The effectiveness of China's regional carbon market pilots in reducing firm emissions

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China has implemented an emission trading system (ETS) to reduce its ever-increasing greenhouse gas emissions while maintaining rapid economic growth. With low carbon prices and infrequent allowance trading, whether China's ETS is an effective approach for climate mitigation has entered the center of the policy and research debate. Utilizing China's regional ETS pilots as a quasi-natural experiment, we provide a comprehensive assessment of the effects of ETS on firm carbon emissions and economic outcomes by means of a matched difference-in-differences (DID) approach. The empirical analysis is based on a unique panel dataset of firm tax records in the manufacturing and public utility sectors during 2009 to 2015. We show unambiguous evidence that the regional ETS pilots are effective in reducing firm emissions, leading to a 16.7% reduction in total emissions and a 9.7% reduction in emission intensity. Regulated firms achieve emission abatement through conserving energy consumption and switching to low-carbon fuels. The economic consequences of the ETS are mixed. On one hand, the ETS has a negative impact on employment and capital input; on the other hand, the ETS incentivizes regulated firms to improve productivity. In the aggregate, the ETS does not exhibit statistically significant effects on output and export. We also find that the ETS displays notable heterogeneity across pilots. Mass-based allowance allocation rules, higher carbon prices, and active allowance trading contribute to more pronounced effects in emission abatement.

climate change | emission trading system | firm emissions

China has pledged that its carbon emissions will peak by 2030 and that it will achieve carbon neutrality by 2060. To meet these ambitious climate targets while maintaining economic growth, it has implemented an emission trading system (ETS) to achieve cost-effective climate mitigation. China has a long history of experimenting with ETS, originating with the SO_2 ETS in the early 1990s (1). Its experience with carbon markets started in the early 2000s through the Clean Development Mechanism, a voluntary carbon offset scheme created by the Kyoto Protocol (2). China's regional carbon ETS pilots, announced in 2011 and launched in 2013, marked its first systematic attempt to use market-based instruments to regulate firm carbon emissions (3). Building on the experience of regional pilots, China brought a national carbon ETS, the largest carbon market in the world, online in 2021. As China is poised to ramp up its effort to fight climate change, whether ETS is an effective approach for climate mitigation has entered the center of debate.

Concerned with the impact of carbon regulations on industrial competitiveness, China has been experimenting with both mass- and rate-based allowance allocation rules in the regional pilots. A mass-based rule sets a cap on total emissions, while a rate-based rule regulates emission intensity. The national ETS, which covers only the power sector, has adopted a rate-based rule. A rate-based rule creates less regulatory pressure than a mass-based rule (4–8). Less regulatory pressure gives rise to low carbon prices and infrequent allowance trading. The average carbon price was $5.6 per ton of CO_2 equivalent (t CO_2 e) in the regional ETS between 2013 and 2015; the average carbon price was $7.8/t CO_2 e for the national ETS in the first week of operation. Allowance trading has been sporadic, with most transactions occurring in the narrow windows close to the compliance deadlines. In this context, two questions arise from China's ETS, especially from the regional ETS pilots: First, can a low carbon price create incentives for firms to reduce emissions? Second, is a thin carbon market with few buying or selling allowances still useful for firms to mitigate the cost of compliance?

The empirical evidence from the European Union and the United States shows that ETS is effective in mitigating climate change (9–14), but the economic consequences are mixed (15–22). In particular, a recent study demonstrates that the EU ETS with low carbon prices still works as long as it sends a credible signal to emission entities that the regulation will become more stringent in the future (23). Some literature on the effectiveness of China's ETS has also started to emerge. However, these studies are only focused on certain companies, such as power generators (24), large firms (25), or publicly listed companies (26, 27). The overall impacts of China's ETS on firms are still largely unknown.

This paper comprehensively evaluates the effects of China's regional ETS pilots on firm emissions and economic outcomes.

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Significance

The emission trading system (ETS) is an important policy instrument for China to achieve its climate targets. However, the effectiveness of ETS in emission reductions and its economic consequences are unknown. Using a unique dataset of firm tax records, we comprehensively assess the impacts of China's regional ETS pilots, taking advantage of the policy experiments in certain sectors across seven jurisdictions. We demonstrate unambiguous evidence that China's ETS leads to a reduction in carbon emissions despite low carbon prices and infrequent trading. We also identify the channels through which firms respond to ETS by adjusting energy consumption and sources, employment, capital, and productivity. The lessons learned from the regional pilots shed light on the design of China's national carbon ETS.

