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RESEARCH ARTICLE

Do different types of carbon mitigation regulations have heterogeneous effects on innovation quality?

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Abstract
Carbon peak and carbon neutralization as a global mission cannot be completed without systematically designed carbon mitigation regulations. In order to achieve the carbon emission reduction as formulated in the Paris Agreement and fulfill the promises made at the United Nations General Assembly, the Chinese government has promulgated various types of regulations to curb carbon emission with the hope of realizing the Porter effect. Selecting low-carbon pilot cities and carbon emission trading schema as the research objects, this study employs a differences-in-differences (DID) model to investigate the effects of carbon mitigation regulations on innovation quality and its heterogeneity. The empirical results reveal that market-based carbon mitigation regulations can significantly achieve the Porter effect and improve innovation quality. Furthermore, the government financial situation and the technical efficiency change have important moderating and mediating effects respectively. It is recommended that a full play of the market be given in China for the Porter effect. The main scientific value of this paper is distinguished the heterogenous effect of different types of environmental regulations, which can enhance the pertinence of environmental regulation.

Keywords Carbon mitigation regulations · Heterogeneous effects · Innovation quality · Quasi-nature experiment

Introduction

Climate change and environmental pollution are challenging issues on the top agenda of nations and generations. As is known to all, every country could be endangered unless all countries are safe. Without global cooperation, it is impossible to combat the threatening results of climate change and pollution, especially during the COVID-19 pandemic. Several researchers have warned that climate change will exacerbate the consequences of COVID-19 (Chagas et al. 2016; Magazzino et al. 2020), which may lead to the superposition of global health crisis and climate crisis blocking the process of global sustainability (Schaltegger 2020). The joint communique of COP 26 as the first global endeavor after the *Paris Agreement* stressed the importance of global cooperation and formulated detailed countermeasures against climate change. How to properly design carbon mitigation regulations to achieve the goal of carbon peak and carbon, as well as the Porter effect, through innovation especially green innovation is among the top priorities of all governments. This study aims to shed new light on the effect of carbon mitigation regulations on innovation quality. There is much research in this field, but the existing research may have to be faced with endogenous problems caused by two-way causality from traditional linear models. Even though Ren et al. (2021) employ the lag term of the independence variable as an instrumental variable to alleviate this concern, the justification of this method is still questionable. Furthermore, few research has probed into the possible heterogeneous effects of different types of environmental regulations. Shen et al. (2019) used proxy variables to explore the heterogeneous effect; it may lead to measurement error, however. To sum up, studies on the potential negative sides of carbon mitigation regulations are far from sufficient.

A factor evaluating the carbon mitigation regulations is whether they can promote innovation, but conclusions

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drawn by different scholars are inconsistent. Specifically, studies supporting the leverage effect reported that well-designed environmental policies can promote R&D effort to promote innovations through investment multiplier (Pan et al. 2019), and the efficiency improvement brought by innovation reduces the production cost (Peng et al. 2018). Researchers backing up the immigration effect found environmental policy reduces air pollution and attracts high-quality talents, thus improving the level of innovation (Qin and Zhu 2018). Market fundamentalists believed the crowding out effect of environmental regulation cannot be ignored, which will have a negative effect on innovation (Kneller and Manderson 2012). Still, other studies revealed the nonlinear relationship between innovation and environmental policy (Wang and Wei 2020).

Investigations of the effect of environmental policy on innovation quality are not adequate. Haner (2002) defined the terminology "innovation quality." With the *Paris Agreement* officially entering into force, innovation quality has become a research hot spot because high-quality innovation can bring about less consumption of natural resources. Existing studies conclude such factors can affect innovation quality as innovation strategy, environmental regulation, and innovation input (Wu and Lin 2011; Pan et al. 2021; Afrifa et al. 2020).

China, like other countries in favor of the *Paris Agreement,* should perform the global citizenship for pollution reduction when promoting domestic development. The following questions thus arise: How do carbon mitigation regulations influence innovation quality? Do different types of carbon mitigation regulations have heterogeneous effects on innovation quality? How to design and implement carbon mitigation regulations to balance the invisible and visible hands? Will carbon mitigation regulations lead to some negative impacts such as industrial-hollowing-out? Although the effect of carbon mitigation regulations on innovation has long been acknowledged in the literature, much less is known about the heterogeneous effects of different kind of carbon mitigation regulations. The recent trend in evaluating policy effect on innovation has put more emphases on the double dividends of carbon mitigation regulations (Bento and Jacobsen 2007; Degirmenci and Aydin 2021), but few studies have focused on the policy design process for the double dividends.

COVID-19 has been playing an important role amid the global pandemic since 2020 (Wang and Zhang 2021). On the initial stage of the pandemic, major economies in the world adopted a lockdown strategic to prevent the transmission of COVID-19, which inevitably make CO_2 emission decline by reducing economic activity (Wang and Su 2020). Even though, after the popularity of the vaccine, almost every country cancelled the limitation of preventing COVID-19, mutant virus, such as Delta and Omicron, still hindering the recovery of the demand side.

In spite of the much literature investigating effects of carbon mitigation regulations on innovation, research gaps are still conspicuous. First, prior studies comparing different environmental regulations have not well addressed the problem of endogeneity caused by the two-way causality between carbon mitigation regulations and innovation, even though Shen et al. (2019) conducted some constructive discussions. Nevertheless, the heterogeneous effects of varied carbon mitigation regulations should be explored so as to design better-targeted and systematic carbon mitigation regulations for desirable positive effects. Second, less scholars probed into the possible negative impacts of carbon mitigation regulations, but a comprehensive analysis of both the negative and positive effects can help to come up with balanced and dialectic policies. In order to fill the above gaps, this paper employs panel data of 269 Chinese mainland cities and regions from 2007 to 2018 to compare the heterogeneous effects of different types of carbon mitigation regulations and carries out a quasi-natural experiment to empirically test the causal effect and heterogeneous effects of command-and-control and market-based carbon mitigation regulations on innovation quality, aiming to establish a new framework for evaluating and comparing different types of environmental regulations. Our empirical results confirm the existence of the heterogeneous effects of different types of carbon mitigation regulations. Specifically, the market-based regulations play a more important role in promoting innovation quality than the command-and-control ones, because the market-based ones, e.g., carbon emission trading schema, can promote innovation quality significantly and their such negative effects as industrial hollowing-out are insignificant. Moreover, the market-based regulations can alleviate the negative effects caused by command-and-control ones. Additionally, providing more technical details and indicates that the promotion effects of both market-based and command-and-control environmental regulations on innovation performance are limited.

