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Does the carbon emission trading pilot policy promote green innovation cooperation? Evidence from a quasi-natural experiment in China

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Abstract

Green and low carbon transition is a broad and profound economic and social systematic change. Green innovation is a critical way to promote energy saving and emission reduction. Has China continuously promoted a carbon emission trading policy to significantly promote green innovation cooperation? Taking the implementation of the carbon emission trading pilot policy as a "quasi-natural experiment," this study answers this question by exploring the impact of the policy on green innovation cooperation. Based on data on 274 cities from 2008 to 2020, the multi-time difference-in-differences model is used to evaluate the impact of the policy on green innovation cooperation. The results reveal that the carbon emission trading pilot policy significantly improved inter- and intra-city green innovation cooperation through the upgrading effect of industrial structure and the coverage effect of digital finance compared with the non-pilot cities at the city level. In addition, there are significant differences in the policy effects among cities with different degrees of openness to the outside world and command-and-control environmental regulation.

Keywords: Carbon emission trading, Digital finance coverage effect, Green innovation cooperation, Industrial structure upgrading effect

Introduction

The European Union (EU) was the first organization to launch a mechanism for trading carbon emissions. Since 2005, this practice has been adopted by other nations across Asia, the Americas, and Australia. According to the World Bank, 64 different carbon trading pricing policies are being implemented worldwide. Thus, assessing the impact of the carbon emission trading system has gradually become a hot issue for academia and policymakers. One of the core policy objectives of carbon emission trading is to promote technological innovation (Caparros et al. 2013). In most cases, this has been assessed via questionnaires, surveys, interviews, and case studies (Anderson et al. 2011). Some studies have evaluated the impact of carbon emission trading systems on the green innovation of enterprises or regions based on empirical models (Calel and Dechezlepretre

2016). There is sufficient empirical evidence that market incentive tools encourage innovation subjects to carry out green innovation to a certain extent.

China's economy is currently transitioning toward high-quality development, and green revolution is a crucial channel for aiming for the forefront of global economic development to boost China's green growth and development. In the 20th National Congress of the Communist Party of China, the president of China, Xi Jinping, said that China aims to peak its carbon emissions before 2030 and achieve carbon neutrality by 2060.[1] To achieve this, the Chinese government initiated a carbon emission trading pilot policy in seven provinces and cities (Beijing, Shanghai, Tianjin, Chongqing, Guangdong, Hubei, and Shenzhen) in 2013.[2] This policy aimed to investigate market mechanisms to achieve greenhouse gas control targets and accumulate experience to establish a carbon emission trading market suitable for China's national conditions. Afterward, the Chinese government extended the scope of this pilot policy and implemented it in the province of Fujian in 2016.[3] The year 2021 marked the beginning of the official building phase of a carbon emission trading policy at the national level.[4]

This indicates that greenhouse gas control targets can be fulfilled through the different action mechanisms of environmental regulation, which can be divided into three types—command-and-control, market-driven, and voluntary. Market-driven environmental regulation has increasingly become the primary means for environmental supervision departments to deal with environmental problems (Liao 2018; Tzankova 2021). Carbon emissions trading policy is a typical type of market-driven environmental regulation. To be more explicit, it indicates that the government will decide on both the maximum allowable level of overall carbon emissions and the initial quota of carbon emission permits for market players. To meet the total carbon emission control goal, an entity that acquires the quota can either sell the surplus emission quota on the carbon emission market or buy the missing emission quota from another entity. The policy is an essential instrument for China to deal with climate change. Academia and government decision-makers in China are paying careful attention to determine whether or not the country's recently introduced carbon emission trading pilot policy would positively impact environmentally friendly innovation (Wang et al. 2019; Yan et al. 2020; Zhang et al. 2019, 2017). Similarly, Xie and Su (2021) explained that cooperation can boost innovative capabilities by facilitating information sharing, the melding of resources, and the dissemination of new technologies. Hence, innovation cooperation between relatively lagging regions and knowledge-rich regions will improve the innovation performance of lagging regions (Noni et al. 2018). The characteristics of a cooperation network, such as centrality, agglomeration, and structural holes, significantly affect innovation performance (Fabrizi et al. 2018; Guan and Liu 2016). However, prior researchers have not addressed the effect of the market-driven carbon emission trading policy on green innovation cooperation at the city level.

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[1] http://www.mofcom.gov.cn/article/i/jyjl/l/202012/20201203020940.shtml.

[2] http://politics.people.com.cn/n/2013/1126/c70731-23662332.html.

[3] http://www.gov.cn/xinwen/2016-12/22/content_5151566.htm.

[4] http://www.gov.cn/xinwen/2021-08/03/content_5629115.htm.

This study employed the difference-in-differences (DID) methodology to investigate how China's carbon emission trading policy influenced collaborative green innovation. The study analyzed panel data on 274 Chinese cities from 2008 to 2020 to uncover the impact mechanism and outcomes of the policy. A big challenge in this study is acquiring and constructing historical data on green innovation at the city level. Previous studies mostly used patents to represent the output of innovation, where patent application reflects the willingness to innovate, and patent authorization reflects the quality of innovation (Ali et al. 2023; Higham et al. 2021; Jin et al. 2022). To fulfill the requirements of this study, the green patent cooperation network matrix must be used to compute the features of the cooperation network. More precisely, the number of invention patents approved for collaboration in the 274 cities across China each year is utilized to create a collaborative innovation network across various cities. Afterward, the yearly network characteristic data for each city is computed. The findings of this study also include a measurement of the data about inter- and intra-city green innovation cooperation at the city-year level.

We further analyze the heterogeneous impact of urban openness and command-and-control environmental regulation intensity. On the one hand, considering the spillover effect of technology, cities with a high degree of openness are more conducive to the introduction of foreign advanced technology and have higher vitality, and innovation subjects are more likely to participate in cooperation (Alcala and Ciccone 2004; Ali et al. 2023; Lin et al. 2009). On the other hand, research from the perspective of policy instruments has revealed that different environmental policy instruments have different effects. For instance, based on Porter's hypothesis, innovation subjects, especially enterprises, have greater innovation motivation when facing environmental and institutional pressure (Desrochers and Haight 2014; Ramanathan et al. 2018; Stavropoulos et al. 2018). This compels us to further investigate the heterogeneity impact of carbon emission trading policy on green innovation cooperation.

This study makes three contributions to the literature. (1) By evaluating the impact of carbon emission trading policy on inter- and intra-city green innovation cooperation, it tests whether market-driven environmental policy can achieve the Porter effect in China. Theoretically, it expands the research on the relationship between environmental regulation and green innovation at the city level. When the urban economy entered the stage of high-quality development, green innovation became an important issue in China and even the entire world. (2) This study analyzes the heterogeneous effect of carbon emission trading policy on green innovation cooperation from the two dimensions of openness and command-and-control environmental regulation. This is significant for cities to take differentiated measures to optimize the policy effects. (3) We further analyze the impact mechanism from industrial upgrading and digital finance coverage perspectives. This study enriches the relevant literature on carbon emission trading and green innovation mechanisms and helps provide theoretical support and empirical evidence for formulating systematic carbon emission trading policies.

The subsequent sections of the paper are structured as follows. The "Literature review" section provides an overview of the relevant literature, presents the policy background, and outlines the theoretical hypotheses. The "Method" section describes the data sources, measurement of variables, and the model. The "Analysis and results" section discusses the empirical analysis of the policy effect on inter- and intra-city green innovation cooperation. It includes baseline results, parallel trend test, placebo test, robustness test, and mediating effect test. The "Heterogeneity analysis" section describes the heterogeneity of the policy impact. The "Conclusion and implication" section presents the conclusions, policy implications, and future research paths.

