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The role of China's carbon emission trading system in economic decarbonization: Evidence from Chinese prefecture-level cities

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ABSTRACT

Based on the panel data from 283 prefecture-level cities in China between 2009 and 2019, this study examines the impact of China's carbon emissions trading system on reducing carbon emissions and its mechanisms, using the PSM-DID method. The findings demonstrate that the carbon emissions trading system can effectively decrease the total carbon emissions in pilot cities in China, and has a positive spatial spillover effect on neighboring cities of the pilot areas. The carbon emission trading system primarily reduces carbon emission by incentivizing businesses to implement eco-friendly practices and improve the industrial structure of pilot cities. Increased financial marketisation can promote the carbon emission reduction effects of the trading system. The impact of the carbon emission trading system on old industrial base cities and inland cities is more significant than those on non-old industrial base cities and coastal cities.

1. Introduction

The challenge of the climate crisis caused by global warming is universal and must not be avoided by any country worldwide. This statement highlights that the climate crisis presents the largest externality issue to the world's economic systems. Additionally, the severity of the free-riding phenomenon increases as the externality problem grows [1]. Therefore, to effectively tackle the climate crisis, international cooperation is essential, as acting alone is ineffectual. Governments are currently working to find common ground while putting aside their differences. Following tough negotiations, the 2016 Paris Agreement established a goal of achieving net-zero emissions by the latter half of this century, indicating that carbon neutrality has become a global consensus. The Paris Agreement relies on nationally determined contributions (NDCs) declared by each party as a vow to reduce carbon emissions. The National Determined Contributions (NDCs) of the United States, Japan, the United Kingdom and the European Union aim to achieve carbon neutrality by 2050. China's NDC aims to peak carbon in 2030 and achieve carbon neutrality in 2060. Given that China is currently the largest consumer of energy globally, achieving carbon neutrality by 2060 is both an ambitious and pressing task. The previous growth model, characterized by high energy consumption and emissions, has led to substantial dependence on emission-heavy growth paths. It is, therefore, necessary to address the problem of carbon emissions and externalities as quickly as possible. The attainment of carbon neutrality objectives relies heavily on utilising environmental regulation to incorporate the external costs arising from carbon emissions. China has undertaken a range of efforts to drive green and low-carbon economic development, and has introduced a

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comprehensive set of policies on environmental regulation, within the parameters of the “30•60″ goals. During the eleventh Five-Year Plan period, China connected the appraisal of local governmental officials’ performance to environmental outcomes and introduced a system of accountability to environmental targets, replacing the focus on GDP. This shift from “soft constraints” to “hard constraints” indicates a change in environmental rules and regulations [2].

Environmental regulation was initially defined as the government’s coercive intervention in the utilization of environmental resources through administrative orders, laws and regulations to address incomplete market issues such as negative externalities arising in the course of the behavior of economic agents [3,4]. As environmental research continues, the definition of environmental control has broadened. Environmental regulation can be classified into two types: command-controlled and market-incentive, based on the different actors and mechanisms involved [5]. Reviewing the history of environmental governance in recent decades, we mainly implemented command-controlled environmental regulation was primarily implemented in the initial years [6,7]. Despite significant improvements in environmental performance, the safety of residents’ drinking water has been ensured, and there have been significant reductions in urban black and smelly water bodies and haze days. However, the severe trend of high-carbon energy consumption structure and ecological destruction has not undergone fundamental change [8,9]. Furthermore, the implementation of environmental regulations under centralized control may heighten the load on businesses, diminish the global competitiveness and innovation capability of regulated entities [7,10–12], and lower their efficiency [13,14]. Therefore, in recent years, there has been a growing interest in market incentives for environmental regulation instruments [15]. However, the market-incentive environmental regulations such as taxes and technologies that have been implenented in China have not directly curtailed the total carbon emissions or met the anticipated goal of reducing them [16]. China’s practical and academic communities have increasingly turned their attention towards the market-based environmental regulation of carbon emission trades. The carbon emission trading system was piloted in seven provinces and municipalities starting in 2013. Implementing this policy provided a unique “quasi-natural experiment” to evaluate the economic, environmental, and social effects associated with a low-carbon transition. China’s 13th Five-Year Plan proposes to “establish a robust system for the initial allocation of energy, water, emission and carbon emission rights, while also and developing a trading market” [17]. In October 2017, Chinese president once again stressed the importance of “building a market-oriented green technology innovation system, developing green finance, and strengthening energy conservation, environmental protection, clean production and clean energy industries.” Since then, the acceleration of China’s carbon emission trading system has become apparent. As of 2021, China has overtaken the European Union as the leading carbon emissions trading market globally [18].

As low-carbon environmental protection has gained prominence in academia, numerous scholars have explored this topic. Dong et al. [19] discovered that the acceleration of low-carbon energy transition can considerably reduce energy poverty in China. Moreover, some studies revealed that Internet development leads to lesser urban carbon emissions through restructuring of the industrial sector, supporting eco-friendly innovation, and enforcing environmental regulations [20]. Additionally, clean technology, green energy, resource management, and FDI are identified as contributors to the cause. China’s greenhouse gas emissions may be reduced in the next decade [21]. Ge et al. [22] discovered that the development of the digital economy has an inverted U-shaped characteristic impact on urban carbon emissions. Furthermore, there is a peripheral spillover effect, and the construction of smart cities can significantly decrease urban carbon emissions [23].

Several studies have demonstrated that the introduction of the carbon emission trading system has had numerous effects on China’s economy, environment, and society. This policy represents a classic example of quantitative regulation [24], A carbon emissions trading system has the potential to significantly reduce total carbon emissions [25–28]. Furthermore, it has the ability to enhance both China’s energy structure and energy efficiency [29–31]. Moreover, the carbon emission trading system remains a key driver behind the push for low-carbon and high-quality urban development across China [32]. This system has been found to promote regional economic growth and environmental optimization in equal measure [33], and has the potential to raise the overall welfare of society as a whole [34]. Furthermore, the carbon emissions trading scheme not only reduces overall carbon emissions and carbon emission intensity [35,36], but it can also enhance investment efficiency in businesses [37], boost technological innovation [5]and add intrinsic value [38]. Overall, while some literature has indicated that the carbon emission trading system did not significantly reduce emissions [39], the majority of studies demonstrate its positive impact on the environment in China [25–28].

In terms of data sample selection, the majority of current literature utilised panel data at the provincial level as the studied sample, with a smaller number of studies utilising city data. There is currently no conclusive evidence on the effectiveness of carbon trading systems for reducing emissions at the city level. It should be noted that prefecture-level cities in China are smaller administrative units than provinces, and as such differ greatly in terms of administrative authority. Hence, the effects and functionality of the carbon emission trading system concerning carbon emissions in prefecture-level cities may differ from those in provinces. Additionally, these cities have emerged as significant regional economic entities in China, significantly contributing towards regional economic growth. Therefore, investigating the impact of a carbon emission trading system on reducing carbon emissions in cities of prefecture-level is crucial in enhancing the effectiveness of the system and promoting green economic transformation and development.

Building on the earlier, this paper investigates, in an empirical manner, the impact of carbon emission trading systems on prefecture-level administrative units through the PSM-DID method based on panel data of 283 prefecture-level cities in China from 2009 to 2019. The paper also explores the underlying mechanisms of carbon emission reductions, approached via green innovation. The research presented in this paper enhances the current literature with empirical evidence at the city level, showcasing the impact of carbon emissions trading systems on carbon emission reduction. This theoretical foundation can be utilised to enhance China’s carbon emission reduction policies.

The marginal contributions of this study are as follows: (1) To investigate the impact of carbon emissions trading policies on reducing carbon emissions in urban areas, broadening the scope of previous research. (2) This study explores the impact of carbon emissions trading policies on carbon emissions and their spillover effects. Furthermore, it conducts a heterogeneity analysis to broaden the research content in related fields. However, this study still has the following shortcomings: (1) Due to data source limitations, samples with significant data gaps were excluded resulting in restricted reliability and generalisability of the research findings. (2) The data samples are sourced from the National Bureau of Statistics of China, which has a limited time span due to the agency's late start in counting particular data. Consequently, there are some limitations in terms of the representativeness of the research findings.

The remainder of the paper is organised as follows: the second part is the theoretical analysis and research hypothesis; the third part is the empirical research design; the fourth part is the analysis of the empirical results; the fifth part is the mechanism test; the sixth part is the analysis of heterogeneity; and the seventh part is the conclusion.

2. Theoretical analysis and research hypothesis

2.1. Carbon reduction effect of carbon emission trading system

The main idea of the carbon trading system is to establish a maximum limit for carbon emissions in each region and allocate carbon emission allowances to enterprises in a justifiable manner within the jurisdiction. These allowances can be traded without restrictions in the carbon emissions trading market. Enterprises implementing effective carbon emission control measures tend to generate lower carbon emissions, resulting in surplus carbon emission allowances [40]. Low-emitting companies can sell their extra credits on the carbon trading market to high-emitting companies that struggle to manage their carbon emissions and need more credits. Therefore, carbon credits provide a benefit to low-emitting companies and represent a cost for high-emitting ones [41]. The release of carbon dioxide into the atmosphere during the production process has a harmful effect on the environment. However, businesses do not bear the associated expenses, leading to a lack of motivation to conserve energy and limit emissions [42]. As a market-oriented policy, a carbon trading system grants carbon emission rights the status of a freely tradable commodity [41]. By imposing the cost of environmental contamination on businesses, it incentivizes them to undertake technological advancements and other measures to reduce emissions, with the goal of achieving carbon emission reduction. In such a system, high-emitting enterprises will face high emissions costs. Low emitters have the option to trade their surplus carbon allowances and gain income to support further research and development on cleaner production technologies. High emitters aim to reduce carbon emission costs and achieve this by accelerating research and development on low carbon technologies and acquiring relevant technical equipment that contributes to carbon emission reduction [43]. Therefore, we propose Hypothesis 1.