This research contributes to the scholarship and policy makers in the following ways. (1) Tries to put different types of environmental regulations into the same analysis framework in order to explore the heterogeneous effects and provide empirical evidence for policy making. (2) Different from Shen et al. (2019), this study employs the differences-in-differences (DID) model addressing endogenous problems. (3) Such potential negative impacts as excessive financialization and industrial hollowing-out are taken into consideration for a holistic and dialectic view of regulations. (4) Some technical details such as innovation performances are offered for a better design of the future carbon mitigation regulations.

Literature review and theoretical hypothesis

Research on the effect of carbon mitigation policies

Several literatures discussed factors affecting carbon emissions, such as energy efficiency, economic, energy, social, and trade structural (Li et al. 2021). Even though divergence still exists, majority of scholars believed regulations play an important role in carbon mitigation. Scholars believing in market failure insist that governmental agencies issuing environmental policies play an important role in carbon management, even though this viewpoint has been questioned by other researchers. In developed countries, strict environmental control is the main reason for the decline of pollutants (Dearfield et al. 2005), which can explain 45% of the decline in pollutant emissions of U.S. enterprises (Shapiro and Walker 2018). Moreover, strict environmental supervision may generate double dividends for both economy and environment (Jefferson et al. 2013). In developing countries, the imperfect market mechanism makes the effect of market-based carbon mitigation policies not significant (Lang and Lanz 2022). Even though the command-and-control environmental regulation may encounter problems including increased cost of economics (Chen et al. 2018) and its long-term effect is not as good as short-term one (Shi et al. 2020), the majority of scholars argue that "the visible hand" should play a more important role than "the invisible hand" in the process of environmental governance (Johnstone et al. 2010).

Many scholars think the impact of command-and-control carbon mitigation regulations upon pollution control is significant, but according to the neo-liberals, these regulations can hardly achieve double dividends for the environment and economy, which are crucial to sustainable carbon mitigation regulation (Tang et al. 2020). Some studies found that market-based carbon mitigation regulation brings less shock to economic development (Zhang et al. 2021a, b), but others argued that market-based carbon mitigation regulation can not play a full role in pollution mitigation, especially in developing country (Li et al. 2016), and the reason is that the imperfect market mechanism makes it insufficiently effective (Shao et al. 2016).

New structural economists argue that both government and the market can learn from each other and should be given full consideration for carbon mitigation. Thus, government subsidy, a carbon mitigation regulation combining command-control type and market-based type, has been discussed by extant research. Obviously, innovation as a high-risk and heavy-investment activity may increase the financing constraints of enterprises. Government subsidy as an effective method to tackle this problem can increase enterprise R&D investment and willingness (Peng et al. 2018). However, government subsidy may spill over private R&D investment and transform the high-quality innovation of enterprises into strategic innovation to obtain subsidies, which may decrease the quality of innovation. Because of the moral hazard of defrauding subsidies, low-quality innovation is more obvious in prior subsidies (Peng et al. 2018).

To sum up, the effects of carbon mitigation regulation in different countries have been investigated by several researchers (Marin and Vona 2019), and existing studies have done plenty of work on the causal effect of carbon mitigation regulation on innovation (Qiu et al. 2017). However, heterogeneous effects of different carbon mitigation regulations can not be well explored because scholars all use proxy variables to measure carbon mitigation regulation, which may lead to measurement errors. This paper tries to employ DID models to assess the heterogeneous effects for more reliable results.

Hypothesis development

Effect of carbon mitigation regulation on innovation quality

The externality theory argues that carbon mitigation regulation may internalize the external cost of carbon emissions and increase the production cost of enterprises as the main body of innovation and innovation quality (Zhou et al. 2022). Command-and-control carbon mitigation regulations focusing on the top-down environmental pressure may reinforce local governmental supervision on pollution emission for not being held accountable by superior departments. Under such circumstances, the compliance costs for businesses are increasing and enterprises will have to reduce their costs in other aspects, especially the innovation investment with high risks and low returns (Chen et al. 2021). In contrast, market-based carbon mitigation regulations aim to change the previous environmental governance model where firms pollute and governments pay for it. The external cost of pollutant emission on social welfare is transferred to firms through the market. Furthermore, such financial market carbon mitigation regulations as green credit limit the financial support for highly polluting enterprises, which may further increase the financial constraint of enterprises (Zhang et al. 2021a, b). Nevertheless, innovation demands for financial support, thus market-based carbon mitigation regulation may hinder innovation.

Even though efficient market believers insist that market mechanism is the most effective way to allocate resources, price fluctuation, and information transparency may cast dissatisfying influences upon innovation. Those having identified market failure deem that the negative externalities caused by greenhouses gas emission can render market mechanism ineffective without properly designed regulations. Moreover, a key indicator of well-designed carbon mitigation regulation is whether it can promote innovation, or produce the Porter effect. For command-and-control carbon mitigation regulation, the increased regulatory pressure discourages firms from following the old mode of an illegal discharge and urges them to carry out environment-friendly innovation. The market-based carbon mitigation regulation motivates enterprises to innovate for pollution mitigation so as to occupy a favorable position in emission trading schema and obtain super profits (Hu et al. 2020). For this reason, firms may put more emphasis on innovation and build a positive cycle of policy and innovation (Lanoie et al. 2008). According to the above analysis, 2 contradicting hypotheses are proposed:

H1a: Environmental policy will hinder innovation quality.
H1b: Environmental policy will promote innovation quality.

