of carbon emissions reduction and air quality improvement in China, with a detailed investigation of the underlying mechanisms and heterogeneous response of different regions. However, due to the data limitation, it is difficult to examine the long-term effect of the policy, which is also a vital component of the policy efficiency. Therefore, with the increasing data availability, it is worthwhile to explore the effect of the carbon emissions trading policy from a longer-term perspective in the future. In addition, a quantitative analysis alone is not enough to obtain general policy suggestions that are suitable for each region. The procedure to design a specific and efficient policy system is beyond the scope of this study. Therefore, we encourage future studies to probe this aspect further using case studies, which would help understand the cities' history and environmental characteristics, and reveal more potent mechanisms to analyze the policy impacts. This could ultimately lead us to sustainable development in the true sense.

CRediT authorship contribution statement

Zhaoyingzi Dong: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Chuyu Xia:** Writing – original draft, Data curation. **Kai Fang:** Methodology, Writing – review & editing. **Weiwen Zhang:** Conceptualization, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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There is no potential competing interest.

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References

Al-Mulali, U., Saboori, B., Ozturk, I., 2015. Investigating the environmental Kuznets curve hypothesis in Vietnam. Energy Pol. 76, 123–131.

Anenberg, S.C., Miller, J., Injares, R.M., Du, L., Henze, D.K., Lacey, F., et al., 2017. Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. Nature 545 (7655), 467.

Bain, P.G., Milfont, T.L., Kashima, Y., Bilewicz, M., Doron, G., Garðarsdóttir, R.B., Gouveia, V.V., Guan, Y., Johansson, L.-O., Pasquali, C., Corral-Verdugo, V., Aragones, J.I., Utsugi, A., Demarque, C., Otto, S., Park, J., Soland, M., Steg, L., González, R., Saviolidis, N.M., 2016. Co-benefits of addressing climate change can motivate action around the world. Nat. Clim. Change 6 (2), 154–157.

Blackman, A., Li, Z., Liu, A.A., 2018. Efficacy of command-and-control and market-based environmental regulation in developing countries. Ann. Rev. Resourc. Econ. 10 (1), 381–404.