Hypothesis 1. The implementation of carbon emission trading system can decrease carbon emissions in pilot areas.

2.2. The action mechanism of carbon emission trading system on carbon emission

As a market-based tool for environmental regulation, the carbon trading system aims to reduce carbon emissions by influencing the resource allocation and investment behaviour of companies [44]. Firstly, the system internalises the negative environmental impacts of corporate carbon emissions [45], making them a cost that firms must bear. Low-carbon emitting companies can enjoy added benefits through trading their surplus emission allowances, while high-carbon emitting firms face greater expenses due to the need to procure extra carbon emission allowances. Consequently, all firms, regardless of their level of carbon emission, are incentivized to pursue innovative measures aimed at decreasing carbon emission levels, and to invest in eco-friendly technologies in order to meet the dual targets of reducing carbon emissions and bringing down costs. Secondly, under the carbon emissions trading system, companies are granted the ability to transfer surplus carbon emission allowances. This leads to an enhancement of anticipated revenue for enterprises in the realm of carbon emission reduction technology innovation, as well as an improvement in the level of risk compensation for investments in green technology innovation. As a result, companies are incentivized to invest in green technology innovation, ultimately leading to a reduction in carbon emissions. According to the above analysis, we propose hypothesis 2.

Hypothesis 2. A carbon emissions trading system can achieve carbon emission reduction by incentivizing enterprises to engage in green technology innovation.

Currently, China is confronted with the dual challenge of decelerating economic growth and intensifying environmental protection. Addressing the conundrum of improving environmental standards while achieving a stable economic advancement is a challenge that must be tackled. Industrial structure upgrading and optimization is a viable solution for resolving the predicament presented between economic development and environmental protection [46]. It is apparent that by increasing the proportion of low-carbon industries within an economy and transforming the industrial structure towards a green and low-carbon direction, it is no longer a conflict to sustain economic development while simultaneously reducing carbon emissions. The carbon emission trading system possesses a robust carbon emission price discovery mechanism that leverages market forces to support enterprises in their quest for greener policies. It further promotes the growth and refinement of society's overall industrial structure [47,48]. Concurrently, larger carbon-emitting organisations operating under this system will encounter greater opportunity costs when pursuing capital investments. As a result, additional capital will opt to invest in industries which integrate low-carbon production technology at their core. This will encourage further transformation and optimization towards green and low-carbon industrial structures [49]. Overall, the carbon emission trading system has the potential to redirect investment towards green and low-carbon industries, thereby optimizing the structure of regional economies and reducing regional carbon emissions. Thus, hypothesis 3 is proposed in this paper.

Hypothesis 3. Carbon emission trading system can achieve carbon emission reduction by optimizing industrial structure.

3. Empirical research design

3.1. Empirical model setting

In this paper, the propensity score matched difference method (PSM-DID) is used to estimate the urban carbon reduction effect of carbon trading system. The baseline regression model is as follows:

$$\ln c_{it} = \alpha_0 + \alpha_1 (treat_{it} \times post_{it}) + \alpha_2 treat_{it} + \alpha_3 post_{it} + \mathbf{Control}_{it}\boldsymbol{\beta} + \varepsilon_{it} \tag{1}$$

In Eq. (1), i, t represent prefecture-level city and year respectively. $\ln c$ is the total carbon emission, and *treat* is the dummy variable of pilot cities for carbon emission trading. The value of carbon emission trading pilot cities is 1, and the value of non-pilot cities for carbon emission trading is 0. *post* is the dummy variable of the implementation time of the carbon emission trading system, with 2014 as the year of policy implementation, 0 before 2014 and 1 after 2014. **Control** is the column vector composed of all control variables. ε_{it} is the random error term. $\alpha_l, l = 0, 1, 2, 3$ and $\boldsymbol{\beta}$ is the parameter to be estimated. α_1 represents the carbon emission reduction effect. If the estimated value is remarkably negative, it indicates that the carbon trading system has a noticeable carbon emission reduction effect.

3.2. Variable selection and measurement

In this paper, the logarithm value of total urban carbon emission is used as the dependent variable, and the measurement method of urban carbon emission is as follows:

$$co_2 = \sum_{j=1}^{n} c_{jt} \times \lambda_j \tag{2}$$

c_{jt} is the total consumption of the j-type fossil fuel in period t. λ_j is the carbon emission coefficient of the j-type fossil fuel. We adopted the treatment method of Fan and Peng [50], and matched the total carbon emission to each city according to the lighting matching method.

In October 2011, the National Development and Reform Commission (NDRC) of China issued a Notice on the Pilot Project of Carbon Emissions Trading, granting approval for the pilot project of carbon trading to be carried out in seven provinces and cities, namely Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen. In the two years after the issuance of the Notice, Shenzhen has been actively fostering the investigation and execution of carbon trading with guidance and support from the National Development and Reform Commission. On June 18th, 2013, Shenzhen launched the carbon emission trading market, making it the first of seven pilot provinces and cities in China. Given this context, 2014–2019 marks the implementation period for the carbon emission trading system. We assign a posterior value of 1 for this period and a value of 0 for 2009–2013. Furthermore, we designate prefecture-level cities in the seven provinces that have initiated the implementation of the carbon emissions trading system as the treatment group, assigned a value of 1, and municipalities in the other provinces as the control group, assigned a value of 0.

We also take population density, industrial structure, industrial scale, per capita GDP, innovation intensity, large-scale industrial enterprises, and energy consumption and other variables as control variables. The specific measurement method is as follows.

(1) population density (*dens*): It is measured by the ratio of the total population to the total area of the municipal district, which represents the human activity in the area.
(2) industrial structure (*st*): It can be measured by the ratio of the value added of the secondary sector to the region's GDP, which reflects the characteristics of the region's overall industrial structure.
(3) industrial scale (*lnind*): The industrial development degree and scale characteristics of the region are measured by the logarithm value of the total industrial output above the scale of prefecture-level cities.
(4) per capita GDP (*pgdp*): It is calculated based on the ratio of year-end regional GDP to total population to reflect the economic development of the region.
(5) innovation intensity (*inn*): The region's emphasis on technological innovation is measured by science spending.
(6) large-scale industrial enterprises (*lnfm*): It is measured by the natural logarithm of the total number of industrial enterprises above the scale of prefecture-level cities.

Table 1
Descriptive Statistics for variables.

var/stas	N	max	min	mid	ave	std.dev	MSA	MSE
lnc	3113	5.44	0.86	3.13	3.11	0.75	4.25	0.56
lnfm	3113	9.79	3	6.59	6.6	1.1	208.18	1.14
lnind	3113	19.73	11.49	16.71	16.69	1.22	160.62	1.44
lne	3113	5.33	−3.28	1.72	1.73	1.23	435.4	1.4
pgdp	3113	467749	99	38709	48354.21	33336.62	451.6	1.36
st	3113	89.75	10.68	47.77	47.36	10.7	5.51 × 1010	1.09 × 109
inn	3113	5500000	753	23084	97840.22	336411.22	3.05 × 1013	1.03 × 1011
den	3113	4647	5	358	442.27	367.53	30952964	125170.15

(7) energy consumption (*lng*): It is measured by the amount of electricity consumed by a municipal district.

The carbon emission data in this paper are calculated based on the latest revised energy data (2015) from the National Bureau of Statistics of China. Fossil fuel data are from the China Energy Statistical Yearbook. Energy and carbon emission parameters were acquired from the IPCC 2006 Carbon Inventory while data for other variables were sourced from the China Urban Statistical Yearbook. Given the scarring absence of statistical data, we exclude all prefecture-level cities under the Tibet Autonomous Region as well as individual cities in other provinces. Ultimately, we employ panel data for 283 prefecture-level cities from 2009 to 2019 and utilize linear interpolation to address some missing values.

The statistical data for the variables is displayed in Table 1. The key independent variables' descriptive statistics demonstrate that the average value of urban carbon emissions is 3.13, with the standard deviation at 0.75, the lowest value noted at 0.86, the median recorded at 3.11, and the highest value seen at 5.44. These results indicate that different regions have considerable total carbon emission variations throughout the sample period of the study. It provides a good foundation for estimating the empirical model that follows. Meanwhile, the descriptive statistics for the other control variables highlight significant gaps between the within-group mean square and between-group mean square. This suggests that there are significant systematic differences between the economic indicators of the control and treatment groups that could impact the regression results. As a result, it is imperative to control for these variables.

4. Empirical results and analysis

4.1. The changing trend of carbon emissions

For comparison, we first adopt the method of Han and Zhang [51]to standardize the total carbon emissions of pilot and non-pilot cities calculated based on Eq. (2). Based on these data, we use the Excel plotting tool to map carbon emission trends. The standardized total carbon emissions are shown in Fig. 1.