Heterogeneous effects of different carbon mitigation regulations on innovation

Different types of environmental policies have different operating mechanisms and thus produce heterogeneity (Shen et al. 2019). Game theorists argue that command-and-control regulations emphasizing competition over cooperation may cause a prisoner's dilemma (Kahn et al. 2015) and push local governments to follow one-size-fits-all policies and add weights at downstream implementation levels, which would result in negative effects on enterprise innovation. Polycentric Governance theory argues that solving this dilemma is inseparable from the joint action of the government and the market. The market-based type aims to allocate more resources to nonpolluting enterprises (Zhang et al. 2021a, b) and firms failing to cannot meet the market requirement will have to be eliminated (Calel and Dechezleprêtre 2016). Hence, enterprises are forced and motivated to strengthen their innovation. In addition, the ever-increasing production cost will make some low-tech enterprises move to non-pilot areas to reduce costs (Zhang et al. 2021a, b). In conclusion, this study holds that market-based carbon mitigation regulation plays a stronger role in promoting innovation than the command-control one.

H2: the effect of market-based carbon mitigation regulation on promoting innovation quality is more significant than that of the command-and-control one.

Research design

Variable definition and data source

Dependent variable: innovation quality

Existing research reports that innovation can be divided into 2 categories: common innovation including design patent and utility model patent, as well as high-quality innovation referring to the invention patents including green invention patents (Ying and He 2021). Only high-quality innovation can increase total factor productivity. For this reason, this study employs the total factor productivity and the granted number of green invention patent to measure innovation quality. The SBM model is adopted to measure the total factor productivity by breaking down into technical change and efficiency change for the investigation of carbon mitigation regulation mechanism. The capital stock, calculated by the perpetual inventory method, and the amount of employed population are selected as the input variables, and the deflated GDP is used as the output variable. According to previous studies, the deception rate is 9.6%.

Independent variable: carbon mitigation regulation

Most researchers use wastewater treatment rate, the number of current effective carbon mitigation regulations and rules of the year, environmental penalty quantity (Kuusela and Lintunen 2020), or the ratio of the amount of pollutant discharge fees collected by each region to the number of discharged households as proxy variables to measure carbon mitigation regulation. Some scholars adopt similar but weighted variables to form a composite index as an alternative variable of carbon mitigation regulation. Nevertheless, carbon mitigation regulations are not only reflected in fines, laws, pollution charges and so on, so employment of these proxy variables may lead to measurement error. What is more, green innovation will reduce such consequences as environmental fines of carbon mitigation regulations, which may result in two-way causality and bring bias in causal effect estimation. For the above reasons, this paper adopts DID model to estimate the causal effect. Briefly, low-carbon

Table 1 Variable's definition and descriptive statistics

	Variables (symbols)	Caculainge method	Unit	Mean	SD	Max	Min
Dependent variables	Total factor productivity (tfp)	DEA-Malmquist	-	0.9967	0.1143	2.3816	0.4223
	Green innovation GI	ln (1 + Green invention patent authorization)	Piece	2.3520	1.6982	8.7133	0
Independent variables	Low carbon city pilot (LC)	Previously described	-	0.0693	0.2539	1	0
	Carbon emission trading schema (ets)		-	0.2051	0.4038	1	0
Control variables	gdp	GDP divided by population	Yuan/preson	10.253	0.7273	13.056	4.5951
	Industrial structure (IS)	Ratio of added value of tertiary industry to added value of secondary industry	%	0.8213	0.3918	4.1115	0.1286
	Population density (PD)	Population per square kilometer	$10^4/km^2$	5.7813	0.8817	7.8817	1.5728
	Unemployment rate (UER)	The number of unemployed divided by the number of working people	%	5.7313	2.3523	55.991	0.2967
	Foreign direct investment (FDI)	Ratio of foreign direct investment to GDP	%	2.1144	0.7272	88.898	0.0012

pilot cities and carbon emission trading schema are chosen as polices variables to measure command-control carbon mitigation regulation and market-based carbon mitigation regulation, respectively. The purposes of the 2 policies are almost the same. Later, the two policies are further distinguished for heterogeneous effects analysis.

Control variables

This study adding control variables into the specification model as described in 1 takes logarithms for all control variables to avoid heteroscedasticity and uses the lag term of variables to alleviate autocorrelation. All the data are from the *Chinese City Statistic Yearbook* (2006–2018) and CSMAR database.

Empirical model

Low carbon pilot cities (LC) and carbon emission trading schema (ets) are both processed in batches, so the common DID model may lead to model misspecification error. This paper following Huo et al. (2022) employs a two-stage DID model. The experimental group and the control group are randomly set, which may address the endogenies. Considering the availability and comparability of data, city panel data during the period 2005 to 2017 are selected for our empirical analysis. The DID model is listed in the following Eq. (1):

$$\mathrm{Ino}_{it} = \alpha + \beta \mathrm{CMR}_{it} + X' \theta + \gamma_i + \delta_t + \varepsilon_{it} \tag{1}$$

CMR_{it} is a dummy variable. If city *i* in period *t* implemented carbon mitigation regulation, the value is 1; otherwise, it is 0. *X* is the matrix of control variables. γ_i and δ_t are city and time-fixed effects, respectively. ε_{it} is the stochastic error term.

Employed DID model to evaluate policy is very common in existing researches; however, there are few literatures that compare the heterogenous effect of different types of environmental regulations using one quasi-natural experimental framework, which has been further explored by this research. This paper filled the gap that the lack of empirical evidence about the several types of regulations how to effect carbon mitigation.