Brajer, V., Mead, R.W., Xiao, F., 2011. Searching for an environmental Kuznets curve in China's air pollution. China Econ. Rev. 22 (3), 383–397.
Cao, H., Wang, B., Li, K., 2021. Regulatory policy and misallocation: a new perspective based on the productivity effect of cleaner production standards in China's energy firms. Energy Pol. 152, 112231.
Chen, J., Gao, M., Cheng, S., Hou, W., Song, M., Liu, X., Liu, Y., Shan, Y., 2020. County-level carbon emissions and sequestration in China during 1997–2017. Sci. Data 7, 39.
Chen, S., Chen, B., 2015. Urban energy consumption: different insights from energy flow analysis, input-output analysis, and ecological network analysis. Appl. Energy 138 (Jan. 15), 99–107.
Chen, Z., Song, P., Wang, B., 2021. Carbon emissions trading scheme, energy efficiency and rebound effect–Evidence from China's provincial data. Energy Pol. 157, 112507.
Cole, M.A., 2004. Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. Ecol. Econ. 48 (1), 71–81.
Dechezleprêtre, A., Glachant, M., 2014. Does foreign environmental policy influence domestic innovation? Evidence from the wind industry. Environ. Resour. Econ. 58 (3), 391–413.
Demena, B.A., Afesorgbor, S.K., 2020. The effect of FDI on environmental emissions: evidence from a meta-analysis. Energy Pol. 138, 111192.
Dong, Z., Chen, W., Wang, S., 2020. Emission reduction target, complexity, and industrial performance. J. Environ. Manag. 260, 110148.
Fan, J., Zhou, L., Zhang, Y., Shao, S., Ma, M., 2021. How does population aging affect household carbon emissions? Evidence from Chinese urban and rural areas. Energy Econ., 105356
Fang, K., Zhang, Q., Long, Y., Yoshida, Y., Sun, L., Zhang, H., et al., 2019. How can China achieve its intended nationally determined contributions by 2030? a multi-criteria allocation of China's carbon emission allowance. Appl. Energy 241 (MAY 1), 380–389.
Greenstone, M., 2002. The impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 clean air act amendments and the census of manufactures. J. Polit. Econ. 110 (6), 1175–1219.
Heft-Neal, S., Burney, J., Bendavid, E., Burke, M., 2018. Robust relationship between air quality and infant mortality in Africa. Nature 559 (7713), 254–258.
Huang, Z., Du, X., 2020. Toward green development? Impact of the carbon emissions trading system on local governments' land supply in energy-intensive industries in China. Sci. Total Environ. 738, 139769.
Jia, R., Shao, S., Yang, L., 2021. High-speed rail and CO2 emissions in urban China: a spatial difference-in-differences approach. Energy Econ. 99, 105271.
Kim, S.E., Xie, Y., Dai, H., Fujimori, S., Hijioka, Y., Honda, Y., Hashizume, M., Masui, T., Hasegawa, T., Xu, X., 2020. Air quality co-benefits from climate mitigation for human health in South Korea. Environ. Int. 136, 105507.
Li, R., Wang, Q., Liu, Y., Jiang, R., 2021. Per-capita carbon emissions in 147 countries: the effect of economic, energy, social, and trade structural changes. Sustain. Prod. Consum. 27, 1149–1164.
Liu, Z., Geng, Y., Lindner, S., Zhao, H., Fujita, T., Guan, D., 2012. Embodied energy use in China's industrial sectors. Energy Pol. 49, 751–758.
Mo, J.L., Agnolucci, P., Jiang, M.R., Fan, Y., 2016. The impact of the Chinese carbon emission trading scheme (ETS) on low carbon energy (LCE) investment. Energy Pol. 89, 271–283.
Newell, R.G., Stavins, R.N., 2003. Cost heterogeneity and the potential savings from market-based policies. J. Regul. Econ. 23 (1), 43–59.
Popp, D., Newell, R., 2012. Where does energy R&D come from? Examining crowding out from energy R&D. Energy Econ. 34 (4), 980–991.
Porter, M.E., Van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9 (4), 97–118.
Ren, S., Yuan, B., Ma, X., Chen, X., 2014. International trade, FDI (foreign direct investment) and embodied CO2 emissions: a case study of Chinas industrial sectors. China Econ. Rev. 28, 123–134.
Ricci, F., 2007. Environmental policy and growth when inputs are differentiated in pollution intensity. Environ. Resour. Econ. 38 (3), 285–310.
Sinn, H.-W., 2009. The green paradox. Munich Reprints Econ. 10 (3), 10–13.
Song, X., Jia, J., Wu, F., Niu, H., Ma, Q., Guo, B., et al., 2022. Local Emissions and Secondary Pollutants Cause Severe PM2. 5 Elevation in Urban Air at the South Edge of the North China Plain: Results from Winter Haze of 2017–2018 at a Mega City, vol. 802. Science of The Total Environment, p. 149630.
Thompson, T.M., Rausch, S., Saari, R.K., Selin, N.E., 2014. A systems approach to evaluating the air quality co-benefits of US carbon policies. Nat. Clim. Change 4 (10), 917–923.