The carbon emissions trading system's effect on the total regional carbon emissions can be evident by examining the carbon emission indexes of pilot cities and non-pilot cities illustrated in Fig. 1. As displayed in Fig. 1, both pilot and non-pilot cities' total carbon emissions followed an upward trend from 2009 to 2014, prior to the policy's implementation. Overall, the carbon emissions in cities part of the pilot program were higher than those in non-pilot cities. Following the policy implementation between 2014 and 2019, there was a clear wave-like downward trend observed for total carbon emissions in pilot cities. In contrast, non-pilot cities experienced an increase in carbon emissions. The carbon emissions of the pilot cities are lower than those of the non-pilot cities. To summarise, there is a clear change in trend for the carbon emissions of pilot cities pre- and post-policy implementation, whilst non-pilot cities remain unchanged. Prior to the policy implementation, carbon emissions from pilot cities were higher than those from non-pilot cities. However, this situation was reversed after the policy implementation. This study provides visual evidence of the potential reduction in carbon emissions through the implementation of a carbon trading system.

We also used Stata 16.0 to map the kernel density distribution of carbon emissions for the treatment and control group cities in the years before and after the carbon emissions trading policy in our sample. Figs. 2–5 report the kernel density estimation results of total emissions of pilot and non-pilot cities in 2013 before the implementation of the carbon emission trading system and 2015 after the implementation. We categorise cities based on total carbon emissions into three categories. Cities with carbon emissions within the specified range are designated as low-emission zones, those with emissions within another specified range are designated as medium

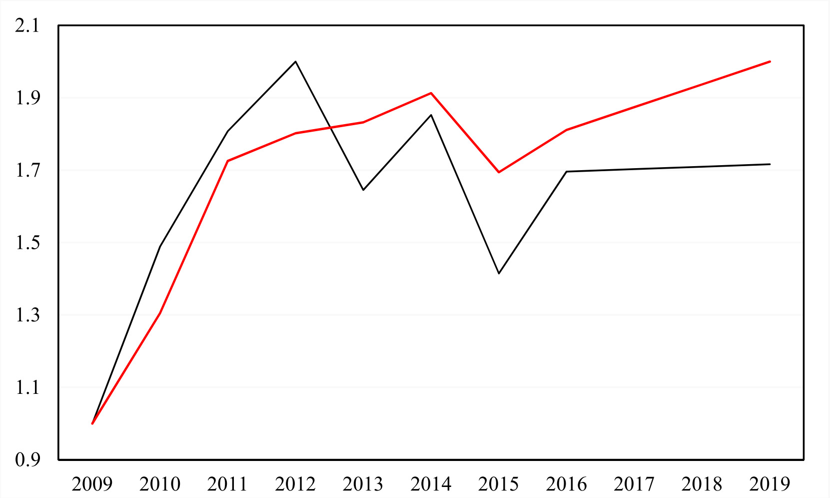

Fig. 1. Total standardized carbon emissions : The black line is the pilot city, and the red line is the non-pilot city. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

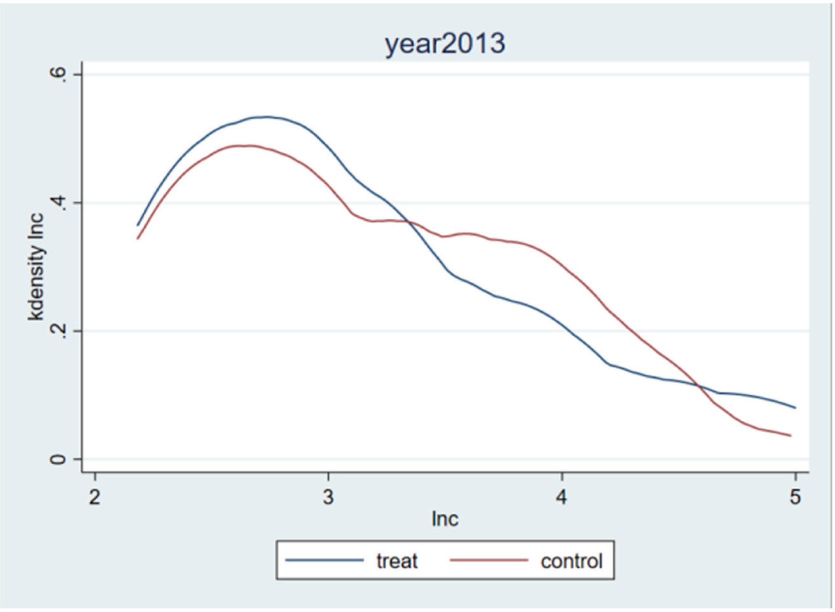

Fig. 2. Kernel density distribution of total carbon emissions in 2013.

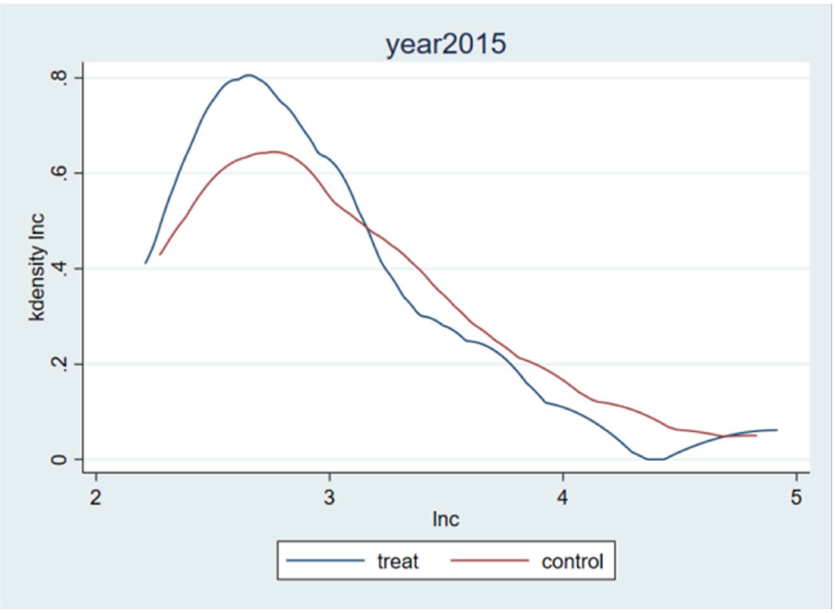

Fig. 3. Kernel density distribution of total carbon emissions in 2015.

emission zones, and those within another range are designated as high-emission zones. The kernel density estimates depicted in Fig. 2 demonstrate a high degree of consistency between pilot and non-pilot cities prior to policy implementation. There is no significant disparity in the distribution of carbon emissions between pilot cities and non-pilot cities prior to the policy's implementation. However, after the implementation of the policy, there was a notable change in the carbon emission distribution in both pilot and non-pilot cities, as illustrated in Fig. 3. Upon analysis of Figs. 4 and 5, it can be concluded that the policy's implementation has led to a noteworthy increase in the proportion of pilot cities within low-emission areas, while the proportion of cities in medium-emission areas has seen little change. Furthermore, there has been a significant decrease in the proportion of cities located in high-emission areas. The percentage of low-emission zones in non-pilot cities has marginally risen post-policy implementation, although the percentage remains significantly lesser than that of the pilot cities. Moreover, the percentage of high-emission zones has slightly decreased, yet it is still relatively lower than that of the pilot cities. The aforementioned outcomes unequivocally demonstrate that the

Fig. 4. Kernel density distribution of total annual carbon emissions in the treatment group.

Fig. 5. Kernel density distribution of total carbon emissions in the control group.

implementation of a carbon emission trading scheme can significantly reduce carbon emissions in urban areas.

4.2. PSM-DID regression result

To ensure the sample's randomness and avoid potential selectivity bias, we initially utilize the PSM method to match the pilot cities and create a new control group. Next, we estimate the DID model shown in Eq. (1). The outcomes are itemized in Table 2, where the first column estimates the average disposal impact of the carbon emissions trading system. The coefficient is significantly negative, thus suggesting that the introduction of the carbon emissions trading system is likely to result in a reduction of carbon emissions. To confirm the existence of a causal relationship between the carbon emissions trading system and the reduction of carbon emissions, we have included control variables in the second column of Table 2 to mitigate the impact of confounding factors. The estimation results

Table 2
Main regression results and dynamic effects.

	Average effect	Average effect	Dynamic effect
	lnc	lnc	lnc
treat × post	−0.1872* (0.1093)	−0.1551*** (0.0567)	
treat × year2014			−0.0145 (0.0828)
treat × year2015			−0.1804** (0.0857)
treat × year2016			−0.1433* (.0839)
treat × year2017			−0.1995** (0.0835)
treat × year2018			−0.1735** (0.0817)
treat × year2019			−0.2066** (0.0821)
treat	−0.2548*** (0.0791)	−0.2805*** (0.0405)	−0.2818*** (0.0404)
post	0.1808** (0.0774)	−0.0608*** (0.0441)	−0.0656 (0.0442)
cons		−1.4324*** (0.3274)	−1.3845*** (0.3288)
control	no	yes	yes
N	616	616	616
Adj-R^2	0.0675	0.7609	0.7612

Notes: Standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

demonstrate a significant reduction in carbon emissions due to the carbon trading system, as indicated by the consistently negative coefficient value. Furthermore, in Table 2's third column, we explore the system's dynamic disposition effect by including the interaction term of the treatment group's dummy variable and the dummy variable for the year following policy implementation. The results of the estimation reveal that solely the coefficient of 2014 is insignificant, but all other years' coefficients are noticeably adverse. The absolute value of this coefficient reaches its maximum extent in 2019, which implies that there exists a time delay and continuity regarding the carbon emission reduction impact of the carbon trading system. It takes approximately one year for the policy to generate a reduction in carbon emissions. Subsequently, the policy's impact will persist for a protracted period without apparent attenuation.