Empirical test

Baseline results

Table 2 shows our results via the baseline model in Eq. (2). Columns 1 and 2 display the estimations of the total factor productivity (tfp). Columns 3 and 4 demonstrate the values of green technology innovation (gtec). The effect of command-and-control environmental regulation (taking low carbon pilot city as an example) on innovation quality is reflected in columns 1 and 3. In column 1, the low carbon pilot city (LC) plays a positive role in tfp, which was identified by (). Compared with the control group, the tfp of low-carbon pilot cities insignificantly increases by 0.0096, that is to say, the result is not significant, and not equal to 0. In column 3, the LC has a negative effect on gtec, which decrease the green

Table 2 Baseline results

	tfp		gtec	
LC	0.0096 (0.0068)		−0.0082 (0.0838)	
ETS		0.0084** (0.0040)		0.0475* (0.0286)
City-control variables	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within
N	2959	2959	3228	3228
R^2	0.5946	0.5966	0.1606	0.1511

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

The Standard error lists in parentheses is robust and clustered in city level, the same below

technology innovation by 0.0082%. In other words, the result is insignificant and nearly equal to 0. Compared with existing papers, this paper furtherly investigates and firstly confirmed that different types of environmental regulation have a heterogeneous effect on carbon mitigation.

The effect of market-based carbon mitigation regulation (taking China carbon emission trading schema as an example) is listed in columns 2 and 4, indicating that the implementation of carbon emission trading schema (ETS) may lead to a 0.0084 increase in total factor productivity and 4.75% increase of green technology. Both results are significant and not equal to 0 in the 10% level. To sum up, the result of the baseline model (2) verifies hypothesis 1 constructed in section 2.

The reason for the baseline results may be attributed to the following 3 aspects: (1) command-and-control carbon mitigation regulations have negative effects on resource allocation efficiency and bring crowding-out consequences on innovation resource because they exert excessive interventions in enterprise management and increase their operation and management costs, which will damage the enthusiasm of enterprise innovation (Kemp and Pontoglio 2011). (2) According to Tian et al. (2020), during the process of carbon mitigation regulation implementation, one-size-fits-all misconducts, as well as malicious weight adding at downstream governments, are more common, and inevitably weaken the policy efficacy and efficiency. (3) In line with Zhang et al. (2021a, b), market-based carbon mitigation regulation may guide the production factors to distribute more reasonably. To be specific, ETS promotes innovation quality by reducing investment in energy-intensive industries and promoting the firms' innovation enthusiasm.

Robustness test

Parallel trend test

For the consistency of DID estimator, there should be no significant difference in the change trend of dependent variables between the treatment group and the control group before the implementation of the policy. This paper employs the dynamic DID model in Eq. (2) to test the parallel trend between the treatment group and the control group.

$$\mathrm{Inq}_{\mathrm{it}} = \sum\nolimits_{\mathrm{i}=-4}^{3} \beta_{\mathrm{i}} \mathrm{CMR}_{\mathrm{it+i}} + \mathrm{X}^{'}\theta + \gamma_{\mathrm{i}} + \delta_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \tag{2}$$

The results of the parallel trend test in Table 3 reveal that estimators of the effects before the implementation of the policy are not significant at the 5% level even though some are significant at the 10% level, indicating that the change trend of dependent variables between the experimental group and the control group is basically the same before the implementation of carbon mitigation regulations.

Table 3 Parallel trend test

	tfp		gtec	
Before4	0.0157 (0.0113)	0.0013 (0.0113)	−0.0166 (0.0762)	0.1161* (0.0704)
Before3	0.0034 (0.0128)	0.0113 (0.0138)	0.0576 (0.0564)	−0.0119 (0.0579)
Before2	0.0125 (0.0099)	−0.0231* (0.0137)	0.1184* (0.0667)	−0.0721 (0.0529)
Before1	−0.0086 (0.0095)	0.0191* (0.0104)	−0.0463 (0.0747)	−0.0069 (0.6111)
Current	−0.0143 (0.0098)	0.0078** (0.0040)	0.0525 (0.0647)	0.0553** (0.0282)
After1	0.0395* (0.0154)	0.0292*** (0.0030)	−0.0381 (0.0808)	−0.0412 (0.0284)
After2	0.0036 (0.0156)	0.0122*** (0.0042)	0.1084 (0.0772)	0.0114 (0.0272)
After3	−0.0049 (0.0086)	0.0022 (0.0038)	−0.1395 (0.0849)	0.0213 (0.0290)
City-control variables	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within
N	2959	2950	2959	2959
R^2	0.5910	0.6060	0.1441	0.1392

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

Table 4 Counterfactual analysis

	Cultural construction	
LC	0.1092 (0.0606)	
ets		0.0073 (0.0162)
City-control variables	Within	Within
Urban-fixed effect	Within	Within
Year-fixed effects	Within	Within
N	2959	2950
R^2	0.0498	0.0407

In addition, Table 3 also shows the command-and-control carbon mitigation regulation only has a short-term positive effect on innovation quality while the market-based one has a long-term positive effect to some extent, which is consistent with the findings of the empirical tests by Zhang et al. (2019) and Shi et al. (2020). Therefore, the market should play a more important role so as to achieve better Porter effects of carbon mitigation regulations.

Placebo test

Base-rate fallacy is common errors in inferring populations from samples. This paper employs LC and ETS to represent command-and-control and market-based regulations, respectively; however, due to publication error, we cannot understand the effective rate of regulations, which may threaten the correctness of our causality inferences. This paper arranges experimental cities in treatment and control groups by way of a randomized block experiment. The results of the placebo test in the Appendix demonstrate that the *t*-value of the estimator in Table 2 is a small probability event, which confirms the robustness of baseline results.