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The pilot ETS provides an excellent setting as a quasi-natural experiment since the pilots cover firms above thresholds in certain sectors in seven jurisdictions (*SI Appendix*, Table S1). Taking advantage of regulatory variations across sectors, regions, and years, this paper employs a matched difference-in-differences (DID) approach to identify the plausible causal effects of ETS on firm carbon emissions and economic outcomes. The empirical analysis is based on a unique panel dataset of firm tax records from the Chinese National Tax Survey Database (CNTSD). The data have broad coverage of firms in terms of sizes, sectors, regions, and years. With detailed information about firm energy and economic activities, the data enable us to comprehensively assess the ETS effects and identify the channels through which firms respond.

The regional ETS pilots also provide a rich set of variations to study the impacts of carbon market design. First, the two-stage launching of the pilots allows us to distinguish the announcement effect from the trading effect. Second, the variation in carbon market performance across regional pilots allows us to identify the impacts of carbon price and allowance liquidity. Third, the heterogeneity of allowance allocation rules allows us to assess the impact of regulatory stringency (*SI Appendix*, Table S2). Although our analysis focuses on the regional ETS pilots, it provides important policy implications for the national carbon ETS. After all, the design of the national ETS closely follows regional pilots. Many issues that occurred in the regional pilots are likely to be scaled up to the national level.

Results

The regression analyses take advantage of the quasi-natural experiment created by China's regional ETS pilots. The estimation of the ETS effects proceeds in two steps. We first construct the comparison group by one-to-one matching. This approach pairs each regulated firm with an unregulated firm in the same sector based on certain observable attributes. We conduct a balancing test to ensure that the unregulated firm can serve as the counterfactual for the regulated firm. With the matched sample, we then employ the DID approach to estimate the effects of ETS on carbon emissions and other firm outcomes of interest.

The Regional Carbon ETS Pilots Are Effective in Reducing Firm Total Emissions and Emission Intensity after the Start of Allowance Trading. Table 1 presents the estimated coefficients and SEs for the effects of ETS on firm carbon emissions based on the baseline model in Eq. **1**. Columns 1 and 2 report the results for total emissions, and columns 3 and 4 show the effects on emission intensity (emissions per unit of output value). The preferred estimation results, contained in columns 2 and 4, control for regional (provincial) and industrial linear trends. We differentiate the ETS effects into two phases: announcement (2011 to 2012) and allowance trading (2013 to 2015). The ETS effect in the announcement phase, capturing the anticipation effect, is negative but statistically insignificant in the preferred model. The ETS effect starts to kick in during the trading phase; the preferred model estimates that the ETS reduces total emissions by 16.7% (95% CI is [–26.4%, –6.9%]) and by 9.7% for emission intensity (90% CI is [–18.7%, –0.6%]).

Table 1. The ETS effects on firm carbon emissions

	Total emissions		Emission intensity	
Dependent variable	(1)	(2)	(3)	(4)
Announcement	–0.075*	–0.088	–0.027	–0.017
	(0.038)	(0.072)	(0.028)	(0.084)
Trading	–0.178***	–0.167***	–0.118**	–0.097*
	(0.053)	(0.047)	(0.043)	(0.053)
Observations	2,416	2,416	2,416	2,416
R-squared	0.047	0.198	0.090	0.220
Firm FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Province trend	N	Y	N	Y
Industry trend	N	Y	N	Y

All dependent variables are in natural logarithms. Announcement equals one for the regulated firms during the announcement period (2011 to 2012). Trading equals one for the regulated firms during the trading period (2013 to 2015). SEs in parentheses are clustered at the industry level. ***, significant at the 1% level; **, significant at the 5% level; *, significant at the 10% level. Y, yes; N, no.