4.3. Parallel trend test

Parallel trends are an essential requirement when trying to evaluate policy treatment effects using the DID model. The accuracy of the policy disposition effect obtained using the DID method highly depends on the satisfaction of the parallel trend assumption by the treatment and control groups prior to the policy implementation. We conduct parallel trend tests in two different approaches.

First, we take 2008 as the base period to test the parallel trend hypothesis by comparing the average variation difference between the control group and the treatment group compared with the base period. The test model is as follows:

$$\ln c_{it} = \alpha_0 + \alpha_1 (treat_{it} \times post_{it}) + \sum_{\tau=2010}^{2013} \gamma_\tau (treat_{i\tau} \times year_\tau) + \alpha_2 treat_{it} + \alpha_3 post_{it} + \mathbf{Control}_{it}\boldsymbol{\beta} + \varepsilon_{it} \tag{3}$$

In Eq. (3), *year* is the binary variable corresponding to each year before the occurrence of the policy. The coefficient of the interaction term *treat* × *year* represents the difference in total carbon emissions between the treatment group and the control group before the policy occurred.

The coefficient of *treat* × *post* denotes the difference in total carbon emissions between the treatment and control groups after the policy occurred, after controlling for the relative change in total carbon emissions between the treatment and control groups before the policy occurred.

The results of the parallel trend test based on Eq. (3) in Table 3 show that the coefficient of *treat* × *post* is still remarkably negative after controlling the relative change between the control group and the treatment group before the occurrence of policy. It means that the carbon emission reduction effect of the carbon emission trading system is still remarkable after considering the relative changes of

Table 3
Results of parallel trend test.

	lnc
treat × post	−0.1568* (0.0825)
treat × year2010	0.0011 (0.0914)
treat × year2011	0.0943 (0.0928)
treat × year2012	−0.0391 (0.0909)
treat × year2013	−.0687 (0.0951)
treat	−0.2773*** (0.0724)
post	−0.0656 (0.0443)
cons	−1.4047*** (0.3325)
control	yes
N	616
Adj-R^2	0.7609

the control group and the treatment group before the policy. At the same time, the coefficient of *treat* × *post* in the first four years of the pilot implementation of carbon emission trading system is not significant. The findings demonstrate that there is no significant contrast in the alteration of overall carbon emissions between the pilot cities and non-pilot cities prior to 2014, which satisfies the parallel trend assumption.

Second, we also use event study methods for parallel trend testing. We separate year dummies and multiply them with treatment group dummies. This was incorporated into a regression model to estimate the relative change between the treatment and control groups over the five years before and after the implementation of the carbon emissions trading system. To determine whether the total carbon emissions of the treatment and control groups satisfy the parallel trend assumption, the experimental model is as follows:

$$\ln c_{it} = \alpha_0 + \alpha_2 treat_{it} + \alpha_3 post_{it} + \sum_{j=2009}^{2019} \gamma_j \left(treat_{ij} \times year_j\right) + \mathbf{Control_{it}\beta} + \varepsilon_{it} \tag{4}$$

In Eq. (4), The coefficient of the multiplication term *treat* × *year* represents the difference in the relative total carbon emissions between the treatment group and the control group in each year.

Fig. 6 presents the results of coefficient estimation based on the multiplication term of Eq. (4).As shown in the figure, the regression coefficients for the years before the policy implementation are around 0, mostly above the axis. In the first year after the policy implementation, the regression coefficient significantly decreases and is negative. This indicates that the total carbon emissions in the pilot areas decreased significantly after the policy implementation compared with the non-pilot areas. There is no significant difference in total carbon emissions between the pilot and non-pilot regions before the policy implementation. The test results of the event study methodology indicate that the study population is consistent with the parallel trend hypothesis.

The above parallel trend test results show that it is appropriate to use DID method to estimate the carbon emission reduction effect of carbon emission trading system in this paper.

4.4. Robustness test

4.4.1. Placebo test

In addition to the implementation of the emissions trading scheme, other policy factors may influence the carbon reduction effects reported above. In order to eliminate these confounding factors and to ensure that the net effect of the emissions trading scheme is obtained, a placebo test is carried out.

Firstly, we randomly sample 283 prefecture-level cities 500 times, select 37 cities each time as virtual pilot cities (treatment group), and reperform the regression based on Eq. (1), so as to obtain the 500 coefficient estimates of the multiplication term *treat*× *post* and T value of the test. If the policy effect is pure, the coefficient of the multiplication term *treat* × *post* should be 0. It should not be statistically significant. In Figs. 7 and 8, the distribution of 500 coefficient estimates and T-values were plotted respectively. As shown in Figs. 7 and 8, the average value of estimated coefficients obtained from 500 random samples is close to 0, and the absolute values of most tested t-values are less than the critical value of 1.96 at 95 % confidence level, indicating that the carbon emission reduction effect of carbon trading system in the virtual pilot cities is not significant.

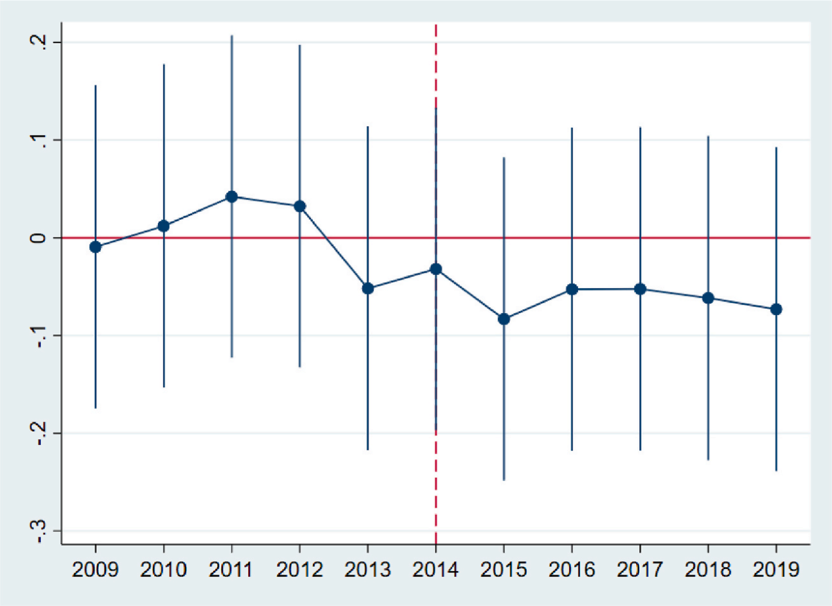

Fig. 6. Parallel trend test based on event study method.

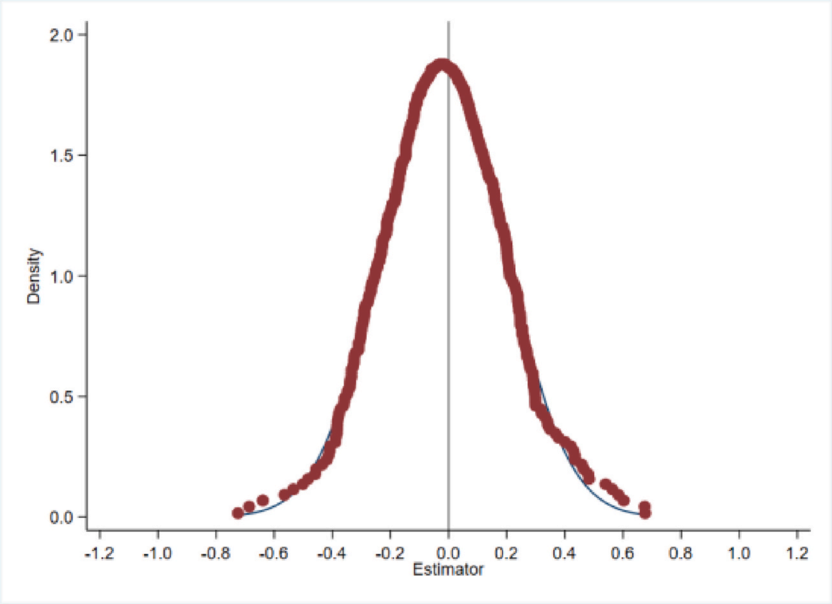

Fig. 7. Distribution of regression coefficients for virtual treatment group.

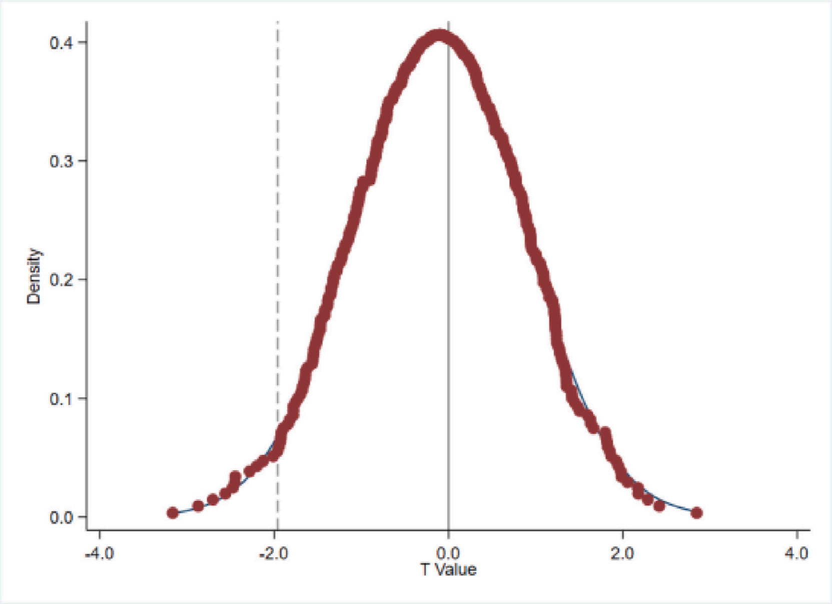

Fig. 8. T-value distribution of regression coefficients for virtual treatment group.