Literature review

This study evaluates the carbon emission trading pilot policy in China and the impact of environmental regulation on green innovation. We first review recent research progress in the above two aspects. Next, based on previous research, we discuss the impact of carbon emission trading policy on inter- and intra-city green innovation cooperation. Finally, we discuss the possible influencing mechanisms—the effects of industrial structure upgrading and digital finance coverage.

Effect of carbon emission trading policy

The carbon emission trading system is the core driving force of low-carbon development in Chinese cities (Wu et al. 2021). A carbon emission trading policy is a powerful means for China to achieve carbon peaking and neutrality. Research on the policy effects mainly focuses on the environmental, economic, and innovation effects.

Regarding the environmental perspective, most studies have explained that a carbon emission trading mechanism reduces carbon emissions and produces positive policy effects. First, the DID model is used to estimate the impact of the pilot policy on the pilot areas. Prior research has revealed that energy consumption in the pilot area is 22.8% lower than in other areas, which is almost 15.5% (Hu et al. 2020a, b). Some scholars also believe that there is a rebound effect in the energy-saving effect of environmental policies, and improving energy efficiency may lead to more energy consumption (Berkhout et al. 2000). Second, a computable general equilibrium model has been used to evaluate the impact of carbon emission trading on carbon emissions under various policy scenarios, finding that China's carbon emission trading can reduce carbon intensity and be economically efficient (Dai et al. 2018; Lin and Jia 2019c; Zhang et al. 2020a, b). Carbon emission trading significantly correlates with carbon emission reduction (Lin and Jia 2019a, b).

From an economic perspective, the conclusions of the impact of carbon emission trading on economic development are inconsistent. One view is that carbon emission trading negatively affects regional gross domestic product (GDP) (Dong et al. 2019; Tang et al. 2015; Wu and Gong 2021), which leads to inevitable welfare loss (Hubler et al. 2014). Another point of view is that carbon emission trading promotes employment, economic growth, and especially low-carbon economic development (Huang et al. 2019). According to Yang et al. (2020), a carbon emission trading strategy can assist with both reducing emissions and boosting the economy. From a micro perspective, the system can assist in the emission reduction efforts of enterprises and provide financial benefits to enterprises that participate in carbon emission trading (Liu et al. 2022a, b; Narayan and Sharma 2015; Wen et al. 2018). This benefit is mainly to obtain economic benefits by reducing the emission reduction cost of enterprises and selling emission permits and quotas (Springer et al. 2019; Wen et al. 2020).

From an innovation perspective, low-carbon technologies are increasingly critical in realizing urban carbon neutrality goals and sustainable urban development (Shang and Lv 2023). As the world's largest carbon trading market, the EU's successful experience is worth emulating by China. Existing research has revealed that the EU carbon trading system promotes green innovation in regulated enterprises and can effectively improve green technology innovation (Calel and Dechezlepretre 2016). The innovation-promoting effect of China's carbon emissions trading pilot policy has also received extensive attention. Some scholars have supported the Porter hypothesis, using data from listed firms to argue that the policy promotes higher levels of firm innovation through the price mechanism of carbon from the perspective of market-incentivized environmental regulation. They argued that China's carbon emissions trading policy significantly contributes to the quantity and quality of innovation by firms (Hu et al. 2020a, b), which is more evident among state-owned enterprises, listed companies in the east, and those with lower financing constraints (Yu et al. 2022). Moreover, a detailed auction mechanism and a strong monitoring mechanism are essential to ensure the dynamic effectiveness of the carbon emissions trading mechanism (Yao et al. 2021).

Impact of environmental regulation on green innovation

Several scholars have employed the "compliance cost" theory and the "innovation compensation" theory to verify the validity of the Porter hypothesis. After summarizing the literature, we found that the impact of environmental regulation policies on enterprise or regional green innovation can be divided into four categories—promotion effect, inhibition effect, nonlinear relationship, and no apparent relationship (Cainelli et al. 2015; Amores-Salvadó et al. 2015; Liu and Li 2022; Petroni et al. 2019; Porter and Vander Linde 1995). Research from a policy instruments perspective reveals that different environmental policy instruments have different effects such as command-and-control tools, and some market-driven tools positively affect green environmental innovation. Some scholars have examined the stimulating effect of command-and-control, emission tax, subsidy, pollution emission permits, and other tools on enterprise technology diffusion and found that the stimulating effect of the auctionable permit was the largest, followed by emission tax and subsidy, and direct control ranked last (Bian and Zhao 2020; Zhang et al. 2020a, b). Only regulatory penalties above a certain threshold will reduce enterprises' free-riding behavior and drive the green supply chain's upstream and downstream enterprises to accelerate emission reduction (Liu et al. 2022a, b). Other scholars have proposed that if the command-and-control policy can bring about innovation that reduces the cost curve of pollution control, it can play a more significant role in stimulating innovation than the market-driven policy (Bauman et al. 2008). Furthermore, some scholars have explored how environmental policy affects innovation cooperation, but the relevant research is not in-depth enough.

In general, previous research has used quasi-natural experiments to reveal the mechanism through which environmental policies influence technological innovation. However, no unified conclusion has been reached, and there is a lack of research on green innovation cooperation, which we try to cover in this study.

Effect on inter- and intra-city green innovation cooperation

Cooperation can facilitate the flow of technology, talent, and knowledge, thus promoting technology transfer and enhancing innovation capacity (Ali et al. 2023; Xie and Su 2021). Research on the effects of innovation collaboration can be divided into three levels—individual, organizational, and regional levels. At the individual level, studies on inventors have found that whom they collaborate with affects innovation performance. At the organizational level, collaboration with the customers of manufacturing firms can enhance green product innovation based on the results of a firm-based study (Kobarg et al. 2020). At the regional level, relatively lagging regions cooperate with relatively advanced regions in innovation based on the pressure of competitive effects and the incentive to learn from imitation effects to ultimately reach the goal of enhancing the innovation performance of lagging regions (Ali et al. 2023; Noni et al. 2018). Studies have revealed that cooperation network characteristics, such as degree centrality and agglomeration coefficient, significantly influence innovation performance (Ali et al. 2023b; Fabrizi et al. 2018).

As innovation cooperation involves different individuals, organizations, and regions, many factors restrict it. Geography, industry, enterprise, technology, culture, capital, and other factors critically impact innovation cooperation (Ali et al. 2023a; b; Steensma and Corley 2000; Tether 2002; Wang et al. 2017). Further research has found that regional attributes, such as economic and technological factors, regional location, and whether it is a provincial capital city affect regional innovation cooperation (Ali et al. 2023a, b; Jiang et al. 2017).

China's low-carbon technological resources and production are concentrated in a small number of economically booming cities due to the agglomeration effect of innovation. Cooperation innovation is crucial due to the technological spillover impact of innovative activities and their features of high investment, high risk, and severe difficulty. The structure of a collaborative network has an important impact on the efficiency of collaborative innovation (Guan et al. 2016) that enterprises actively seek from external knowledge sources (Chesbrough 2003).

One issue is the lopsided dispersal of China's low-carbon technology research and development (R&D) and technological change. Low-carbon technological resources are abundant in industrialized areas and scarce in less developed areas. The transfer and transformation of low-carbon technologies in academic and research institutions are less developed and inadequate. Enough resources are not put into R&D by small and medium-sized enterprises in economically depressed urban areas, hampering their ability to innovate with low-carbon technologies and effectively disseminate their findings. These lead to "technology lock-in" and "high carbon lock-in" in some regions. Due to the adoption of carbon emission trading policy, relevant enterprises are compelled to engage in green innovation. Enterprises in less developed areas will increase their cooperation in the area of green innovation if there is increased environmental regulation. This policy would help facilitate the free flow of low-carbon technology resources, talents, capital, and other factors through technology transfer hubs and other platforms and encourage green innovation cooperation within and between cities (Chen et al. 2019; De Marchi et al. 2022).