Counterfactual analysis

This paper explores the effect of carbon mitigation regulations on cultural construction by taking book collection per 100 people as the proxy variable. If the estimator of the effect of carbon mitigation regulation on cultural construction is not significant, the interference of other factors on the empirical results could be excluded. Table 3 offers the result of the counterfactual analysis and confirms the robustness of baseline results (Table 4).

Changing calculating methods and key coefficient[1]

The difference between such key parameter settings as the depreciation rate and such calculating methods as input or output-oriented ones can change the calculation of TFP and affect the results of empirical research. According to related literature, the maximum depreciation rate is 13.1% and the minimum one is 5%. This study recalculates TFP by setting the depreciation rate above the coefficient and changing output oriented to input-oriented method. The results of repeated baseline regressions basically remain the same.

[1] Due to space limitation, results of this section are not listed in the main body of this paper.

Table 5 Granger-cause test

Null hypothesis	$\widehat{Z}$ test(*P*-value)
tfp is not Granger-cause of LC	1.1452 (0.2518)
gtec is not Granger-cause of LC	1.0433 (0.2958)
tfp is not Granger-cause of ETS	0.9714 (0.2838)
gtec is not Granger-cause of ETS	0.7733 (0.4644)

Discussion about the endogeneity

(1) **Measurement error**
Innovation quality is reflected via not only TFP and green invention patent, but also some factors difficult to observe, which may lead to measurement error. The least-square attenuation will occur and the estimator is underestimated. Even though the consistency of our estimator is threatened, the estimator of the baseline model is significantly larger than 0, indicating that the measurement error will not affect the causal inference.

(2) **Reverse causality**
The dependent variables do not affect the independent variables, which is the core condition of consistency and the minimum requirement for causal inference of the OLS estimator, as well as the key factor for the suitability of DID method. In order to verify the hypothesis that innovation quality does not affect carbon mitigation regulations, according to Yu et al. (2021), Hurlin (2012), this paper proposes the Granger causality test for the potential causality of innovation quality on carbon mitigation regulations. The results of the Granger causality test listed in Table 5 show that all $\widehat{Z}$ test estimators are not significantly equal to 0, which indicates that the null hypothesis cannot be rejected. The Granger test reveals that the reverse causality is not obvious.

(3) **Omitting variable bias (OVB)**

Omitting variables can be a key factor causing the inconsistency of the OLS estimator when the omitted variables are correlated with the independent variables. This paper controls several external factors related to innovation quality.

Table 6 Heterogeneous effect analysis

	tfp			gtec		
dLC	0.0044 (0.0074)			0.0111 (0.0844)		
dets	-	0.0076* (0.0040)			0.0545* (0.0297)	
Total	-		0.0166 (0.0110)			− 0.0604 (0.0928)
City-control variables	Within	Within	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within	Within	Within
N	2959	2959	2959	3228	3228	3228
R^2	0.5947	0.5964	0.5948	0.1614	0.1606	0.1617

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

However, due to the sampling limitation, such internal factors as input of innovation resource of firms cannot be observed. When omitting variable is present, the bias of the OLS estimator is expressed in Eq. (3).

$$\widehat{\rho} = \rho + \gamma \frac{\mathrm{COV(X, UV)}}{\mathrm{Var(UV)}} \tag{3}$$

γ is a real coefficient measuring the effect of the unobservable variable (UV) on dependent variables (Y), COV (X, UV) is the Covariance of independent variable (X) and UV. In this paper, such internal unobservable variables as the input of innovation resource of firms is positively correlated with innovation quality, so γ is expected to be positive. In contrast, regulations may internalize the external cost of carbon emissions and result in increased financing constraints and reduced innovation resources, so COV (X, UV) is expected to be negative. For this reason, this paper argues that the estimator in the baseline model is underestimated for the omitting variable and OVB will not threaten our causal inference even when it is present.

Heterogeneous effect

The heterogenous effect of different types of environmental regulations on innovation quality has been verified via the baseline model. Furthermore, the net effect and the synthetic effect are also noteworthy (Mi et al.,). This section changes the key variable in the baseline model via the following method: dLC, dets, and total are all dummy variables and equal to 1 when city i implements low carbon pilot city regulations, or carbon emission trading schema, or both, in year t. Table 6 shows the results of the net effect and synthetic effect.

Columns 1–13 list the result of net effect and synthetic effect of carbon mitigation regulations on tfp. Column (1) shows that cities implementing only LC rather than ETS may promote tfp by 0.0044 unit, but the estimator is not significant in 10% level; column 2 reveals that cities implementing ETS instead of LC may increase tfp by 0.0076 unit and the result is significantly larger than 0 in 5% level. However, the synthetic effect of LC and ETS on tfp is 0.0166 but not significant. Conclusions inferred from columns 4–6 remain roughly the same.

The possible explanations may lie in the following aspects. (1) From the perspective of resource allocation, the promotion effect of market-based regulations on resource allocation may be offset by command-and-control regulations. (2) Regarding the relationship between the government and the market, the mechanism of the market in developing countries is imperfect, so the market-based and command-and-control regulations cannot form a joint force well, leading to synthesis deviation (Shao et al. 2016).