At the same time, we also take 500 random samples of the multiplication terms *treat* × *post*. Eq. (1) is re-estimated according to each sampling result, so that 500 coefficient estimates of the multiplication term and T-value of the test can be obtained. If the policy effect is a net effect, the coefficient of the multiplication term *treat* × *post* should be 0. Figs. 9 and 10 report the distribution of 500 coefficient estimates and T-values. It can be found that the average value of the 500 coefficient estimates is close to 0, and the absolute value of most T-values is less than the critical value of 1.96 under the 95 % confidence level. This further indicates that the carbon emission reduction effect of carbon trading system in the virtual pilot cities is not significant.

To some extent, the results of placebo test above indicate that the difference in the carbon emissions between the of pilot cities before and after policy implementation is mainly due to the implementation of the carbon trading scheme, whose carbon emission reduction effect is pure.

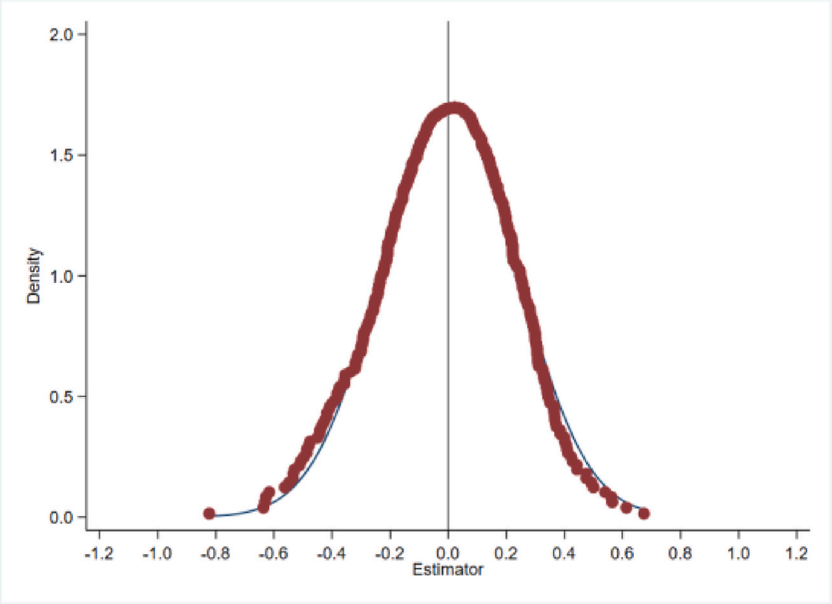

Fig. 9. Distribution of regression coefficients of virtual interaction term.

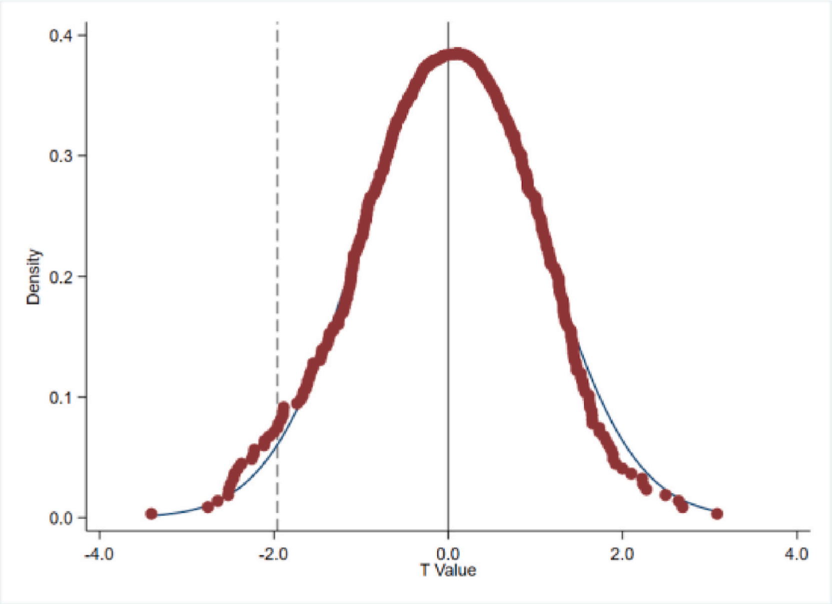

Fig. 10. T-value distribution of regression coefficients of virtual interaction term.

4.4.2. *Counterfactual test*

If the effect of policy implementation is real, there should be a significant difference between the carbon emission characteristics of pilot cities and non-pilot cities after the policy implementation. Assuming no carbon emissions trading system is implemented, the carbon emissions of pilot and non-pilot cities should remain the same one year after the policy implementation. Therefore, if the year before the policy implementation is taken as the hypothetical policy implementation time, the policy effect obtained by the DID method should be negligible because the policy has not been implemented at this time. Otherwise, the carbon emission reduction effect obtained in the original regression may not be caused by the carbon emissions trading system, which is a counterfactual test. Based on the above ideas, this paper uses the method of Hung et al. [52] to re-estimate Eq. (1), assuming that the policy implementation year is 2010 or 2011. The regression results in Table 4 show that the coefficient estimation of the multiplication term *treat*× *post* is not significant. This shows that the carbon emission reduction effect is indeed the result of the implementation of the carbon emission trading system, therefore, the conclusion obtained above is robust.

4.5. Endogenous discussion

The selection of pilot cities for the carbon trading system may not be completely random, which will lead to sample selection bias and further endogenous problems. We will use a two-stage instrumental variable approach to address this issue.

Based on the approach of Hering and Poncet [53], this paper uses the air circulation coefficient as an instrumental variable to determine whether a city is a pilot or not. The main reasons are as follows. First of all, when the total amount of carbon emissions is constant, the concentration of pollutants in the air and the air circulation coefficient have a reverse change relationship. Therefore, the air quality of a city with a smaller air circulation coefficient is worse, and the local government is more inclined to adopt stricter environmental regulation policies. Therefore, the smaller the air circulation coefficient is, the more likely the city is to be selected as the pilot city, which conforms to the hypothesis that instrumental variables are related to endogenous variables. Secondly, the air circulation coefficient is determined by natural environmental factors such as meteorological geography, and has nothing to do with other unknown factors that can affect carbon emissions, which conforms to the exogeneity hypothesis of instrumental variables. We match the wind speed information of 10 m height and boundary layer height from the ERA dataset released by the European Centre for Medium-Range Weather Forecasts to the prefecture-level cities in China based on latitude and longitude. And the product of wind speed and boundary layer height for each prefecture-level city is used to measure the air circulation coefficient of the region.

The estimation results of the two-stage instrumental variable method are shown in Table 5. In the first stage of regression, the coefficient of the interaction term $iv \times post$ between the instrumental variable and the time dummy variable is significantly different from 0, and the F value is greater than 10, indicating that it is a strong instrumental variable. It shows that the selection of instrumental variables meets the required conditions. In the second stage regression, the interaction term $treat \times post$ between the pilot city dummy variable and the time dummy variable is significantly negative at the significance level of 1 %, which is consistent with the conclusion of the original regression results. This indicates that the original regression results are robust.

4.6. Spatial spillover effect of carbon emission trading system

To further explore whether the carbon emissions trading policy will have spillover effects on the surrounding areas of pilot cities, this paper refers to Zhang [54] and defines the prefecture-level cities under the neighboring provinces of pilot cities as surrounding cities with dummy variables *near*. The neighboring cities are 1 and the non-neighboring cities are 0. Meanwhile, the pilot cities of the carbon emission trading system in the sample period are excluded from the sample. The experimental model is as follows.

$$\ln c_{it} = \gamma_0 + \gamma_1 (near_{it} \times post_{it}) + \gamma_2 near_{it} + \gamma_3 post_{it} + \mathbf{Control}_{it}\boldsymbol{\theta} + \varepsilon_{it} \tag{5}$$

In Eq. (5), if the coefficient γ_1 is significant in both statistical and economic sense, it indicates that the carbon emission trading system has spillover effect on the surrounding areas.

According to the estimated results based on Eq. (5) in Table 6, the estimated coefficient of $near \times post$ is negative at the significance level of 1 %, and the absolute value of this coefficient is greater than the absolute value of the main regression coefficient is greater, indicating that the carbon emissions trading policy has a significant positive spillover effect on the neighboring areas of the pilot cities. This indicates that the carbon emissions trading system can not only reduce carbon emissions in the pilot cities, but also have carbon emission reduction effects on the neighboring provinces of the pilot cities.

5. Mechanism test

The above studies show that the carbon emission trading system has a significant and robust carbon emission reduction effect. Next, according to the theoretical analysis results above, we will test the internal mechanism of this effect through the intermediary effect model from the perspective of green innovation and industrial structure optimization.