Conversely, green high-tech industries gather scientific and technological resources, and their innovation depends more on accelerating knowledge flow efficiency. The carbon emission trading mechanism strengthens the interaction between low-carbon enterprises and enables them to grasp the market dynamics quickly, make adjustments, and optimize the efficiency of resource allocation (Ma et al. 2021; Yin et al. 2020). According to the resource-based theory, enterprises complement the required assets and capabilities through cooperation (Williamson 1981). While sharing resources can stimulate the creation and diffusion of knowledge, green high-tech industries are knowledge- and technology-intensive, are characterized by large R&D investment and high risk, and often require the participation of multiple industries inside and outside the city. Therefore, developing high-tech industries will be conducive to collaborative innovation within and between cities.

Mediating effect of industrial structure upgrading

The carbon emission trading system changes the cost–benefit relationship of firms. To pursue profit maximization, enterprises adjust their factor structure, product location, product structure, and technology level to absorb the increase in cost caused by environmental protection (Song et al. 2021). For example, to achieve carbon neutrality as soon as possible, China has been promoting the development of the lithium battery industry (Bai et al. 2022). Some enterprises with solid competitiveness can adapt to high-standard carbon emission requirements as soon as possible and achieve sustainable development (Yu and Wang 2021). Moreover, some less competitive enterprises may not be able to afford the high cost of carbon emissions. Thus, it drives the transformation and upgrading of industrial structures at the macro level. The upgrading of industrial structure means the transformation of cities from capital- and labor-intensive to technology-intensive and also means the rise of the tertiary industry, which are conducive to reducing the energy demand of enterprises with high energy consumption, thus promoting green innovation (Ju et al. 2015; Liu and Sun 2021).

First, the optimization and upgrading of the industrial structure will realize healthy and coordinated development among various industries, further promote the technological innovation and management adjustment of the whole industrial chain, and thus promote the free flow of factor resources (Yuan et al. 2020; Zhao et al. 2022). Second, upgrading the industrial structure can strengthen the interrelation within and between industries, enhance the communication and cooperation between innovation subjects inside and outside an industry, and promote regional innovation (Li et al. 2014). Third, the demand and synergy effects of industrial structure upgrading require innovation subjects to improve technology and service methods and enhance the level of technological innovation, thereby promoting cooperation.

Mediating effect of digital financial coverage

As the object of each regional carbon emission trading platform, the distribution of carbon emission rights occurs in cities that are participating in the pilot program for trading carbon emissions. To promote the rapid development of the carbon emission trading market, it is crucial to establish a carbon financial mechanism system to ensure the orderly operation of the carbon trading market (Paramati et al. 2021; Zhou and Wang

2022). The Chinese government promotes the seamless integration of digital technology and carbon finance, harnessing cutting-edge tools such as big data, blockchain, and intelligent investment consulting. These technologies are leveraged to support investment choices, transaction pricing, and the dissemination of information.

On the one hand, compared with other technological innovations, green innovation requires more investment in R&D funds. However, innovation-subject financing often cannot meet its needs through internal financing. Compared with traditional finance, digital finance has the advantages of a low financing threshold and comprehensive coverage, which helps innovation subjects overcome financing challenges and improves the efficiency of green innovation (Arner et al. 2020; Demertzis et al. 2018; Zhang et al. 2023). On the other hand, the synergy between digital finance and carbon finance can accelerate the output of diversified green financial products and services and improve the green innovation willingness of innovation subjects.

The urgent problems of green innovation are few financing channels, high financing costs, and the mismatch between credit supply and demand. The breadth of digital finance refers to the extent to which users can be guaranteed corresponding services, reflecting the audience's scope of digital finance. Expanding the coverage and breadth of digital finance requires using mobile Internet to open electronic accounts on a large scale, eliminating the limitations of time and space differences, and broadening the contact surface of financial services (Wang et al. 2022; Xu et al. 2022). The greater the breadth of use, the more green innovation subjects it serves. By coordinating the allocation of credit resources and driving more social capital to invest in low-carbon development, digital finance has virtually strengthened the cross-regional allocation of green credit resources among cities and effective cooperation between governments.

Method

This study evaluates the effect of the carbon emission trading pilot policy at the city level with the well-reputed DID approach. We chose 274 cities as the research sample, including 46 pilot cities and 228 nonpilot cities after considering unavailable data and administrative adjustments. The Patsnap patent database and the official website of the State Intellectual Property Office are the platforms where we can get information on green patents. The World Intellectual Property Organization also provides the International Patent Classification (IPC) Green List on 300,000 green-authorized inventive patents. The "IPC Green Inventory" was developed by the Expert Committee of IPC and is divided into seven green patent topics, including alternative energy, transportation, energy conservation, waste treatment, agriculture and forestry, administrative supervision and design, and nuclear power generation and covering about 200 categories directly related to environmentally friendly technologies. The rest of the data are from the China Statistical Yearbook, the China Statistical Yearbook on Science and Technology, the annual statistical bulletins of each city, and the CNRDS data platform. This study selects the data from 2008 to 2020 for empirical analysis.

In 2008, the United Nations developed the "Global Green New Deal" idea in response to the international financial crisis. China is an active participant and pioneer in the theory and time of green development. China officially began to advocate green development and entered the fast lane of green innovation development in 2008. This is why the starting point of the study is 2008. In 2021, China officially established a unified national carbon emission trading market. The carbon emission trading policy has moved from the pilot stage to the policy diffusion stage, so the research deadline is 2020. In addition, considering a certain time lag from R&D innovation to patent application, the study lagged the independent variable and all control variables by one period (Guan et al. 2016).

Measures

Dependent variables

Inter-city green innovation cooperation (Egic) It is represented by the degree centrality index of each city node in the inter-city green patent cooperation network. In this study, green patents with patent applicants in different cities are considered inter-city cooperative green patents. The higher the degree of centrality of a node, the more influential the node is in the cooperative network.

Intra-city green innovation cooperation (Agic) It is represented by the number of green patents of two or more innovative entities within the same city. Invention patents can represent the output of innovation, where the application of patents reflects the willingness to carry out green technology innovation, and the authorization of patents has stricter approval procedures, which are objective and stable. The data processing procedure is as follows:

The first step is to retrieve nearly 300,000 pieces of green patent information according to the restrictions of application time, authorized invention, and IPC classification number. The second step is to eliminate the green patents in which the applicant is an individual or in which there is only one innovation institution. The third step is to link the company name information of all applicants to Baidu Map to get their city information. The fourth step is to build a collaborative innovation network among cities. For example, if University A1 in City A and Enterprise B1 in City B jointly apply for Patent P1 for cooperative invention, the data of green innovation cooperation between Cities A and B can be constructed through Patent P1. In the fifth step, to obtain the degree of centrality and other indicators that represent the characteristics of the cooperative network, it is necessary to use the cooperative network matrix for calculation. The number of authorized invention patent cooperation between the 274 cities in each year is used to calculate the collaborative innovation network between each region numerically. Then, UCINET software is used to calculate the characteristic data of each city's annual network structure.