Government support plays an important role in the innovation process and in promoting innovation demands for government finance. In areas with abundant financial resources, the government can better promote innovation, so the effect of carbon mitigation regulation on innovation quality might be better. For the investigation of the heterogeneous effect, the interaction-DID model in Eq. (4) is employed to explore the heterogeneous effect of government finance.

$$\mathrm{Inq}_{it} = \beta_1 \mathrm{CMR}_{it} + \beta_2 \mathrm{fdr}_{it} + \beta_3 \mathrm{CMR}^{*}\mathrm{fdr}_{it} + X^{'}\theta + \gamma_i + \delta_t + \varepsilon_{it} \tag{4}$$

fdr_{it} is the logarithm of the government deficit rate. Table 7 lists the results of the interaction-DID model. As seen in column 2, the interaction term is less than 0 at 1% significance level, which means that the higher the fiscal deficit rate, the weaker the ability of carbon mitigation regulations to promote the quality of innovation. In column 1, the interaction term is not significant at 10% level, indicating that the promotion effect of command-and-control carbon mitigation regulations on innovation quality is limited. In addition, neither interaction term is significant at 10% level for green innovation. The interaction-DID model partially confirmed the moderating effect of financial constraint on innovation quality, which also confirmed the important role of government on the Porter

Table 7 Heterogeneous effect of government finance

	tfp		lgtec	
LC*fdr	0.0043 (0.0046)		−0.0139 (0.0253)	
Ets*fdr		−0.0108*** (0.0037)	-	−0.0056 (0.0214)
LC	0.0033 (0.0092)		−0.0007 (0.0786)	
ets		0.0275*** (0.0088)		0.0317 (0.0454)
fdr	0.0008*** (0.0002)	0.0097*** (0.0017)	−0.0052 (0.0112)	−0.0091 (0.0125)
City-control variables	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within
N	2959	2959	3228	3228
R^2	0.5974	0.6014	0.1377	0.1412

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

Table 8 Mediating effect

	tec		tc	
LC	0.0101 (0.0069)		−0.0004 (0.0006)	
ETS	-	0.0087** (0.0041)	-	−0.0009 (0.0007)
City-control variables	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within
N	2959	2959	2959	2959
R^2	0.5926	0.5948	0.8927	0.8927

effect of carbon -mitigation regulations. A possible explanation is that China's industry is not high-end enough, and government finance is mainly used to improve total factor productivity instead of green innovation.

Mediating effect analysis

IN order to probe into the inner mechanism of carbon mitigation regulations affecting innovation quality, the decomposition method proposed by Aoki (2012) is employed and the total factor productivity is divided into 2 categories: technology efficiency change (tec) and technology change (tc), so as to explore the mediating effect of carbon mitigation regulations. Table 8 gives the results of mediating effect analysis and reveals that the mediating effect of market-based carbon mitigation regulation is technology efficiency change instead of technology change. Compared with the control group, the implementation of the carbon emission trading schema evenly increases the technical efficiency by 0.0084.

Further analysis

Potential negative effect discussion

Rational actors' theory argues that economic individuals pursue the maximization of interests. Carbon emission is an inevitable by-product in the production process. Obviously, implementation of carbon mitigation regulations can achieve carbon mitigation, but it may push out manufacturing firms and lead to too much finance and industrial hollowing-out. This paper discusses whether carbon mitigation regulations may cause these problems. Equations (5) and (6) provide the empirical models:

$$FD_{it} = \alpha_0 + \alpha_1 CMR_{it} + X' \beta + \sigma_t + \mu_i + \varepsilon_{it} \tag{5}$$

$$IHO_{it} = \alpha_0 + \alpha_1 CMR_{it} + X' \beta + \sigma_t + \mu_i + \varepsilon_{it} \tag{6}$$

FD_{it} is an independent variable.

Table 9 shows the result of the potential negative effect of carbon mitigation regulations. Columns 1–4 list the result of regulation on the financial market. Columns 2 and 4 reveal that ETS has some insignificant negative effects on financial development and LC has significant negative impacts upon financial development efficiency. In addition, the above results and the findings in column 6 prove that the market-based carbon mitigation regulations will not lead to industrial hollowing-out, but improve the quality of manufacturing. A possible explanation is that the promoting effect of high-end manufacturing is higher than the restraining effect of traditional manufacturing.

Table 9 Potential negative effect

	FDD		FDE		IHO	
LC	0.0406 (0.0338)	-	−0.0707** (0.0356)		0.0123 (0.0466)	-
ETS	-	−0.0064 (0.0116)		−0.0208 (0.0154)	-	−0.1577*** (0.0243)
City-control variables	Within	Within	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within	Within	Within
N	3228	3228	3228	3228	3228	3228
R^2	0.0713	0.0630	0.0306	0.0368	0.2707	0.2761

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

Table 10 Technical detail analysis

	Subinn_per		Strinn_per	
LC	0.0481 (0.0718)		0.0276 (0.0308)	
ETS	-	0.0676* (0.0347)	-	−0.0132 (0.0206)
City-control variables	Within	Within	Within	Within
Urban-fixed effect	Within	Within	Within	Within
Year-fixed effects	Within	Within	Within	Within
N	2959	2959	2959	2959
R^2	0.1907	0.0063	0.0506	0.0471

"***," "**," "*" represent the estimator is significant in 1%, 5%, and 10% level, respectively

Technical detail analysis

Even though this paper empirically tests the hypothesis that carbon mitigation regulations may promote innovation quality, but there are some studies arguing that regulations may promote strategic innovation rather than substantive innovation (Van Leeuwen and Mohnen 2016) and decrease the innovation performance (Zhang et al. 2021a, b).

The input variables are R&D investment and the number of R&D personnel and the output variable is the authorized amount of design patents and new invention patent authorization. Table 9 lists the empirical results based on models 6 and 7.

In column 2 of Table 9, the estimator of market-based carbon mitigation regulation is promoting substantive innovation significantly at 10% level, while other key estimators are not significant at 10% level. Results in Table 9 indicate that the carbon mitigation regulations have not played a more important role in promoting innovation performance, especially command-and-control regulations, in line with Hsu et al. (2021). The possible explanation is when the government facing the environmental pressure from its superior, it will invest more in R&D, while enterprises hope to get more funds through more innovations, especially less difficult strategic innovations, and decrease their innovation performance (Table 10).