We test the assumption that the regulated firms and the matched comparison firms follow a similar emission trend by regressing the dynamic effects model in Eq. **2**. The estimated coefficients for the prepolicy indicators are not statistically significant at any conventional level (*SI Appendix*, Fig. S1). These estimates cannot reject the null hypothesis that carbon emissions were not statistically different between the regulated and matched comparison firms prior to the initiation of ETS. After trading started, the estimated coefficients for the postpolicy indicators display a downward trend. In *SI Appendix*, Tables S7–S14, we conduct a series of robustness checks with regard to alternative specifications, potential threats from confounding policies, and data treatment. The main conclusion survived all these sensitivity analyses. Furthermore, to examine heterogeneous ETS effects by sectors, we run the baseline regressions for the electricity and manufacturing sectors separately. We find that the ETS effects for the manufacturing sector are similar to the baseline results, while the effects for the power sector are statistically insignificant. This can be partly due to a lack of statistical power since our data only include a small sample size of matched regulated power plants (*SI Appendix*, Table S15).

Firms Achieve Carbon Emission Reductions Through Energy Conservation and Fuel Switching. Under carbon regulations, firms can abate emissions through conserving energy, improving energy efficiency, and/or switching to low-carbon fuels (14, 28–30). To investigate the channels through which firms achieve emission reductions, we estimate the effects of ETS on firm energy consumption, energy consumption per unit of output value (energy/output), carbon emissions per unit of energy consumption (emission/energy), and the ratio of natural gas to total energy. Fig. 1 illustrates the estimated effects of ETS on each component based upon the baseline model in Eq. **1**.

Consistent with the baseline conclusion, the ETS effects mainly occur during the trading phase. Specifically, the ETS reduces firm energy consumption—including coal, gasoline, natural gas, and electricity—by 13% (95% CI is [–23.3%, –2.6%]). Carbon emission abatement is also achieved through

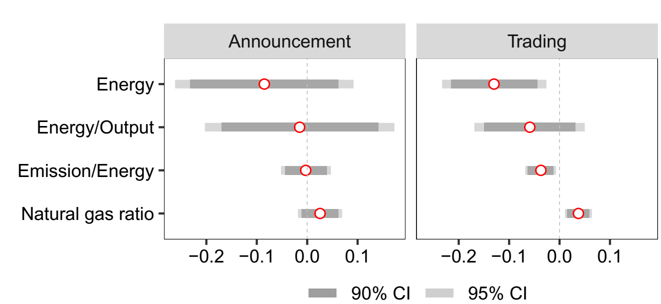

Fig. 1. The channels of carbon emission reductions. The dependent variables except for natural gas ratio are in log form (*y* axis). (*Left*) Announcement designates the ETS effects during the announcement period (2011 to 2012). (*Right*) Trading designates the ETS effects during the trading period (2013 to 2015). Firm and year fixed effects, as well as province linear trend and industry linear trend, are included.

fuel switching. Regulated firms reduce emissions per unit of energy consumption by 3.7% (95% CI is [–6.8%, –0.7%]) by switching to low-carbon energy sources. In particular, the ETS increases the share of natural gas by 3.7% (95% CI is [1.1%, 6.4%]). In a nutshell, we find that energy conservation results in the largest portion of emission reductions, while fuel switching also contributes to lower emissions.

Firms Respond to the ETS by Reducing Labor and Capital Inputs, Improving Productivity While Maintaining the Same Level of Output. We examine how firms make economic adjustments in response to the ETS. Specifically, we consider three categories of firm attributes, including output (output value, value added, and export), input (labor, capital, capital–labor ratio, wage, and investment), and productivity (output–labor ratio, output–capital ratio, and total factor productivity [TFP]). Fig. 2 illustrates the estimation results for each attribute based upon the baseline model in Eq. **1**.

We find that regulated firms adjust factors of production in response to carbon pricing. The ETS reduces employment by 6.6% (95% CI is [–11.8%, –1.4%]) in the announcement phase and by 11.8% (95% CI is [–23.1%, –0.4%]) in the trading phase. The ETS reduces capital by 15.6% (95% CI is [–30.2%, –1.0%]) in the trading phase, while the effect is statistically insignificant in the announcement phase. Since the relative price of capital and labor is not affected, the ETS has no statistically significant effect on the capital–labor ratio. The ETS effects on wage rate and investment are also statistically insignificant.

While the ETS induces firms to reduce emissions, it also encourages firms to innovate and improve productivity. Our results show that during the trading phase, the ETS increases productivity by 29.1% (95% CI is [0.8%, 57.5%]) or 25.6% (90% CI is [2.9%, 48.2%]), following two alternative TFP measures (31, 32). In addition, the ETS has positive effects on output per unit of labor and output per unit of capital, although the estimates are statistically insignificant.