Independent variable

Carbon emission trading pilot policy (Policy) The study design involves classifying the 46 cities that sequentially implemented carbon emission trading since 2013 as the treatment group, while the remaining non-pilot cities serve as the control group. A dummy variable is employed to represent the carbon emission trading pilot policy created through the interaction between the group dummy variable "Treat" and the time dummy variable "Post." A "Treat" value of 1 indicates a city's participation in the carbon emission trading pilot, whereas a "Treat" value of 0 signifies its absence. Similarly, the "Post" variable takes

Table 1 Descriptive statistics and correlation analysis

Variable	Observation	Mean	SD	Min	Max
Inter-city green innovation cooperation	3288	4.18	10.69	0.00	177.00
Intra-city green innovation cooperation	3288	6.86	52.15	0.00	1184.00
Population density	3288	7.96	0.77	5.56	9.33
The level of economic development	3288	10.55	0.63	9.03	11.96
Human capital	3288	0.046	1.00	− 2.61	2.28
Infrastructure	3288	2.70	0.43	1.44	3.60
Government expenditure on science and technology	3288	− 4.52	0.88	− 6.69	− 2.31
Urban openness	3288	0.19	0.36	0.00	8.13
Command-and-control environmental regulation intensity	3288	0.05	0.00	0.00	0.022
Industrial structure upgrading	3288	0.92	0.50	0.09	5.17
Digital financial coverage	2740	166.06	67.27	1.88	326.49

on a value of 1 for the year that a city became a pilot city and the subsequent years, while it takes on a value of 0 for the year before the policy implementation.

Mediating variables

Industrial structure upgrading (Isu) It is represented by the proportion of the ratio of the tertiary industry to the ratio of the secondary industry. The secondary industry is carbon emission intensive and concentrates on technological innovation. The evolution of industrial structure is closely related to green innovation.

Digital financial coverage (Dfc) We measure this variable as the coverage breadth index in the Digital Inclusive Financial Index released by the Digital Research Center of Peking University (Feng et al. 2020). The Digital Inclusion Index was first published in 2011. Therefore, the research period during which it is used as the mediating variable is from 2011 to 2020.

Control variables

Population density (Pd) is expressed as the number of people per square kilometer. *The level of economic development (Pgdp)* is expressed by a city's per capita gross domestic product. The higher the level of urban economic development, the larger the market size; the more the innovation factors, such as technology, talent, and capital are concentrated; and the stronger the ability and motivation of green technology innovation. *Human capital (Hum)* is calculated by the population of ordinary college or above (10,000)/the city's permanent population (10,000) *100. A high-quality labor force with skilled labor with rich knowledge reserves is an essential guarantee for scientific research and innovation activities. *Infrastructure (Infr)* is expressed as road area per capita. *Government expenditure on science and technology (Gov)* is represented by the proportion of government science and technology expenditure in the general budget of local finance. The control variables are treated in logarithms in the regression analysis. The definition and descriptive statistics of the variables are presented in Table 1. The average values of cross- and intra-city green innovation cooperation are 4.18 and 6.86, respectively. There is a significant difference between

Table 2 The principle of the DID model

	Before the implementation of the policy	After the implementation of the policy	Difference
Treatment group	A+B	A+B+C+D	C+D
Control group	A	A+C	C
Difference	B	B+D	D (difference in difference)

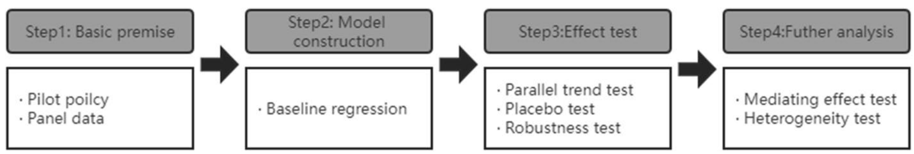

Fig. 1 Specific analysis steps of the DID model

the maximum and the mean values, indicating a large gap in the level of urban green innovation cooperation. Some cities have a high level of green innovation cooperation, but the overall level needs to be improved.

Model design

The DID method has been widely used in recent years to evaluate the effect of policy implementation as a quasi-experiment exogenous to the economic system (Beck et al. 2010; Bertrand and Mullainathan 2003; Zhang et al. 2020a, b). On the one hand, the implementation of China's carbon emission trading pilot policy may lead to differences in a pilot city before and after the implementation of the policy. On the other hand, it may also cause differences between pilot and non-pilot cities at the same time. Therefore, China's carbon emission trading pilot policy can be regarded as a quasi-natural experiment, and the DID method can be used to identify the net impact of policy shocks on green innovation cooperation at the city level. In this study, the empirical analysis of the DID model can be divided into four steps—basic premise, model construction, effect test, and further analysis. The theoretical explanation of the DID model is presented in Table 2, and the specific empirical analysis steps are depicted in Fig. 1. As the carbon emission trading pilot policy is launched in two batches, this study uses the multi-time DID model for evaluation. Then, we propose the following models:

$$Egic_{it+1} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 cont_{it} + \mu_{it} + \gamma_{it} + \epsilon_{it} \tag{1}$$

$$Agic_{it+1} = \beta_0 + \beta_1 Policy_{it} + \beta_2 cont_{it} + \mu_{it} + \gamma_{it} + \epsilon_{it} \tag{2}$$

In Eqs. 1 and 2, i denotes the city ; t denotes time; $\alpha_0$andβ_0 are the regression coefficient and the core parameters, and their significance level reflects the effect of the pilot policy on green innovation cooperation; $cont_{it}$ represents the control variable; μ_{it} represents the year-fixed effect; γ_{it} represents the city fixed effect; and ϵ_{it} represents the random error term. The study uses Stata16.0 software to perform the statistical analysis.

Table 3 Results of the benchmark regression

	(1)	(2)	(3)	(4)
Carbon emission trading pilot policy (Policy)	1.685**	1.670**	11.628**	11.725**
Population density		0.099		0.873**
The level of economic development		− 1.434**		− 7.645***
Human capital		− 1.124**		− 4.242*
Infrastructure		− 0.416		− 0.470
Government expenditure on science and technology		0.134		0.624
Cons	3.363***	20.330**	2.249**	83.978**
Year	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
R-squared	0.159	0.168	0.027	0.032
N	3288	3288	3288	3288

*, **, ***Significance levels of 10%,5% and 1%, respectively

Analysis and results

Baseline results

Based on the outlined benchmark model, we investigate the influence of the carbon emission trading pilot policy on inter- and intra-city green innovation collaborations. The findings from the estimation are presented in Table 3. In columns (1) and (2), the focus is on inter-city green innovation cooperation, while in columns (3) and (4), the emphasis shifts to intra-city green innovation cooperation. Columns (1) and (3) specifically incorporate fixed effects, excluding control variables. To accurately estimate the impact of the carbon emission trading pilot policy on green innovation cooperation, the analysis considers city-year fixed effects along with the control variables. The calculated coefficient for the instrumental variable (IV) in Column (2) is 1.670, attaining statistical significance at the 5% level. This outcome indicates that, compared with that of nonpilot cities, the average increase in collaborative cities in pilot cities is approximately 1.670. Similarly, the IV coefficient in Column (4) is 11.725, also demonstrating statistical significance at the 5% level. This result indicates that, relative to non-pilot cities, the average augmentation in intra-city green innovation cooperation in pilot cities is about 11.725 times.

Parallel trend test

As a quasi-natural test method, the important prerequisite for the results of the DID method is to meet the parallel trend hypothesis that is, the green innovation cooperation of the treatment and control groups has the same time trend before the policy shock occurs (Jacobson et al. 1993). This study selects data samples from five years before and after the implementation of the policy to conduct parallel trend tests on *Egic* and *Agic*, respectively, and the results are depicted in Fig. 2. In the years before the pilot of the carbon emission trading policy, the estimated coefficients of the two groups fluctuated around 0, which is not rejected at the 95% confidence interval. The test results are consistent with the hypothesis of the parallel trends.