Table 4
Counterfactual test results.

	lnc	lnc
treat × post2011		−0.0621 (0.0825)
treat × post2010	−0.0476 (0.0720)	
treat	−0.3176*** (0.0712)	−0.3099*** (0.0547)
post	−0.1410*** (0.0322)	−0.1352*** (0.0329)
cons	−1.3553*** (0.3312)	−1.3884*** (0.3327)
control	yes	yes
N	616	616
Adj-R^2	0.7581	0.7584

Table 5
Regression results of instrumental variables.

	First stage	Second stage
	treat × post	lnc
iv × post	−0.0001*** (8.95 × 10^{-6})	
treat × post		−5.4472*** (0.6035)
cons	0.3514*** (0.0756)	−2.3922*** (0.4364)
control	yes	yes
N	3113	3113
F-Value	43.57	

Table 6
Spillover effect of carbon emission trading policy.

	lnc
near × post	−0.1820*** (0.0362)
near	−0.3325*** (0.0283)
post	−0.0198 (−0.0301)
cons	−3.6863 (0.2075)
control	yes
N	2706
Adj-R^2	0.6244

5.1. Green innovation perspective

The annual number of green patents in each prefecture-level city is selected as the proxy variable of green innovation. By referring to Zhu and Tang [55], the three-step mediation effect test method is adopted, and the test model is as follows.

$$\ln c_{it} = \alpha_{10} + \alpha_{11}(treat_{it} \times post_{it}) + \alpha_{12}treat_{it} + \alpha_{13}post_{it} + \mathbf{Control_{it}\beta_1} + \varepsilon_{\mathrm{it}} \tag{6}$$

$$gi_{it} = \alpha_{20} + \alpha_{21}(treat_{it} \times post_{it}) + \alpha_{22}treat_{it} + \alpha_{23}post_{it} + \mathbf{Control_{it}\beta_2} + \varepsilon_{\mathrm{it}} \tag{7}$$

$$\ln c_{it} = \alpha_{30} + \alpha_{31}(treat_{it} \times post_{it}) + \gamma gi_{it} + \alpha_{32}treat_{it} + \alpha_{33}post_{it} + \mathbf{Control_{it}\beta_3} + \varepsilon_{\mathrm{it}} \tag{8}$$

In Eq. (7), *gi* is the intermediary variable, representing the number of green patents in each city each year. The test results based on Eqs. (6) and (7)and (8) are shown in Table 7.In the first column, the coefficient of the interaction term *treat* × *post* is remarkably positive, indicating that the implementation of carbon emission trading system has enhanced the level of green innovation of enterprises in pilot areas. In the second column, the coefficient of the interaction term *treat* × *post* is remarkably negative, indicating that the carbon emission trading system has a significantly negative total effect on the total carbon emission. In the third column, the coefficient of green innovation is remarkably negative, indicating that the improvement of green innovation level can reduce the total carbon emission. Moreover, the coefficient of the interaction term *treat* × *post* is not remarkable, which indicates that green innovation is the complete intermediary path for the effect of carbon emission trading system on carbon emissions. In other words, the implementation of carbon emission trading system mainly achieves carbon emission reduction effect by encouraging the improvement of green innovation level, which also confirms hypothesis 2.

5.2. Industrial structure optimization perspective

Drawing on Yuan and Zhu [56], the following mediating effect test model was constructed by using the level of industrial structure rationalization as a proxy variable for industrial structure optimization.

$$\ln c_{it} = \alpha_{10} + \alpha_{11}(treat_{it} \times post_{it}) + \alpha_{12}treat_{it} + \alpha_{13}post_{it} + \mathbf{Control_{it}\beta_1} + \varepsilon_{\mathrm{it}} \tag{9}$$

$$indstr_{it} = \alpha_{20} + \alpha_{21}(treat_{it} \times post_{it}) + \alpha_{22}treat_{it} + \alpha_{23}post_{it} + \mathbf{Control_{it}\beta_2} + \varepsilon_{\mathrm{it}} \tag{10}$$

$$\ln c_{it} = \alpha_{30} + \alpha_{31}(treat_{it} \times post_{it}) + \gamma \mathrm{indstr_{it}} + \alpha_{32}treat_{it} + \alpha_{33}post_{it} + \mathbf{Control_{it}\beta_3} + \varepsilon_{\mathrm{it}} \tag{11}$$

In Eq. (10), *indstr* is the intermediary variable, representing the optimization degree of the industrial structure of the city. Table 8 shows the results of the institutional tests based on Eqs.(9) and (10)and (11). The first column shows that the carbon emissions trading system can significantly promote the optimization of industrial structure in the pilot cities. According to the regression results in the second column, the carbon emission trading system can significantly reduce the carbon emission level of the pilot cities. The regression results in the third column show that industrial structure optimization helps to reduce the total carbon emissions of the cities. Meanwhile, after considering the industrial structure optimization factor, the carbon emission trading system still has carbon emission

Table 7
The mediation effect test from the perspective of green innovation.

	gi	lnc	lnc
treat × post	10.8659*** (4.1995)	−0.0911* (0.0525)	−0.0716 (0.0520)
gi			−0.0018*** (0.0003)
treat	0.4192 (3.1462)	−0.2792*** (0.0393)	−0.2785*** (0.0389)
post	−2.1930 (1.9161)	−0.1819*** (0.0239)	−0.1859*** (0.0237)
cons	32.1887 (20.05122)	−3.3784*** (0.2506)	−3.3207*** (0.2482)
control	yes	yes	yes
N	2321	2321	2321
Adj-R^2	0.5820	0.5735	0.5905

Table 8
The mediation effect test from the perspective of industrial structure optimization.

	Indstr	lnc	lnc
treat × post	0.2416** (0.0956)	−0.1051** (0.0515)	−0.0935* (0.0514)
Indstr			−0.0479*** (0.0097)
treat	−0.0216 (0.0717)	−0.2597*** (0 .0387)	−0.2607*** (0.0385)
post	0.4045*** (0.0399)	−0.1595*** (0.0215)	−0.1401*** (0.0217)
cons	−2.0402*** (0.3818)	−3.4476*** (0.2056)	−3.5453*** (0.2057)
control	yes	yes	yes
N	3091	3091	3091
Adj-R^2	0.3425	0.5973	0.6003

reduction effect. This suggests that industrial structure optimization is an incomplete mediator of the carbon emission reduction effect of the carbon trading system. In other words, the carbon emissions trading system can play a role in carbon emission reduction partly because it can promote the optimization of urban industrial structure.

5.3. *Financial marketisation perspective*

As a representative of market-based environmental regulatory policy, carbon emissions trading policy mainly relies on the financial system of the pilot region to achieve the corresponding policy objectives. The level of marketisation of the financial system usually affects the efficiency of the allocation of various factors of production such as capital. So, does the level of financial marketisation in the pilot cities affect the policy effect of carbon emissions trading policy? This issue will be further investigated using the moderating effect model later.

Currently, China's financial system is mainly dominated by the banking sector [57]; the strength of regional bank competition reflects the local financial marketisation level to a large extent, and we draw on the methodology of Jiang et al. [58], which adopts the percentage share of branches of the region's top four largest banks (CR4) to measure the level of financial marketisation in prefectural-level municipalities, with the following calculation formula

$$CR4 = \frac{\sum_{n=1}^{4} branch_n}{branches_{total}} \tag{12}$$

In Eq. (12), $branch_n$ denotes the number of branches in the region of the bank ranked n in the number of branches, $branches_{total}$ is the total number of branches of all banks in the region. Considering the special types of banks whose business is quite different from commercial banks, referring to the practice of Chen [59], we exclude the samples of policy banks, rural cooperative banks, and rural credit unions. The moderating effects model can explore more intuitively how the moderating variables affect the relationship between

Table 9
Regression results on the moderating effect of financial marketisation.

	lnc
CR4 × treat × post	−7.4296** (3.4603)
treat × post	0.0026 (0.0671)
CR4	−11.9229*** (1.1242)
treat	−0.2392*** (0.0382)
post	−0.1573*** (0.0211)
cons	−1.9141*** (0.2329)
control	yes
N	3113
Adj-R^2	0.6058

the explanatory variables and the explained variables, this paper intends to use the moderating effects model to study the impact of the financial marketisation level on the policy effects of the carbon emissions trading policy, the measurement model is as follows:

$$GE_{it} = \alpha_0 + \alpha_1(\mathrm{CR4}_{it} \times \mathrm{treat}_{it} \times \mathrm{post}_{\mathrm{it}}) + \alpha_2\mathrm{CR4}_{it} + \alpha_3\mathrm{treat}_{\mathrm{it}} + \alpha_4\mathrm{post}_{\mathrm{it}} + \mathbf{Control_{it}\beta} + \varepsilon_{\mathrm{it}} \tag{13}$$

In Eq. (13), $CR4$ is the percentage of branches of the top four banks in prefecture-level cities, this regression focuses on the regression coefficient CR4 × treat × post and significance of the cross-multiplier term α_1. If α_1 is less than 0, it indicates that the improvement of the financial marketisation level helps to enhance the carbon emissions trading policy to reduce carbon emissions in the pilot area, and vice versa.

The regression results based on Eq. (13) are shown in Table 9, and the regression coefficient of the cross-multiplier term CR4× treat × post is significantly negative at the 1 % significance level, indicating that with the promotion of financial marketisation, the effect of the carbon emissions trading policy in reducing urban carbon emissions will also be significantly enhanced. The reason for this may stem from the fact that the increase in the level of financial marketisation means that innovative enterprises have more financial innovations and products to build asset portfolios to diversify the risks brought by their innovative behaviours, which in turn improves the enterprises' awareness of green innovation [60] and enhances the carbon emission reduction effect.