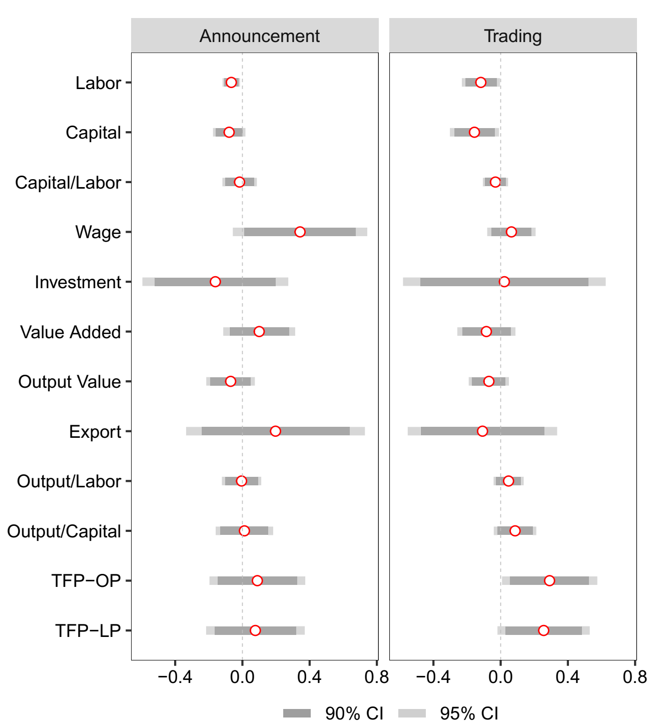

Fig. 2. The ETS effects on firm economic attributes. The dependent variables are in log form (*y* axis). (*Left*) Announcement designates the ETS effects during the announcement period (2011 to 2012). (*Right*) Trading designates the ETS effects during the trading period (2013 to 2015). Firm and year fixed effects, as well as province linear trend and industry linear trend, are included.

Because the ETS not only increases the cost of production but also boosts firm productivity, the aggregate effects of ETS on firm output can be ambiguous. We find no statistically significant effects of ETS on output values and value added. This result suggests that emission abatement is probably not being achieved through cutting production. This finding also speaks to the concern that regulating carbon emissions will impose a competitive disadvantage on firms that are exposed to trade. Our empirical result rejects the null hypothesis that the ETS has a negative effect on firm export.

High Carbon Prices and Active Allowance Trading Are More Likely to Stimulate Firms to Engage in Emission Abatement. Heterogeneous carbon market designs lead to variance in market performance. We focus on carbon price and trading activeness. The daily carbon price of the regional ETS pilots ranged from \$1.38 to \$20.88/t CO_2 e between 2013 and 2015, with the average carbon price at \$5.6/t CO_2 e. The turnover rate of carbon allowance, measured by the ratio of exchanged allowances to total allowances, was 0.018 on average in the same period. Allowance trading is infrequent and mainly occurs before the deadline for compliance.

We interact the trading dummy with carbon price and allowance turnover rate using a variant of the baseline model defined in Eq. **3**. Table 2 reports the estimation results. In columns 1 and 3, the estimates show that a 1% increase in carbon price results in a 0.043% decline (95% CI is [–0.065%, –0.020%]) in total emissions and a 0.022% decline (90% CI is [–0.044%, –0.001%]) in emission intensity. In columns 2 and 4, we find that a higher turnover rate also stimulates emission reductions. When the turnover rate increases by 0.01, it can lead to a 3.75% decrease (95% CI is [–5.715%, –1.794%]) in total emissions and a 2.41% decrease (95% CI is [–4.656%, –0.169%]) in emission intensity. The findings highlight the pivotal role of carbon price and trading activeness in incentivizing firm emission reductions.

A Mass-Based Allowance Allocation Rule Creates Stronger Incentives for Emission Abatement Than Does a Rate-Based Rule. The regional ETS pilots adopt two types of allowance allocation rules: mass-based and rate-based. Under a mass-based rule, the total allowance for a regulated firm is determined in advance of the compliance period based on its historical emission level or a fixed reference production quantity. In contrast, under a