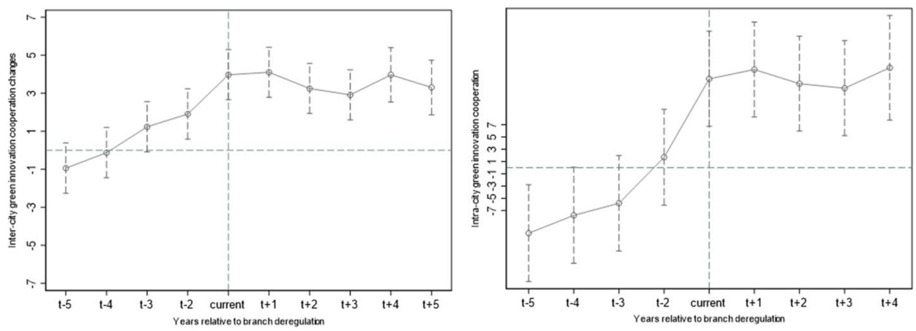

Fig. 2 Results of the parallel trend test

Table 4 Results of the time placebo test

	(1)	(2)
Carbon emission trading pilot policy (Policy)	0.622	1.658
Population density	0.120	1.067**
The level of economic development	− 1.335*	− 6.728**
Human capital	− 1.151**	− 4.527*
Infrastructure	− 0.485	− 1.140
Government expenditure on science and technology	0.167	0.956*
Cons	19.608**	77.590**
Year	Yes	Yes
City	Yes	Yes
R-squared	0.162	0.023
N	3288	3288

*, **, ***Significance levels of 10%,5% and 1%, respectively

Placebo test

Time placebo test Drawing on previous studies, we postpone the pilot year by two years to examine whether there is still a promotion effect on green innovation cooperation (Topalova 2010). If the estimated coefficients of the core variable are insignificant, the impact of some potential unobservable factors on green innovation cooperation can be excluded. Columns (1) and (2) of Table 4 present the effects on inter- and intra-city green innovation cooperation, with the outcomes revealing coefficient estimates of 0.622 and 1.658 for the policy variable, respectively. However, these estimates do not achieve statistical significance at the 10% level, passing the time placebo test.

City placebo test A city placebo test is employed to mitigate the potential influence of unobservable omitted variables on the benchmark regression outcomes (Cai et al. 2016). This study randomly selects a pseudo-treatment group comprising 46 cities from the sample cities, while the remaining cities constitute the pseudo-control group. This arrangement is designed to gauge the coefficient estimates associated with implementing a carbon emission trading pilot policy at the city level, focusing on inter- and intra-city green innovation cooperation.

This procedure is repeated 500 times to generate a collection of 500 regression coefficients alongside their corresponding p-values. After visualizing the kernel density

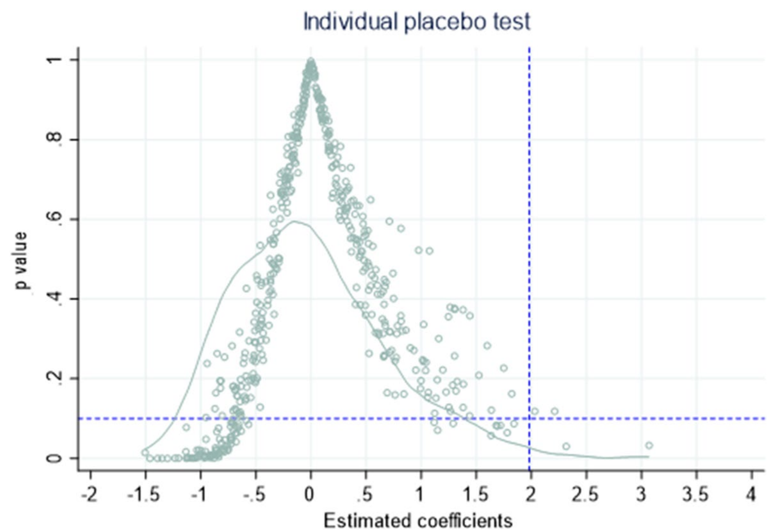

Fig. 3 Results of the city placebo tests

Table 5 Results of the robustness test

	(1)	(2)	(3)	(4)	(5)	(6)
Policy	30.741**	25.951**	2.808**	23.576**	2.866***	14.546**
Pd	0.742	1.826**	0.283	3.708	0.389***	1.747**
Pgdp	− 19.606**	− 16.243***	− 3.274**	− 21.764***	− 1.772**	− 13.634***
Hum	− 19.606**	− 9.860*	− 2.096	− 13.905	− 0.829	− 3.573
Infr	1.844	− 1.206	− 0.945	3.105	0.255	3.145
Gov	0.915	1.396	− 0.066	− 0.363	− 0.143	− 0.282
Cons	216.682**	179.885**	0.000	0.000	0.000	0.000
Year	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.039	0.032	0.188	0.051	0.142	0.033
N	3288	3288	1074	1074	2040	2040

*, **, ***Significance levels of 10%,5% and 1%, respectively. Carbon emission trading pilot policy (Policy), Population density (Pd), The level of economic development (Pgdp), Human capital (Hum), Infrastructure (Infr), Government expenditure on science and technology (Gov)

distribution and p-values of these 500 coefficient estimates (as depicted in Fig. 3), the majority of these coefficients cluster around the 0 mark, aligning with a normal distribution pattern. Furthermore, most of these regression results do not reach statistical significance. The estimated coefficients of the benchmark regression are positioned in the upper tail of the distribution of spurious regression coefficients. This occurrence is a rare event in the context of the urban placebo test. Consequently, the city placebo test is deemed successful and aligns with the expected results.

Robustness test

This study employs three robustness testing approaches to enhance the reliability of the findings. First, the measurement method of the dependent variable is substituted. Second, the study utilizes a propensity scores matching (PSM) model. Third, the potential

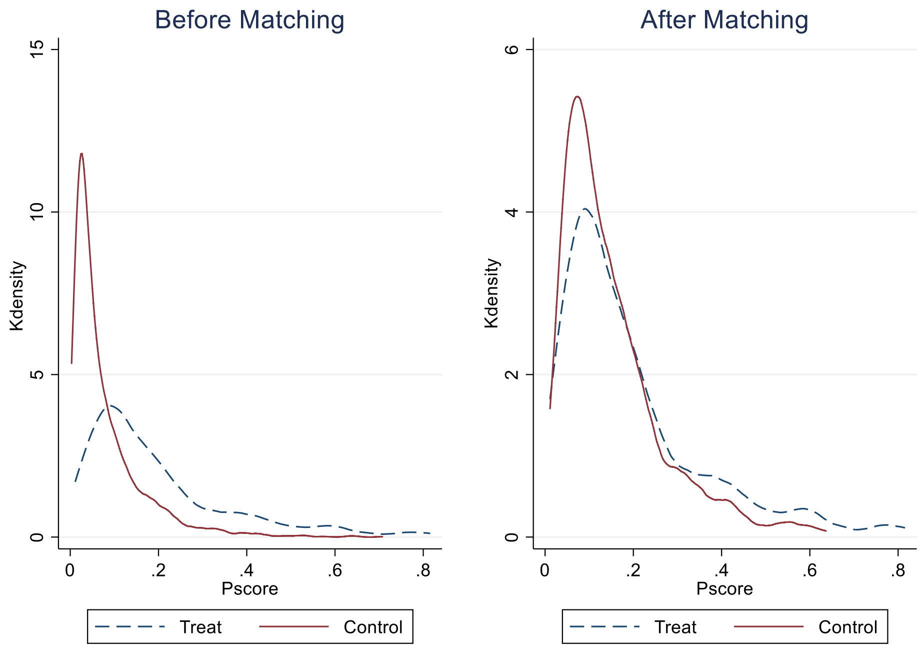

Fig. 4 Kernel density functions before and after matching

influence of other policies is isolated when implementing the carbon emission trading policy. The outcomes of these robustness tests are presented in Table 5.