6. Heterogeneity analysis

6.1. The influence of industrial resource endowment

Every region's development depends on its natural resource endowment. Areas rich in natural resources tend to have more mature industrial development and first-mover advantages, which may have a positive impact on technological progress in the region [45]. However, rich resources may also make cities over-rely on resource-intensive industries, hinder the innovation of green and clean production technologies, and maintain a state of high pollution and high emissions for a long time [61].China has a special class of cities, that is the old industrial base cities.

Industry in the old industrial base cities is mainly high-polluting and high-emitting manufacturing. Highly polluting industries account for a large proportion. Their energy intensity is 30 % higher than the national average. Their CO_2 emissions per unit of GDP are 50 % higher than the national average [62]. They have a lot of room to reduce their carbon emissions. The introduction of a carbon trading scheme may have a different impact on cities in China's old industrial bases than on other cities. Let us explore the possibility of such differences.

China has 120 old industrial base cities in 27 provinces. After eliminating cities with severe data loss, the final number of old industrial base cities is 92. We divide the data samples into two groups: old industrial base cities and other cities, and estimated PSM-DID model respectively. According to the regression results in Table 10, the coefficient estimates of the multiplication term *treat*× *post* of the two groups regression are significantly negative, indicating that the carbon emission trading system has significant carbon emission reduction effect on the old industrial base cities and other cities. However, the absolute value of the *treat* × *post* coefficient of cities with old industrial bases is much higher than that of other cities, indicating that the carbon emission trading system has stronger carbon emission reduction effect on cities with old industrial bases.

6.2. The influence of the level of economic development

There are large regional differences in the level of economic development of Chinese cities, showing a geographic distribution characteristic that eastern cities are stronger than western cities and coastal cities are stronger than inland cities. The economic activities of less developed inland cities have stronger demand-side pull and supply-side push on carbon emissions in the region than those of more developed coastal cities [63], and thus inland cities may have higher sensitivity to carbon emissions trading systems. On the other hand, coastal cities have a good economic foundation and a relatively low proportion of high-polluting and high-emitting industries in their economic structure, so the impact of carbon emissions trading systems may be relatively small. To test the above idea of investigating the heterogeneity of the policy effects of carbon emissions trading systems on cities with different levels of economic development, 283 prefecture-level cities are divided into coastal and inland cities according to the geographical location of

Table 10
Heterogeneity analysis of urban industrial resource endowment.

	lnc	
	Old industrial base cities	Other cities
treat × post	−0.3312*** (0.1241)	−0.1994*** (0.0724)
treat	−0.1698** (0.0832)	−0.2520*** (0.0512)
post	0.0429 (0.1104)	−.0547 (0.0547)
cons	−4.3295*** (1.0491)	−2.2319*** (0.5043)
control	yes	yes
N	144	422
Adj-R^2	0.6368	0.776

the province in which they are located. The PSM-DID method is used to conduct regression analysis on the two groups of city samples, respectively. The estimated results are shown in Table 11.

According to the estimated results in Table 11, the impact of the carbon emission trading system on the carbon emissions of both coastal cities and inland cities is significantly negative, and the absolute value of the *treat* × *post* coefficient of inland cities is higher than that of coastal cities, indicating that inland cities have stronger sensitivity to the carbon emission trading system and better carbon emission reduction effect.

Overall, there is regional heterogeneity in the impact of carbon emissions trading policies on carbon emissions. From the perspective of the city's industrial resource endowment, the carbon emission reduction effect of the old industrial base cities is stronger than that of other cities' policies; from the perspective of the level of economic development, inland cities with a relatively backward level of economic development have a better carbon emission reduction effect than coastal cities with a relatively superior level of economic development.

7. Conclusion

Based on the panel data of Chinese prefecture-level cities, this paper empirically tests the urban carbon emission reduction effect of China's carbon emissions trading system using the PSM-DID model, and draws the following conclusions. (1) The carbon emissions trading system can significantly reduce the total carbon emissions of the pilot cities. (2) The carbon emission trading system also has a positive spatial spillover effect on the neighboring cities of the pilot cities. (3) The carbon emission trading system achieves carbon emission reduction mainly by encouraging enterprises to make green innovation and promoting the optimization of urban industrial structure. (4) Increased financial marketisation can significantly enhance the carbon emission reduction effect of carbon emissions trading policy. (5) The carbon emission trading system has a stronger carbon emission reduction effect on old industrial base cities and inland cities than on non-old industrial base and coastal cities.

The research conclusions have rich policy implications. (1) The pilot expansion of the carbon emission trading system should be accelerated to give full play to the effect of carbon emission reduction policies. (2) The carbon emissions trading system itself should be enhanced further. Enterprise green innovation intensity may be taken as the basis for determining carbon emission quota. Enterprises with high green innovation intensity can increase carbon emission quota appropriately to enhance their green innovation willingness. (3) Co-ordinate the promotion of financial marketisation and the gradual promotion of carbon emissions trading policies to enhance policy effectiveness. (4) The carbon emission trading system should be implemented in multiple regions in order to exert the spatial spillover effect of policies. (5) The carbon emission trading system should be implemented according to local conditions. Differentiated policies and measures should be implemented for cities with different resource endowments and at different stages of development.

Although the existing carbon emission trading system plays a positive role in the market-oriented process of environmental regulation, more attention should be paid to how to ensure the fairness and efficiency of initial carbon emission allowances according to the characteristics of the carrying capacity of urban resources and environment, how to build a cross-regional carbon emission trading market, and how to overcome the backlash effect of the system. These issues require urgent attention in practice. They are also worth discussing.

Data availability statement

Data will be made available on request, further inquiries can be directed to the corresponding author.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Kunming Li: Writing – original draft, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Zhijie Luo:** Writing – original draft, Visualization, Software, Investigation, Data curation. **Ling Hong:** Writing – review &

Table 11
Regression results of different city samples.

	lnc	
	Coastal city	Inland cities
treat × post	−0.2675*** (0.0734)	−0.3355*** (0.0957)
treat	−0.3463*** (0.0531)	−0.0574 (0.0673)
post	0.1263** (0.0573)	−.1122 (0.0798)
cons	−1.3607*** (0.3997)	−1.5922*** (0.6140)
control	yes	yes
N	345	217
Adj-R^2	0.8087	0.7396

editing. **Jianhua Wen:** Writing – original draft, Data curation. **Liting Fang:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] H. Zhang, Reflections on post-Copenhagen international climate change cooperation, Int. Econ. Rev. (4) (2010) 102–113+5 (In Chinese).
[2] C. Han, W. Zhang, Z. Feng, How does environmental regulation remove resource misallocation: an analysis of the first obligatory pollution control in China, China industrial economics (4) (2017) 115–134 (In Chinese).
[3] N. Crafts, Regulation and productivity performance, Oxf. Rev. Econ. Pol. 22 (2) (2006) 186–202.
[4] Y. Yuan, R. Xie, Research on the effect of environmental regulation to industrial restructuring: empirical test based on provincial panel data of China, China industrial economics (8) (2014) 57–69 (In Chinese).
[5] Q. Hu, N. Huang, H. Sheng, Can Market - Incentive environmental regulation promote corporate innovation? A natural experiment based on China's carbon emissions trading mechanism, J. Financ. Res. (1) (2020) 171–189 (In Chinese).
[6] S. Ren, J. Zhen, D. Liu, et al., Does emissions trading system improve firm's total factor productivity-evidence from Chinese listed companies, China industrial economics (5) (2019) 5–23 (In Chinese).
[7] F. Tao, J. Zhao, H. Zhou, Does environmental regulation improve the quantity and quality of green innovation: evidence from the target responsibility system of environmental protection, China industrial economics (2) (2021) 136–154 (In Chinese).
[8] H. Zhang, X. Wei, Green Paradox or forced emission-reduction: dual effect of environmental regulation on carbon emissions, China Population Resources and Environment 24 (9) (2014) 21–29 (In Chinese).
[9] J. Sun, R. Huang, Constructing the modernization of harmonious coexistence between man and nature, Environ. Protect. 49 (5) (2021) 8–9 (In Chinese).
[10] W.B. Gray, The cost of regulation: OSHA, EPA and the productivity slowdown, Am. Econ. Rev. 77 (5) (1987) 998–1006.
[11] A.B. Jaffe, R.N. Stavins, Dynamic incentives of environmental regulations: the effects of alternative policy instruments on technology diffusion, J. Environ. Econ. Manag. 29 (3) (1995) S43–S63.
[12] W.B. Gray, R.J. Shadbegian, Plant vintage, technology, and environmental regulation, J. Environ. Econ. Manag. 46 (3) (2003) 384–402.
[13] D.W. Jorgenson, P.J. Wilcoxen, Environmental regulation and US economic growth, Rand J. Econ. (1990) 314–340.
[14] A.J. Barbera, V.D. McConnell, The impact of environmental regulations on industry productivity: direct and indirect effects, J. Environ. Econ. Manag. 18 (1) (1990) 50–65.
[15] B. Wang, S. Qi, The effect of market-0riented and command-and-control policy tools on emissions reduction innovation——an empirical analysis based on China's industrial patents data, China industrial economics (6) (2016) 91–108 (In Chinese).
[16] Y. Lu, Green policies and jobs in China: a double dividend? Econ. Res. J. 46 (7) (2011) 42–54 (In Chinese).
[17] Central People's Government of the People's Republic of China ,The Outline of the National Plan for Cultural Development and Reform during the 13th Five-Year Plan Period, 2017. https://www.gov.cn/zhengce/2017-05/07/content_5191604.htm.
[18] T. Yun, China will become the world's largest carbon trading market, with up to $400 billion, China Strategic Emerging Industry (25) (2016) 32–33 (In Chinese).
[19] K. Dong, Q. Jiang, M. Shahbaz, et al., Does low-carbon energy transition mitigate energy poverty? The case of natural gas for China, Energy Econ. 99 (2021), 105324.
[20] M. Pan, X. Zhao, J. Rosak-Szyrocka, et al., Internet development and carbon emission-reduction in the era of digitalization: where will resource-based cities go? Resour. Pol. 81 (2023), 103345.
[21] F. Shaheen, M.S. Lodhi, J. Rosak-Szyrocka, et al., Cleaner technology and natural resource management: an environmental sustainability perspective from China, Clean Technologies 4 (3) (2022) 584–606.
[22] L. Ge, L. Mo, N. Huang, Development of digital economy, upgrading of lndustrial structure and urban carbon emission, Modern Finance and Economics-Journal of Tianjin University of Finance and Economics 42 (10) (2022) 20–37 (In Chinese).
[23] L. Ge, J. Yu, Smart city construction and urban carbon emissions:the test based on digital technology empowerment path, Sci. Technol. Prog. Policy 39 (23) (2022) 44–54 (In Chinese).
[24] H. Qian, L. Wu, F. Ren, From "spurring a willing horse" to efficiency driven: a study of China's regional CO2 emission permit allocation, Econ. Res. J. 54 (3) (2019) 86–102 (In Chinese).
[25] Z. Huang, Is carbon emission trading beneficial to carbon emission reduction—— research based on double difference method, J. Arid Land Resour. Environ. 32 (9) (2018) 32–36 (In Chinese).
[26] K. Liu, L. Zhao, J. Li, Research on the emission reduction effect and mechanism of China's carbon emissions trading pilot, Industrial technology & economy 41 (12) (2022) 53–60 (In Chinese).
[27] Z. Li, J. Wang, Spatial emission reduction effects of China's carbon emissions trading: quasi-natural experiments and policy spillovers, China Population Resources and Environment 31 (1) (2021) 26–36 (In Chinese).
[28] K. Liu, L. Zhao, J. Li, Research on the emission reduction effect and mechanism of China's carbon emissions trading pilot, Industrial technology & economy 41 (12) (2022) 53–60 (In Chinese).
[29] L. Tang, J. Wu, L. Yu, et al., Carbon allowance auction design of China's emissions trading scheme: a multi-agent based approach, Energy Pol. 102 (3) (2017) 30–40.
[30] X. Zhang, T. Qi, X. Ou, et al., The role of multi-region integrated emissions trading scheme: a computable general equilibrium analysis, Appl. Energy 185 (2017) 1860–1868.
[31] H. Liu, W. Guo, Carbon emission trading policy pilot and energy-environmental efficiency:An empirical study of 287 prefecture-level cities in China, J. Xi'an Jiaotong University (Social sciences) 42 (5) (2022) 72–86 (In Chinese).
[32] Y. Wu, L. Shen, C. Shuai, et al., Key driving forces on the development of low carbon city (LCC) in China, Ecol. Indicat. 124 (2021), 107379.