Table 2. Effects of carbon price and allowance liquidity

	Total emissions		Emission intensity	
Dependent variable	(1)	(2)	(3)	(4)
Announcement	–0.074	–0.054	–0.006	0.000
	(0.068)	(0.068)	(0.081)	(0.075)
Carbon price	–0.043***		–0.022*	
	(0.011)		(0.013)	
Turnover rate		–3.754***		–2.412**
		(0.940)		(1.075)
Observations	2,416	2,416	2,416	2,416
R-squared	0.198	0.194	0.219	0.219
Firm FE, year FE	Y	Y	Y	Y
Province trend	Y	Y	Y	Y
Industry trend	Y	Y	Y	Y

The dependent variables and carbon price are in natural logarithms, while turnover rate is shown as a ratio. Announcement equals one for the regulated firms during the announcement period (2011 to 2012). Carbon price and turnover rate are only available for the regulated firms during the trading period (2013 to 2015) and are shown as zero otherwise. SEs in parentheses are clustered at the industry level. ***, significant at the 1% level; **, significant at the 5% level; * significant at the 10% level.

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rate-based rule, the total allowance may be adjusted at the end of each compliance period based on a firm's production level during this period. A rate-based rule allows a regulated firm to increase emissions as long as its emission intensity is compliant. Therefore, a rate-based rule implicitly subsidizes production and poses weaker regulatory pressure than a mass-based rule does (7).

We examine the effect of allowance allocation rules following the regression model in Eq. **4**. The estimation results, presented in Table 3, support the argument that the mass-based rule is more effective in incentivizing emission reductions. Specifically, the preferred estimates in columns 2 and 4 show that the mass-based rule reduces firm total emissions by 39.9% (95% CI is [–70.6%, –9.2%]) and 43.6% (95% CI is [–63.7%, –23.6%]) for emission intensity. However, under the rate-based rule, the effect of the ETS on total emissions is diminished by 28.4 percentage points (90% CI is [4.2%, 52.5%]), and the effect on emission intensity is weakened by 41.4 percentage points (95% CI is [23.5%, 59.3%]). Further, we combine the two regression models in Eqs. **3** and **4**. The results (*SI Appendix*, Table S16) are consistent with the main conclusions.

Discussion

This paper demonstrates that China's regional ETS pilots were effective in reducing firm emissions in the early trading phase (2013 to 2015) despite low carbon prices and allowance liquidity. The magnitude of the effect, a 16.7% reduction in carbon emissions, is on par with that of the EU ETS (8 to 12%) in the second trading phase (2008 to 2012) (14, 33, 34). Nevertheless, the regulated firms in China and the European Union have responded differently in terms of emission abatement channels. Whereas the EU ETS has reduced consumption of natural gas and petroleum products by manufacturing firms in Germany (33) and France (14), the firms regulated by China's regional ETS have increased natural gas consumption. Because China's energy mix is dominated by coal, switching to natural gas can still reduce carbon emissions.

The cost of regulations is a major concern for many countries, including China, in deciding to take more aggressive climate actions. On one hand, we find that ETS has a negative impact on employment. By putting a price on carbon, ETS imposes additional costs of production since energy conservation and fuel switching can be costly. To maintain competitive advantages, regulated firms reduce labor inputs. Our analysis contributes to the heated debate on the impact of carbon regulations on the labor market. Most studies find that ETS has a negative (20, 35) or muted impact (14, 17, 33, 34) on employment. Our finding also contributes to the literature on how environmental regulations affect employment (20, 36–38). These results, including those in this paper, suggest that it is important to provide assistance to the workers displaced from carbon-intensive sectors to ensure a just transition.

On the other hand, the measures that firms undertake to reduce emissions may also contribute to higher production efficiency. This hypothesis is supported by our empirical results. We find that ETS stimulates firms to improve productivity. This finding is consistent with the literature documenting how ETS has sparked low-carbon innovation in the European Union (39, 40) and in China's regional ETS pilot areas (25–27). Productivity growth reduces the cost of compliance with carbon regulations, which alleviates the concern of policymakers regarding the tradeoff between climate mitigation and economic growth.

Firms respond to carbon regulations by reducing labor and capital while improving energy efficiency. This suggests that firms take advantage of low-hanging fruit to reduce energy consumption and carbon emissions. The literature on greenhouse gas abatement cost curves has identified a plethora of technologies that can help achieve this (41). In addition, firm management practices are positively associated with energy efficiency and productivity (42, 43). For example, firms use sensors and big data to better dispatch cooling systems. This smart technology could free up some air conditioners and reduce capital stocks. It also reduces labor demand since firms need fewer people to manage air conditioners.