Replacing the measurement method of the dependent variable Inter-city green innovation cooperation is represented by the sum of the number of green patents jointly applied by a city with other cities. Intra-city green innovation cooperation is represented by the total number of times that enterprises or institutions in a city participated in cooperation within the same city. The results are presented in columns (1) and (2) of Table 5. The estimated coefficient of IV in column (1) is 30.741, and that of IV in column (2) is 25.951. They pass the significance test at the 5% level. The results indicate that compared with non-pilot cities, the number of green patents jointly applied by different cities increased by 30.741 times on average, and the number of times enterprises or institutions in the city cooperated increased by 25.951 on average. This robustness test proves that the policy positively impacts inter- and intra-city green innovation cooperation, which is consistent with the benchmark regression analysis.

Using the PSM-DID model To ensure that the treatment and control groups share similar developmental trends in the absence of the pilot policy (Rosenbaum and Rubin 1985), we employ the PSM technique. This methodology aims to counterbalance individual discrepancies between these two groups. The process unfolds in the following manner: Initially, we match the treatment and control groups based on comparable individual characteristics, utilizing a nearest-neighbor matching approach with a 1:4 ratio. Then, the outcomes of this matching procedure undergo validation, which is visually depicted in Fig. 4. Once validated, the matched samples are utilized in the DID estimation analysis. The resulting estimates are presented in columns (3) and (4) of Table 5. The IV coefficients in columns (3) and (4) are 2.808 and 23.576, respectively, with both passing the significance tests at the 5% level. This suggests that, compared with that of non-pilot cities, on average, the policy's implementation led to an increase of approximately 2.808 in

Table 6 Results of the mediation effect test

Dv	Mv	Proportion of indirect effect	Category	Observed coefficient	Standard error	95% confidence interval	
						lower limit	upper limit
Egic	Isu	33.46%	Indirect effect	1.667	0.532	0.874	3.062
			Direct effect	3.315	1.027	1.448	5.458
	Dfc	4.59%	Indirect effect	0.191	0.104	0.025	0.416
			Direct effect	3.974	1.046	2.064	6.144
Agic	Isu	35.84%	Indirect effect	8.201	3.103	3.692	16.510
			Direct effect	14.681	6.186	4.915	28.373
	Dfc	3.86%	Indirect effect	0.709	0.388	0.075	1.615
			Direct effect	17.660	6.732	5.874	32.768

Inter-city green innovation cooperation (Egic), Intra-city green innovation cooperation (Agic), Industrial structure upgrading (Isu), Digital financial coverage (Dfc)

inter-city green innovation cooperation and approximately 23.576 in intra-city innovation cooperation within pilot cities. A comparison of the estimation outcomes from the baseline regression and the PSM-DID approach demonstrates consistent direction and significance of the coefficients. This reaffirms the robustness of the baseline regression results.

Interference from other policies is ruled out By collecting and organizing documents, this study found two pilot policies that may affect green innovation cooperation. They are the *Notice of the National Development and Reform Commission on Promoting the Pilot Work of National Innovative Cities* and the *Notice on Carrying out the Pilot Work of Low-carbon Provinces and Regions and Low-carbon Cities*. This study eliminates the sample of cities in the control group affected by these two policies. The regression outcomes are displayed in columns (5) and (6) of Table 5. In column (5), the estimated coefficient of the IV is 2.808, and it attains statistical significance at the 1% level. In column (6), the estimated IV coefficient is 14.546 and passes the significance test at the 5% level. Moreover, the estimation results are similar to the baseline regression results.

Mediating effect test

The test results of the mediating effect of the industrial structure upgrading and the digital financial coverage are presented in Table 6. We use the bootstrap method to determine whether the mediating effect exists through the critical value of the confidence level. Duplicate sampling was set for 500 times.

We verify the mediating effect of industrial structure upgrading first. For inter-city green innovation cooperation, the indirect effect of industrial structure upgrading is 1.667, with a 95% confidence interval of [0.874, 3.062], and the direct effect is 3.315, with a 95% confidence interval of [1.448, 5.458]. None of the confidence intervals contains 0. For intra-city green innovation cooperation, the indirect effect of industrial structure upgrading is 8.201, with a 95% confidence interval of [3.692, 16.510], and the direct effect is 14.681, with a 95% confidence interval of [4.915, 28.373]. None of the confidence intervals contains 0. This indicates that the upgrading of industrial structure has a partial mediating effect.

Then, we verify the mediating effect of the coverage breadth of digital finance. For inter-city green innovation cooperation, the indirect effect of digital finance coverage is

Table 7 Results of the heterogeneity test

	High Open		Low Open		High Cer		Low Cer	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Policy	1.569*	23.424**	0.644**	0.553	1.908**	18.073**	1.976***	12.438***
Pd	1.189*	8.873***	0.111	0.112	0.279	0.493	-0.375*	0.133
Pgdp	− 1.374	− 14.058**	− 0.671*	0.255	-2.968*	-18.683**	-0.418	-2.197**
Hum	− 3.446***	− 24.264***	− 0.900**	− 1.160***	-1.207***	-8.841***	-1.541***	-4.230***
Infr	− 2.576	1.562	0.531**	− 0.590*	0.411	0.489	-0.767*	-0.369
Gov	0.263	1.636*	− 0.034	0.046	-0.204	-0.095	0.160	0.427
Cons	0.000	0.000	0.000	0.000	0.000	0.000	15.540***	32.457**
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.273	0.091	0.162	0.036	0.188	0.050	0.189	0.071
N	798	798	2216	2216	1330	1330	1684	1684

Carbon emission trading pilot policy (Policy), Population density(Pd), The level of economic development (Pgdp), Human capital (Hum), Infrastructure (Infr), Government expenditure on science and technology (Gov)

0.191, with a 95% confidence interval of [0.025, 0.416], and the direct effect is 3.974, with a 95% confidence interval of [2.064, 6.144]. None of the confidence intervals contains 0. For intra-city green innovation cooperation, the indirect effect of digital finance coverage is 0.709, with a 95% confidence interval of [0.075, 1.615], and the direct effect is 17.660, with a 95% confidence interval of [5.874, 32.768]. None of the confidence intervals contains 0. This indicates that the coverage breadth of digital finance has a partial mediating effect.

Heterogeneity analysis

Urban openness

In the historical process of China's opening up to the outside world, cities have always been the most important carriers. Local enterprises or institutions will inevitably face fierce international competition when they go out. To expand the space for survival and development, these enterprises must undertake R&D investment in high-quality products to obtain foreign advanced technology spillovers to promote green innovation (Cai et al. 2016; Muhammad and Khan 2019). In this study, a city's degree of openness is represented by the proportion of total import and export volume in its urban GDP. The analysis involves a group regression based on the yearly average of each city's external openness. The results are detailed in Table 7. In columns (1) and (3), the dependent variable pertains to inter-city green innovation cooperation, while in columns (2) and (4), the focus shifts to intra-city green innovation cooperation. The findings in columns (1) and (3) reveal that the estimated coefficient for cities with high openness is 1.569, whereas for cities with low openness, the coefficient is 0.644, and both are significant. This indicates that the carbon emission trading pilot policy improves the level of inter-city green innovation cooperation more significantly in cities with a higher degree of openness. Columns (2) and (4) reveal that the estimated coefficient of the group with a high degree of openness is 23.424, which is significant at the 5% level. The estimated coefficient of the group with low openness is 0.553, which is insignificant. This indicates that the carbon emission trading pilot policy significantly improves intra-city green innovation cooperation in cities with a higher degree of openness.