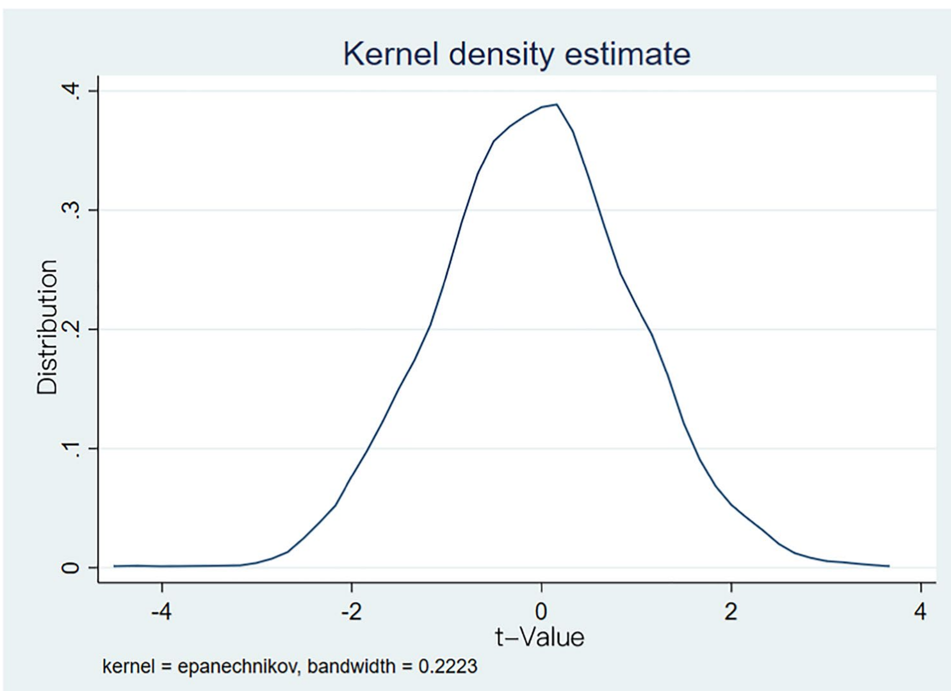
Conclusion limitation and policy implication

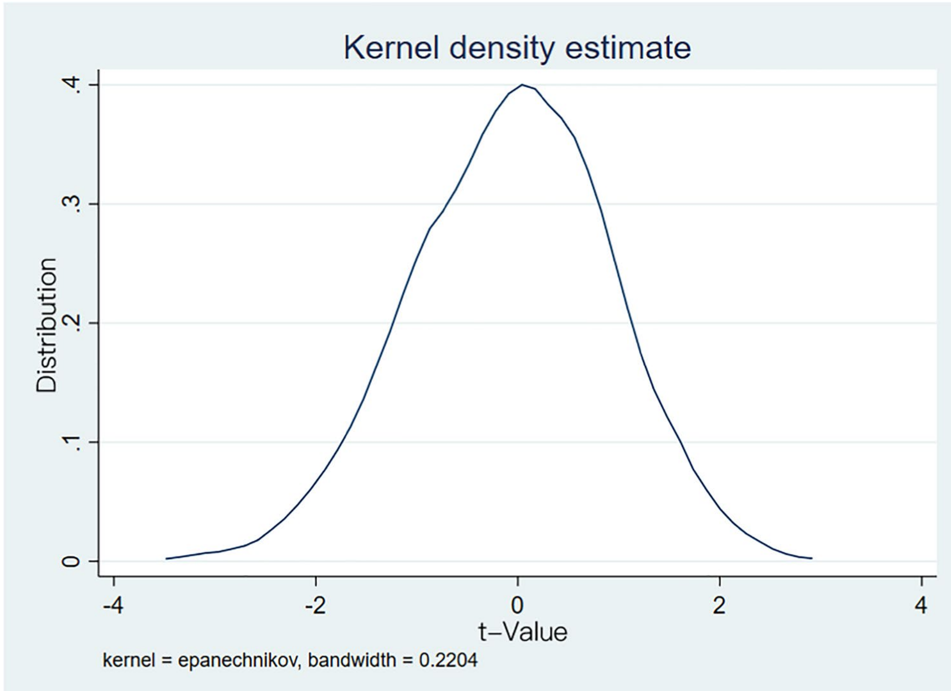
This study constructs a quasi-nature experiment based on low-carbon pilot cities and carbon emission trading schema and employs a DID model to explore the causal effect between carbon mitigation regulations and innovation quality as well as the heterogeneous effects of different types of carbon mitigation regulations. The main scientific value is comparing the heterogenous effect of different environmental regulations on carbon mitigation, which supplied empirical evidence for policy making and implementation. The following conclusions are reached: (1) Our theoretical analyses show that well-designed carbon mitigation regulations can alleviate negative externality of carbon emission and achieve a double dividend of carbon mitigation and innovation. (2) Our empirical studies evaluate the heterogeneous effects of different types of carbon mitigation regulations on innovation quality and prove that the effect of market-based regulation is more obvious that of command-and-control one, which partially supports the Polycentric Governance theory of carbon mitigation. (3) The synthetic effect of different types of regulations is not well formed because the EMH in such developing countries as China is not established. (4) The potential negative effect of regulations is not significant in market-based ones; however, command-and-control regulations may bring a negative effect on market efficiency, indicating that the sole government-led carbon mitigation model needs to be improved.