This paper sheds important light on the policies regarding carbon markets. First of all, carbon price plays a central role in incentivizing emission reductions. The carbon price in China's regional ETS pilots is relatively low compared with the social cost of carbon or the level in other mature carbon markets. A major cause of low carbon prices is the excess supply of carbon allowances (3). For example, the Guangdong and Shenzhen ETS pilots failed to auction allowances in the primary market, suggesting that carbon allowances were oversupplied. Another concern is that the carbon market is thin and carbon allowances are illiquid. Infrequent trading results from firms' lack of capacity in managing carbon allowances. In addition, most transactions occurred at the end of a compliance period due to the fact that total allowances are not known until the final output is determined under the rate-based allowance allocation rule. A low carbon price is inadequate to support China's climate ambition. If China could increase its carbon price to the same level as California's cap-and-trade program (\$17/t CO_2 e), it would reduce emissions by 8.83%. If the carbon price could be further increased to the level of the EU ETS (\$32/t CO_2 e), it would reduce emissions by 20.39%. If the carbon price could reach the social cost of carbon (\$50/t CO_2 e) (44), one would expect a 34.31% emission reduction.

Another important policy implication is that allowance allocation rules matter. A mass-based rule creates stronger regulatory pressure than a rate-based rule because the latter implicitly subsidizes production (6–8). Nevertheless, the national carbon ETS launched in 2021, which covers only the power generation sector, uses a rate-based approach. Given that China has pledged to achieve a carbon emission peak by 2030 and carbon neutrality by 2060, a national ETS without an explicit emission cap is unlikely to achieve China's ambitious climate targets. It is therefore urgent to design a transition from the rate-based system to a mass-based rule.

This paper leaves several areas for future study. First, we are not able to reliably measure firms' entry and exit in the tax survey data. Therefore, this paper only focuses on the intensive margin. Second, our analysis estimates the short-run effects of ETS.

Table 3. Heterogeneous effects by allowance allocation rules

	Total emissions		Emission intensity	
Dependent variable	(1)	(2)	(3)	(4)
Announcement	–0.083**	–0.120*	–0.047	–0.068
	(0.039)	(0.063)	(0.033)	(0.073)
Trading	–0.342***	–0.399**	–0.367***	–0.436***
	(0.098)	(0.147)	(0.076)	(0.096)
Trading × rate	0.212***	0.284*	0.319***	0.414***
	(0.067)	(0.140)	(0.079)	(0.086)
Observations	2,416	2,416	2,416	2,416
R-squared	0.055	0.207	0.102	0.233
Firm FE, year FE	Y	Y	Y	Y
Province trend	N	Y	N	Y
Industry trend	N	Y	N	Y

All dependent variables are in natural logarithms. Announcement equals one for the regulated firms during the announcement period (2011 to 2012). Trading equals one for the regulated firms during the trading period (2013 to 2015). Rate equals one if the regulated firms are categorized into the rate-based group. SEs in parentheses are clustered at the industry level. ***, significant at the 1% level; **, significant at the 5% level; *, significant at the 10% level.

Although it is important to trace out the behavioral responses of firms in the long run, such an analysis is implausible since the regional ETS pilots are in the process of being incorporated into the national carbon market. Therefore, this question can only be answered after waiting for the national ETS to operate for several years. Third, this analysis considers only carbon emissions from energy consumption, including direct emissions from burning fossil fuels and indirect emissions from purchased electricity. Due to data limitations, we are not able to include the emissions of other greenhouse gases beyond CO_2, especially those from certain chemical reactions in the manufacturing sectors. Firm-level greenhouse gas emissions are not systematically documented, especially for those firms that are not covered by the ETS. Conducting a more comprehensive analysis in the future should overcome the hurdle of emission data availability.

Data and Methods

Data.

Firm attributes. The primary firm data are obtained from the CNTSD, a large-scale annual survey conducted by China's Ministry of Finance and State Administration of Taxation. This database documents the detailed energy consumption and economic information at the firm level. One notable advantage is its broad coverage of firms. Unlike another widely used Chinese firm-level dataset—the Annual Survey of Industrial Enterprises (ASIE)—that only comprises large firms, the CNTSD covers a much wider range of firms (45). Another advantage is the detailed firm-level information about energy consumption by source, including coal, oil, natural gas, and electricity. Note that a firm is not the perfect unit of analysis compared with a plant or facility. It is difficult to determine the regulatory status of a multiple-plant firm operating in different jurisdictions. This is a caveat in the Chinese firm data collection system. Nevertheless, more than 95% of firms in the ASIE are single plants (46). Since ASIE and CNTSD follow similar protocols, dominant single plants should mitigate our concern about misclassification of ETS regulatory status.