Command-and-control environmental regulation intensity

Environmental regulation is important for the government to guide and manage ecological and environmental problems. Improving command-and-control environmental regulation has a critical impact on the ecological environment (Horbach 2008; Lee et al. 2011; Zhao et al. 2015). This study uses the proportion of the word frequency related to environmental protection in local government reports to represent the intensity of command-and-control environmental regulation. The grouped regression analysis is conducted based on the annual average value of a city's command-and-control environmental regulation intensity; the results are presented in Table 7. The dependent variable in columns (5) and (7) is inter-city green innovation cooperation, and the dependent variable in columns (6) and (8) is intra-city green innovation cooperation. Columns (5) and (7) reveal that the estimated coefficient of the group with high command-and-control environmental regulation is 1.908, and the estimated coefficient of the group with low command-and-control environmental regulation is 1.976 and significant. Columns (6) and (8) reveal that the estimated coefficient of the group with high command-and-control environmental regulation is 18.073. The estimated coefficient of the group with low command-and-control environmental regulation is 12.438. Both of them are significant. This indicates that the pilot policy has a more significant effect on improving intra-city green innovation cooperation in cities with high command-and-control environmental regulation intensity. This may be because, under the constraints of environmental regulation, enterprises or institutions in the same city face similar pressure, have sufficient motivation to carry out green innovation cooperation, and cope with the pollution reduction cost that increases with the intensity of government environmental regulation. The possible reason is that under the constraints of environmental regulation, enterprises or institutions in the same city face similar pressure and have sufficient motivation to carry out green innovation cooperation to cope with the cost of pollution reduction that increases with the intensity of government environmental regulation.

Conclusion and implications

Research conclusion

(1) The carbon emission trading pilot policy is found to promote inter- and intra-city green innovation cooperation positively. The coefficient of the independent variable remains significantly positive at the 5% statistical significance level. This assertion is true even after subjecting the analysis to rigorous robustness tests.
(2) The influence of the carbon emission trading pilot policy on green innovation cooperation has a heterogeneous pattern. The impact of the policy is more pronounced in inter- and intra-city green innovation cooperation in cities with lower levels of openness than those with higher levels of openness. Similarly, while the effect on inter-city green innovation cooperation remains relatively consistent across cities with varying levels of command-and-control environmental regulation intensity, the promotion effect on intra-city green innovation cooperation is notably stronger.

These findings emphasize significant variations in the effects of carbon emission trading pilot policies across diverse city contexts.

(3) The relationship between the carbon emission trading pilot policy and green innovation cooperation is partially mediated by two factors—industrial structure upgrading and the extent of digital financial coverage. Enhancing industrial structure drives the evolution of urban green innovation, while embracing digital finance coverage facilitates the seamless transfer of urban carbon emission rights, thereby ensuring the successful implementation of policy measures.

Policy implications

Based on the research conclusions, we propose the following policy implications.

(1) China is currently in the process of consolidating the lessons learned from the implementation of the carbon emission trading pilot policy and scaling it up nationwide. The pilot policy adheres to the incremental reform approach of "pilot first and then expansion," mirroring the principles of China's reform and opening-up strategy. This strategy is particularly relevant to the green and low-carbon transformation of the economy and society. Such a gradual approach minimizes and manages the potential risks associated with extensive transformations while simultaneously enabling the exploitation of best practices for achieving green and low-carbon objectives. The findings of this study underscore the significant role of pilot cities in propelling green innovation cooperation. In July 2021, China marked a pivotal milestone as its carbon emission trading market officially commenced trading operations. Local pilots have made positive progress after years of development, accumulating experience in constructing China's carbon market. This initiative will make a substantial contribution toward attaining the goals of carbon peak and neutrality.

(2) The government should take differentiated roads of low-carbon transformation according to the characteristics of openness and command-type environmental regulation intensity. For cities with low openness, the government should encourage enterprises to seize the opportunity of opening-up and promoting the flow of regional factors. It should also command and control environmental regulations to pressure enterprises to carry out R&D and production activities. Market-driven environmental regulation will stimulate enterprises' enthusiasm for energy conservation, emission reduction, and green innovation. For cities with low command-and-control environmental regulation intensity, the government should use two different environmental regulation tools to expand the promotion benefits of the carbon emission trading pilot policy on green innovation cooperation.

(3) Relevant supporting policy documents should be issued during the carbon market construction to upgrade a city's industrial structure and the development of digital finance. First, the government should foster and strengthen advanced manufacturing, strategic emerging, and modern service industries; reduce the proportion of industries with high energy consumption and high emissions; build green transportation infrastructure; and guide green travel. Second, the government should pro-

mote the development of green finance, develop technology patents as collateral for industrial upgrading loans, and effectively allocate social capital to promote participation in green and low-carbon construction. Third, the government should popularize Internet financial knowledge education for local enterprises and other institutions. This will promote the penetration of green financial services into micro, small, and medium-sized enterprises; transfer part of the business from offline to online; greatly reduce the original resource loss; and achieve win–win benefits and environmental protection.

Limitations and future research

Although this study has certain theoretical value and practical significance, there are still some limitations that future research can improve. The research object of this study is the level of green innovation cooperation at the city level, so we adopt the panel data of prefecture-level cities. Future studies can be further refined as data collection becomes more detailed. First, green innovation cooperation can be further subdivided into school–enterprise and enterprise–enterprise cooperation. Second, a shift from static to dynamic research can make the results have a more far-reaching impact. Third, environmental regulation policies may produce different effects in different industries. Therefore, future research will evaluate the effects of carbon emission trading policies on different industries. Fourth, we will collect more detailed data, such as cooperation data on green services and products, to measure green innovation cooperation more comprehensively.

Through the study of the two intermediary effects, we put forward some suggestions for the implementation of the policy from the two aspects of adjusting the industrial structure and promoting the development of digital finance. We did not analyze the comprehensive effects of these two mediating effects but simply divided them into direct and indirect effects for verification, which was scattered. Therefore, future studies should deeply analyze the comprehensive effect of the interaction between different mediating effects and the interaction between different environmental protection policies. Then, effective low-carbon development strategies can be formulated based on in-depth analysis.

Abbreviations

EU	European Union
DID	Difference-in-differences
GDP	Gross domestic product
IPC	International Patent Classification
WIPO	World Intellectual Property Organization
Egic	Inter-city green innovation cooperation
Agic	Intra-city green innovation cooperation
Isu	Industrial structure upgrading
Dfc	Digital financial coverage
Pd	Population density
Pgdp	The level of economic development
Hum	Human capital
Infr	Infrastructure
Gov	Government expenditure on science and technology

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Author contributions
PX was responsible for research design, manuscript writing and structure, research project funding, cross-checking results and interpretation. WJ is accountable for the research paper's structure, format, design, writing, and proofreading and assists in analysis. CY was responsible in data collection, design, conceptualization, proofreading and analysis. SA was responsible for proofreading, interpretation, data analysis, cross-checking results and editing, authenticity checking, Patent and copyrights matters handling, and assisting in rewriting, correcting, and supervising. All authors read and approved the final manuscript.

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Availability of data and materials
The Patsnap patent database (https://www.zhihuiya.com/) and the State Intellectual Property Office's official website (https://pss-system.cponline.cnipa.gov.cn/conventionalSearch) are the platforms where we can get data on green patents. The World Intellectual Property Organization (WIPO) also provides the International Patent Classification (IPC) Green List on 300 thousand green-authorized inventive patents (https://www.wipo.int/classifications/ipc/en/). "IPC Green Inventory" was developed by the Expert Committee of IPC and is divided into seven green patent topics, including alternative energy, transportation, energy conservation, waste treatment, agriculture and forestry, administrative supervision and design, and nuclear power generation, covering about 200 categories directly related to environmentally friendly technologies. The rest data comes from the China Statistical Yearbook (https://pss-system.cponline.cnipa.gov.cn/conventionalSearch), the China Statistical Yearbook on Science and Technology (http://www.stats.gov.cn/zsk/), the annual statistical bulletins of each city, and the CNRDS data platform (http://www.cnrds.com/).