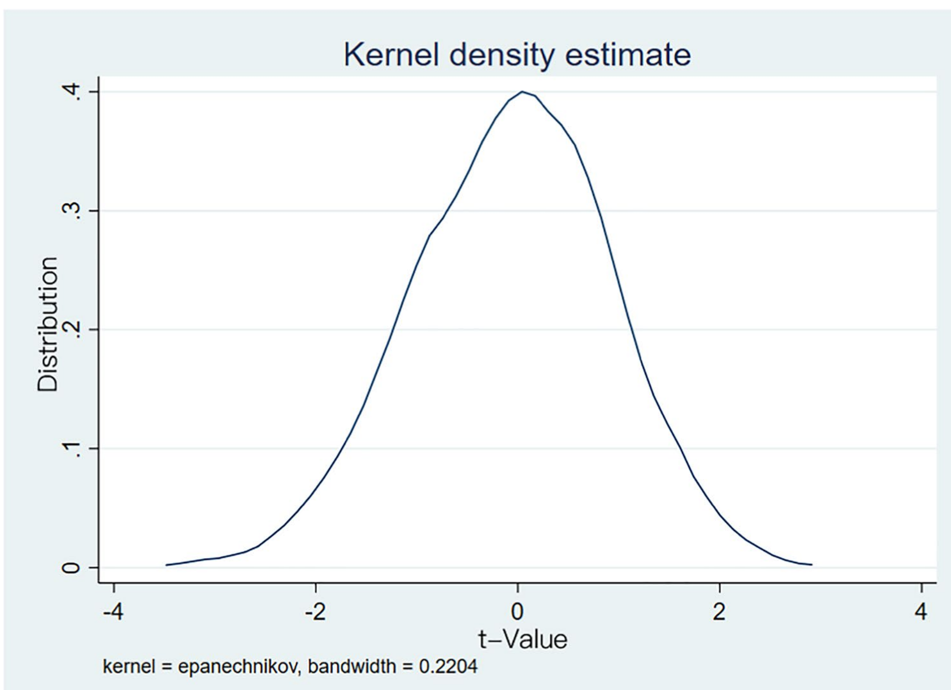
This research has the following policy implications. (1) The traditional Chinese relying-on-government-only model will have to fall into a prisoner's dilemma. As for the carbon neutralization governance, mechanism design should make incentive compatibility among multiple agents, such as more reasonable calculation of carbon emission limits of various regions and enterprises. (2) According to the empirical analysis, the market plays a more important role than the government in promoting innovation quality. Therefore, the power of the market should be given a full play so as to achieve the double dividends of carbon emission reduction and technological progress. Governments should reduce unnecessary administrative interference with the market and avoid maliciously enhanced supervision or one-size-fits-all regulation in the implementation process. (3) This paper confirms that the synthetic effect of government and market in carbon mitigation is not significant, implying that China should boost both governance capacity and market mechanism so as to enable the visible hand and the invisible hand to collaborate with each other.

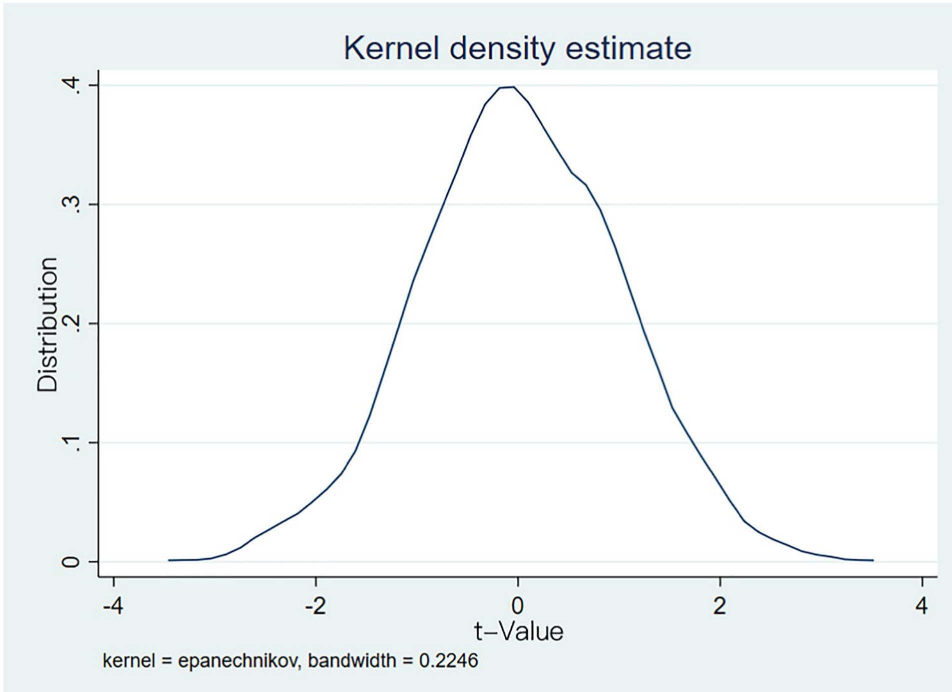
There are some limitations in this study, which might pave the way for future research. (1) Carbon peak and carbon neutralization, which were set an object and ambitious goal in Paris Agreement, are hot issues about climate change, exploring regulation effect has significant research values for the following research. Due to the space and power limitation, this paper has not reached this area. (2) Due to data limitations, this paper does not find a still better variable to measure the innovation quality, which may lead to measurement error. (3) The errors caused by the non-randomness of the policy pilot cities should be further discussed.

Appendix The results of the placebo test




Kernel density estimate
Distribution
0
.1
.2
.3
.4
-4
-2
0
2
4
t−Value
kernel = epanechnikov, bandwidth = 0.2204


Kernel density estimate
Distribution
0
.1
.2
.3
.4
-4
-2
0
2
4
t−Value
kernel = epanechnikov, bandwidth = 0.2204


Kernel density estimate
Distribution
0
.1
.2
.3
.4
-4
-2
0
2
4
t–Value
kernel = epanechnikov, bandwidth = 0.2246

Author contribution Zhenhuan Yang collected and analyzed the data, the introduction, literature review, and theoretical analysis. Yi Xu is responsible for the conclusion and policy implication and perfect language.

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Data availability All data generated or analyzed during the current study are presented in this article. Raw data will be also accessible from the author group if requested.

Declarations

Ethics approval and consent to participate The locations of material collected here are neither privately owned lands nor protected areas. No specific permits were required for our research.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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