ETS rules and performances. The ETS rules in the seven regional pilots are compiled from the official websites of local Development and Reform Commissions, which regulate carbon emissions and carbon markets (*SI Appendix*, Table S1). We compile a list of regulated firms and classify them into a rate- or mass-based system according to the allowance allocation rules (*SI Appendix*, Table S2). In addition, we obtain the carbon allowance trading data—including price and volume—from the seven carbon exchanges.

Variable construction. This paper considers both direct emissions from combustion of fossil fuels and indirect emissions from purchased electricity. Emissions are calculated from the CNTSD energy consumption data by source and carbon emission factors (*SI Appendix*, Table S3). Emission intensity is defined as the ratio of total carbon emissions to gross output value. Firm economic attributes include output value, value added, export, labor, capital, wage, and investment. Firm TFP is measured by means of two standard approaches in the economics literature (31, 32).

Summary statistics. Merging the ETS data with the firm data, the final dataset includes 51,179 unique firms associated with 254,378 firm-year observations during the 2009 to 2015 period. The procedure of data cleaning and matching is documented in *SI Appendix*. The summary statistics for the variables of interest are reported in *SI Appendix*, Table S5.

Empirical Strategy.

One-to-one matching. We use matching to construct a comparison group with firms not regulated by the ETS to serve as the counterfactuals for the treatment group with regulated firms. The estimation of ETS effects can be biased if the treatment and control groups significantly differ in their pretreatment characteristics (47). To address this concern, we employ a one-to-one nearest neighbor matching technique. For each regulated firm, we match the closest unregulated firm within the same sector according to the shortest Mahalanobis distance. This distance is calculated based on total carbon emissions, emission intensity, and energy consumption in the 2 y before the announcement of ETS (i.e., 2009 and 2010). In addition, matching within the sector–year cell can help control for sector-specific, time-variant unobservables that affect both treatment and comparison units. We allow matching with replacement to avoid introducing extra bias in the selection of control units, ensuring that each treated firm is matched with the closest comparison firm.

We carefully assess the credibility of the matching procedure using balancing tests. Specifically, we compare the sample means of covariates between the treatment and matched control groups (*SI Appendix*, Table S6). We find no significant differences between the two groups in all covariates used in matching and even for those not used. These results suggest that our matching strategy performs well in extracting reasonable comparison firms that are similar to the regulated firms within the same sector prior to the announcement of ETS.

Baseline model. Using China's regional ETS pilots as a quasi-natural experiment, which regulates carbon emissions for the firms in certain sectors over seven jurisdictions, we employ a DID approach to estimate the ETS effects on firm outcomes. For firm i in sector j from region r at year t, the baseline model specification is given by

$$Y_{ijrt} = \beta_1 \text{Announcement}_{rt} + \beta_2 \text{Trading}_{it} + \gamma_i + \lambda_t + \eta_{rt} + \delta_{jt} + \varepsilon_{ijrt}. \quad \textbf{[1]}$$

In this form, Y_{ijrt} denotes firm carbon emissions (including total emissions and emission intensity, in logarithms) or corporate financial outcomes (input, output, and productivity). The dummy Announcement_{rt} equals one if region r at year t (between 2011 and 2012) has announced its participation in ETS and zero otherwise. The dummy Trading_{it} takes a value of one for regulated firms in the trading phase and zero otherwise. Correspondingly, β_1 captures the announcement effect, and β_2 measures the trading effect.

In addition, we include firm-level fixed effect γ_i to control for unobservable firm attributes that are time-invariant. The time fixed effect indexed by λ_t absorbs year-specific unobservables. We add regional linear trend η_{rt} and industrial linear trend δ_{jt} to control for the region- and industry-specific time-varying unobservables that affect firm outcomes. In the robustness checks, we also use region-by-year and industry-by-year fixed effects. Finally, ε_{ijrt} is an unobserved error term. With the control group constructed by the matching approach, we can consistently estimate the matched-DID model in Eq. **1** using ordinary least squares.