[33] P. Yu, X. Liu, Research on the effects of carbon trading market size on environment and economic growth, China soft science (4) (2020) 46–55 (In Chinese).

[34] Y. Zhang, X. Wang, The impact of carbon emissions trading scheme on sustainable economic welfare in China[J], Systems Engineering-Theory & Practice 43 (2) (2023) 309–320 (In Chinese).

[35] H. Shen, N. Huang, L. Liu, A study of the micro-effect and mechanism of the carbon emission trading scheme, J. Xiamen Univ. (1) (2017) 13–22 (In Chinese).

[36] X. Yang, J. Li, X. Guo, The impact of carbon trading pilots on emission mitigation in China: empirical evidence from synthetic control method, Journal of Xi'an Jiaotong University (Social sciences) (3) (2021) 93–104 (In Chinese).

[37] T. Zhang, M. Wu, L. Zhou, Human capital, technological progress and steady economic growth: theoretical mechanism and empirical evidence, Zhejiang Soc. Sci. (1) (2022) 39–47. ±157-158.(In Chinese).

[38] C. Hou, The impact of the launch of the national carbon emission trading market on enterprise value – based on theoretical analysis and empirical research, Wuhan finance monthly (9) (2022) 81–88 (In Chinese).

[39] D. Streimikiene, I. Roos, GHG emission trading implications on energy sector in Baltic States, Renew. Sustain. Energy Rev. 13 (4) (2009) 854–862.

[40] Z. Hu, S. Wu, The rules of lnitial quota allocation of carbon emission rights from the perspective of social justice[J], J. Jishou Univ. (Nat. Sci. Ed.) 41 (1) (2020) 59–71 (In Chinese).

[41] Y. Liu, Based on the analysis of the components of subsidies in the agreement on subsidies and countervailing measures[J], Stud. Law Bus. 33 (2) (2016) 172–182 (In Chinese).

[42] C. Tian, L. Xiao, The lmpact of carbon emission right trading on low carbon transformation of enterprises:quasi natural experiment based on carbon trading pilot markets[J], East China Economic Management 37 (2) (2023) 64–74 (In Chinese).

[43] Q. Wu, L. Miao, Carbon emission reduction, carbon trading and the financialization of real enterprises[J], Finance and Accounting Monthly (23) (2022) 39–48 (In Chinese).

[44] S. Albrizio, T. Kozluk, V. Zipperer, Environmental policies and productivity growth: evidence across industries and firms, J. Environ. Econ. Manag. 81 (2017) 209–226.

[45] D. Shi, S. Li, Emissions trading system and energy use efficiency——measurements and empirical evidence for cities at and above the prefecture level, China industrial economics (9) (2020) 5–23 (In Chinese).

[46] M. Liu, S. Chen, Does of carbon emission trading scheme promote the optimization and upgrading of regional industrial structure, Management review 34 (7) (2022) 33–46 (In Chinese).

[47] H. Jiang, M. Sun, Carbon emission trading, industrial structure and regional emission reduction, Modern economic research (11) (2021) 65–73 (In Chinese).

[48] L. Du, Z. Ding, B. Li, Industrial structure adjustment is upgrading: boost from the mechanism of carbon finance: empirical research based on European data-base, Journal of Tsinghua University(Philosophy and social sciences) 27 (5) (2012) 143–150+161 (In Chinese).

[49] D. Yang, J. Liu, The impact of China's carbon finance on industrial structure and energy consumption structure: an empirical study based on CDM perspective, Jilin Univ. J. Soc. Sci. Ed. 52 (5) (2012) 98–105 (In Chinese).

[50] Z. Fan, F. Peng, C. Liu, Political connections and economic growth: evidence from the DMSP/OLS satellite data, Econ. Res. J. 1 (2016) 114–126 (In Chinese).

[51] G. Hang, C. Zhang, Impact of fiscal decentralization and promotion incentives on urban environmental pollution, Urban problems (2) (2018) 25–35 (In Chinese).

[52] M. Hung, J. Shi, Y. Wang, The effect of mandatory CSR disclosure on information asymmetry: evidence from a quasi-natural experiment in China, Social science electronic publishing 33 (5) (2013) 1–17.

[53] L. Hering, S. Poncet, Environmental policy and trade performance：Evidence from China, J. Environ. Econ. Manag. 68 (4) (2014) 296–318.

[54] G. Zhang, M. Tong, H. Li, et al., Evaluation of economic growth effect and policy effectiveness in pilot poverty alleviation reform zone, China industrial economics (8) (2019) 136–154 (In Chinese).

[55] S. Zhu, C. Tang, The Impact of going public on quality upgrading of export products——evidence from China's manufacturing firms, China industrial economics (2) (2020) 117–135 (In Chinese).

[56] H. Yuan, C. Zhu, Do national high-tech zones promote the transformation and upgrading of China's industrial structure, China industrial economics (8) (2018) 60–77 (In Chinese).

[57] X. Fan, Financial system and economic growth, evidence from China, J. Financ. Res. (3) (2006) 57–66 (In Chinese).

[58] F. Jiang, W. Cai, X. Cai, et al., Microeconomic effects of bank competition: evidence from corporate financial constraints, Econ. Res. J. 54 (6) (2019) 72–88 (In Chinese).

[59] X.Bank Cheng, Competition, market power and bank lending channelof monetary transmission, Finance & Trade Economics 38 (2) (2017) 63–76 (In Chinese).

[60] Z. Wang, W. Sheng, Financial ecological Environment,Debt heterogeneity and technology lnnovation nvestment–an empirical research on Chinese manufacturing listed companies, Business and Management Journal 35 (12) (2013) 130–139 (In Chinese).

[61] H. Li, Q. Zou, Environmental regulations, resource endowments and urban industry transformation: comparative analysis of resource-based and non-resource-based cities, Econ. Res. J. 11 (2018) 184–200 (In Chinese).

[62] National Development and Reform Commission of the People's Republic of China, Notice of the National Development and Reform Commission on Printing and Distributing the National Old Industrial Base Adjustment and Transformation Plan, 2013, 2022). (2013-3-18)[2023-1-23], https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/201304/t20130402_962134.html.

[63] T. Zhang, T. Chen, Simulation of carbon emission reduction effect and explanation of regional emission reduction differences from the perspective of regional economic correlation in China, Economic science (6) (2017) 31–44 (In Chinese).