Van Donkelaar, A., Martin, R.V., Brauer, M., Hsu, N.C., Kahn, R.A., Levy, R.C., et al., 2016. Global estimates of fine particulate matter using a combined geophysical-statistical method with information from satellites, models, and monitors. Environ. Sci. Technol. 50 (7), 3762–3772.
Wang, Q., Jiang, R., 2019. Is China's economic growth decoupled from carbon emissions? J. Clean. Prod. 225, 1194–1208.
Wang, Q., Zhang, F., 2021. The effects of trade openness on decoupling carbon emissions from economic growth–evidence from 182 countries. J. Clean. Prod. 279, 123838.
Wang, Q., Su, M., Li, R., Ponce, P., 2019. The effects of energy prices, urbanization and economic growth on energy consumption per capita in 186 countries. J. Clean. Prod. 225, 1017–1032.
Wen, F., Zhao, L., He, S., Yang, G., 2020. Asymmetric relationship between carbon emission trading market and stock market: evidences from China. Energy Econ. 91, 104850.
West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., et al., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat. Clim. Change 3 (10), 885–889, 0.
Xia, C., Xiang, M., Fang, K., Li, Y., Liu, J., 2020. Spatial-temporal distribution of carbon emissions by daily travel and its response to urban form: a case study of Hangzhou, China. J. Clean. Prod. 257, 120797.
Xiao, H., Shan, Y., Zhang, N., Zhou, Y., Wang, D., Duan, Z., 2019. Comparisons of CO2 emission performance between secondary and service industries in Yangtze River Delta cities. J. Environ. Manag. 252, 109667.
Xiao, J., Li, G., Zhu, B., Xie, L., Hu, Y., Huang, J., 2021. Evaluating the impact of carbon emissions trading scheme on Chinese firms' total factor productivity. J. Clean. Prod. 306, 127104.
Xie, Y., Dai, H., Xu, X., Fujimori, S., Hasegawa, T., Yi, K., et al., 2018. Co-benefits of climate mitigation on air quality and human health in Asian countries. Environ. Int. 119 (OCT), 309–318.
Xu, L., Fan, M., Yang, L., Shao, S., 2021. Heterogeneous green innovations and carbon emission performance: evidence at China's city level. Energy Econ. 99, 105269.
Yan, Y., Zhang, X., Zhang, J., Li, K., 2020. Emissions trading system (ETS) implementation and its collaborative governance effects on air pollution: the China story. Energy Pol. 138, 111282.
Yang, L., Li, Y., Liu, H., 2021. Did carbon trade improve green production performance? Evidence from China. Energy Econ. 96.
Yang, Xi, Teng, Fei, 2018. Air quality benefit of China's mitigation target to peak its emission by 2030. Clim. Pol. 18 (1–5), 99–110.
Yang, Z., Shao, S., Fan, M., Yang, L., 2021. Wage distortion and green technological progress: a directed technological progress perspective. Ecol. Econ. 181, 106912.
Yu, D.-J., Li, J., 2021. Evaluating the employment effect of China's carbon emission trading policy: based on the perspective of spatial spillover. J. Clean. Prod. 292, 126052.
Yu, F., Xiao, D., Chang, M.S., 2021. The impact of carbon emission trading schemes on urban-rural income inequality in China: a multi-period difference-in-differences method. Energy Pol. 159, 112652.
Zaman, K., Abd-el Moemen, M., 2017. Energy consumption, carbon dioxide emissions and economic development: evaluating alternative and plausible environmental hypothesis for sustainable growth. Renew. Sustain. Energy Rev. 74, 1119–1130.
Zhang, G., Zhang, N., 2020. The effect of China's pilot carbon emissions trading schemes on poverty alleviation: a quasi-natural experiment approach. J. Environ. Manag. 271, 110973.
Zhang, P., Shi, X.P., Sun, Y.P., Cui, J., Shao, S., 2019. Have China's provinces achieved their targets of energy intensity reduction? reassessment based on nighttime lighting data. Energy Pol. 128 (MAY), 276–283.
Zhang, Q., Fang, K., Chen, J., Liu, H., Liu, P., 2022a. The role of sectoral coverage in emission abatement costs: evidence from marginal cost savings. Environ. Res. Lett.
Zhang, Q., Wiedmann, T., Fang, K., Song, J., He, J., Chen, X., 2022b. Bridging planetary boundaries and spatial heterogeneity in a hybrid approach: a focus on Chinese provinces and industries. Sci. Total Environ. 804, 150179.
Zhang, Y.J., Hao, J.F., 2017. Carbon emission quota allocation among China's industrial sectors based on the equity and efficiency principles. *Ann. Oper. Res.* 255 (1), 117–214.
Zhang, Y.J., Liu, Z., Zhang, H., Tan, T.D., 2014. The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. Nat. Hazards 73 (2), 579–595.
Zhang, Y., Zhang, S., 2018. The impacts of GDP, trade structure, exchange rate and FDI inflows on China's carbon emissions. Energy Pol. 120, 347–431.