Dynamic effects. The validity of the DID model relies on the assumption that the regulated firms do not exhibit a different emission trend from the matched comparison firms. To check this assumption, we conduct the following parallel trends test by running a variant of the DID model while controlling for the lags and leads of the policy year dummies:

$$Y_{ijrt} = \sum_{m=1}^{2} \alpha_{1m} \text{ETS}_{i,t-m} + \sum_{n=0}^{4} \alpha_{2n} \text{ETS}_{i,t+n} + \gamma_i + \lambda_t + \eta_{rt} + \delta_{jt} + \varepsilon_{ijrt}. \quad \textbf{[2]}$$

In this form, the dummy variable, denoted by ETS_{it}, integrates the preannouncement, announcement, and trading effects. $\text{ETS}_{i,t-m}$ is a prepolicy dummy indicating the mth lag of announcing ETS pilots in 2011, while $\text{ETS}_{i,t+n}$ denotes a postpolicy indicator for the nth lead. The latter measures the announcement effect for $n \in [0, 1]$ and the trading effect for $n \in [2, 4]$. Controlling for lags allows us to examine the pre-ETS effect as a parallel trends test. Controlling for leads helps trace out the treatment effects in the years after the launching of allowance trading.

Carbon market performances. The performance of carbon ETS pilots varies across regions due to diverse market designs. Carbon price signals marginal cost of abatement, and turnover rate measures the activeness of allowance trading. Utilizing carbon price and turnover rate across pilots and years, we examine how carbon market performance relates to abatement activities. A variant of the baseline model is given by

$$Y_{ijrt} = \beta_1 \text{Announcement}_{rt} + \beta_2 \text{Trading}_{it} + \beta_3 \text{Trading}_{it} \times \text{Market}_{rt} + \gamma_i + \lambda_t + \eta_{rt} + \delta_{jt} + \varepsilon_{ijrt}, \quad \textbf{[3]}$$

where Market_{rt} denotes either carbon price or turnover rate at pilot r in year t. The coefficient β_3 captures the effect of carbon market performances.

Allowance allocation. We classify regulated firms into a rate- or mass-based allowance allocation system. The baseline specification is modified to compare the treatment effects between these two allocation rules by adding another dimension of the variation. A variant of the baseline model is proposed below:

$$Y_{ijrt} = \beta_1 \text{Announcement}_{rt} + \beta_2 \text{Trading}_{it} + \beta_3 \text{Trading}_{it} \times \text{Rate}_i + \gamma_i + \lambda_t + \eta_{rt} + \delta_{jt} + \varepsilon_{ijrt}, \quad \textbf{[4]}$$

where Rate_i is a binary indicator, equaling one if firm i is in a rate-based allowance allocation system, otherwise zero. The coefficient β_3 captures the difference in treatment effects between rate- and mass-based systems. Some unregulated firms may be used to construct the control groups for both rate- and mass-based treatment groups due to matching with replacement.

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Nevertheless, in the matched sample, very few unregulated firms appear in both the rate- and mass-based control groups; they are dropped in the analysis.

Robustness checks. To test the stability of the baseline estimates, we conduct a series of sensitivity analyses. First, we consider alternative data cleaning approaches (*SI Appendix*, Table S7). Second, to address the concern of missing data on emissions from industrial processes, we run additional regressions without steel, chemical, petrochemical, cement, lime, glass, and other building materials sectors (*SI Appendix*, Table S8). Third, we isolate the influence of potential confounders at the regional and firm levels (*SI Appendix*, Table S9). In particular, we account for contemporaneous local air pollution control and energy policies. We also try to control for unobservables with alternative fixed effects. Fourth, we employ alternative empirical strategies such as different matching numbers (*SI Appendix*, Table S10), different sets of firm-level covariates for matching (*SI Appendix*, Table S11), alternative matching approaches including propensity score matching, inverse probability of treatment weighting, and coarsened exact matching (*SI Appendix*, Table S12). Further, we consider four alternative classifications and different model specifications (*SI Appendix*, Tables S13 and S14). All these results lend strong support to the conclusion that the mass-based allowance rule achieves a more pronounced carbon mitigation impact than the rate-based one does. Overall, our main conclusions survived all these robustness checks.

Data Availability. The Chinese National Tax Survey Database (CNTSD) can be made available upon request to the State Administration of Taxation of China or the Ministry of Finance of China. The code used for the analyses are available at GitHub, https://github.com/yzheng37/PNAS_ChinaETS.git.

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