Declaration

Competing interests
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

Alcala F, Ciccone A (2004) Trade and productivity. Quart J Econ 119(2):613–646. https://doi.org/10.1162/0033553041382139

Ali S, Ashraf J, Ghufran M, Xiaobao P, Zhiying L (2023) Innovation sharing a remedial measure: the case of Covid-19 pandemic. Eur J Innov Manag (ahead-of-print)

Ali S, Ghufran M, Ashraf J, Xiaobao P, ZhiYing L (2023) The role of public and private interventions on the evolution of green innovation in China. IEEE Trans Eng Manag

Anderson B, Convery F, Maria CD (2011) Technological change and the EU ETS: the case of Ireland. IEFE Working Paper, 43. https://doi.org/10.2139/ssrn.1855495

Amores-Salvadó J, Castro G-d, Navas-López JE (2015) The importance of the complementarity between environmental management systems and environmental innovation capabilities: a firm level approach to environmental and business performance benefits. Technol Forecast Soc Chang 96(4):288–297. https://doi.org/10.1016/j.techfore.2015.04.004

Arner DW, Buckley RP, Zetzsche DA, Veidt R (2020) Sustainability, FinTech and financial inclusion. Eur Bus Org Law Rev 21(1):7–35. https://doi.org/10.1007/s40804-020-00183-y

Bai SZ, Bi XR, Han CJ, Zhou QJ, Shang WL, Yang M, He H (2022) Evaluating R&D efficiency of China's listed lithium battery enterprises. Front Eng Manag 9(3):473–485. https://doi.org/10.1007/s42524-022-0213-5

Bauman Y, Lee M, Seeley K (2008) Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications. Environ Resource Econ 40(4):507–527. https://doi.org/10.1007/s10640-007-9167-7

Beck T, Levine R, Levkov A (2010) Big bad banks? The winners and losers from bank deregulation in the United States. J Financ 65(5):1637–1667. https://doi.org/10.1111/j.1540-6261.2010.01589.x

Berkhout PHG, Muskens JC, Velthuijsen JW (2000) Defining the rebound effect. Energy Policy 28(6–7):425–432. https://doi.org/10.1016/s0301-4215(00)00022-7

Bertrand M, Mullainathan S (2003) Enjoying the quiet life? Corporate governance and managerial preferences. J Polit Econ 111(5):1043–1075. https://doi.org/10.1086/376950

Bian J, Zhao X (2020) Tax or subsidy? An analysis of environmental policies in supply chains with retail competition. Eur J Oper Res 283(3):901–914. https://doi.org/10.1016/j.ejor.2019.11.052

Cai XQ, Lu Y, Wu MQ, Yu LH (2016) Does environmental regulation drive away inbound foreign direct investment? Evidence from a quasi-natural experiment in China. J Dev Econ 123:73–85. https://doi.org/10.1016/j.jdeveco.2016.08.003

Cainelli G, De Marchi V, Grandinetti R (2015) Does the development of environmental innovation require different resources? Evidence from Spanish manufacturing firms. J Clean Prod 94:211–220. https://doi.org/10.1016/j.jclepro.2015.02.008
Calel R, Dechezlepretre A (2016) Environmental policy and directed technological change: evidence from the European Carbon Market. Rev Econ Stat 98(1):173–191. https://doi.org/10.1162/REST_a_00470
Caparros A, Pereau J-C, Tazdait T (2013) Emission trading and international competition: the impact of labor market rigidity on technology adoption and output. Energy Policy 55:36–43. https://doi.org/10.1016/j.enpol.2012.09.017
Chen X, Wang X, Zhou M (2019) Firms' green R&D cooperation behaviour in a supply chain: technological spillover, power and coordination. Int J Prod Econ 218:118–134. https://doi.org/10.1016/j.ijpe.2019.04.033
Chesbrough H (2003) The logic of open innovation: managing intellectual property. Calif Manag Rev 45(3):33. https://doi.org/10.2307/41166175
Dai HC, Xie Y, Liu JY, Masui T (2018) Aligning renewable energy targets with carbon emissions trading to achieve China's INDCs: a general equilibrium assessment. Renew Sustain Energy Rev 82:4121–4131. https://doi.org/10.1016/j.rser.2017.10.061
De Marchi V, Molina-Morales FX, Martinez-Chafer L (2022) Environmental innovation and cooperation: a configurational approach. Technol Forecast Soc Change 182:1. https://doi.org/10.1016/j.techfore.2022.121835
Demertzis M, Merler S, Wolff GB (2018) Capital markets union and the fintech opportunity. J Financ Regul 4(1):157–165. https://doi.org/10.1093/jfr/fjx012
Desrochers P, Haight CE (2014) Squandered profit opportunities? Some historical perspective on industrial waste and the Porter Hypothesis. Resour Conserv Recycl 92:179–189. https://doi.org/10.1016/j.resconrec.2014.07.001
Dong F, Dai Y, Zhang S, Zhang X, Long R (2019) Can a carbon emission trading scheme generate the Porter effect? Evidence from pilot areas in China. Sci Total Environ 653:565–577. https://doi.org/10.1016/j.scitotenv.2018.10.395
Fabrizi A, Guarini G, Meliciani V (2018) Green patents, regulatory policies and research network policies. Res Policy 47(6):1018–1031. https://doi.org/10.1016/j.respol.2018.03.005
Guan JC, Liu N (2016) Exploitative and exploratory innovations in knowledge network and collaboration network: a patent analysis in the technological field of nano-energy. Res Policy 45(1):97–112. https://doi.org/10.1016/j.respol.2015.08.002
Guan JC, Zuo KR, Chen KH, Yam RCM (2016) Does country-level R&D efficiency benefit from the collaboration network structure? Res Policy 45(4):770–784. https://doi.org/10.1016/j.respol.2016.01.003
Feng G, Jingyi W, Fang W, Tao K, Xun Z, Zhiyun C (2020) Measuring China's digital financial inclusion: index compilation and spatial characteristics. China Econ Q 19(4):1401–1418. https://doi.org/10.13821/j.cnki.ceq.2020.03.12
Higham K, de Rassenfosse G, Jaffe AB (2021) Patent quality: towards a systematic framework for analysis and measurement. Res Policy 50(4):1. https://doi.org/10.1016/j.respol.2021.104215
Horbach J (2008) Determinants of environmental innovation—New evidence from German panel data sources. Res Policy 37(1):163–173. https://doi.org/10.1016/j.respol.2007.08.006
Hu J, Pan X, Huang Q (2020a) Quantity or quality? The impacts of environmental regulation on firms' innovation–Quasi-natural experiment based on China's carbon emissions trading pilot. Technol Forecast Soc Chang 158:120122. https://doi.org/10.1016/j.techfore.2020.120122
Hu YC, Ren SG, Wang YJ, Chen XH (2020b) Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China. Energy Econ 85:14. https://doi.org/10.1016/j.eneco.2019.104590
Huang H, Roland-Holst D, Springer C, Lin J, Cai WJ, Wang C (2019) Emissions trading systems and social equity: A CGE assessment for China. Appl Energy 235:1254–1265. https://doi.org/10.1016/j.apenergy.2018.11.056
Hubler M, Voigt S, Loschel A (2014) Designing an emissions trading scheme for China An up-to-date climate policy assessment. Energy Policy 75:57–72. https://doi.org/10.1016/j.enpol.2014.02.019
Jacobson LS, LaLonde RJ, Sullivan DG (1993) Earnings losses of displaced workers. Am Econ Rev 83(4):685–709
Jiang SQ, Shi AN, Peng ZH, Li X (2017) Major factors affecting cross-city R&D collaborations in China: evidence from cross-sectional co-patent data between 224 cities. Scientometrics 111(3):1251–1266. https://doi.org/10.1007/s11192-017-2358-2
Jin P, Mangla SK, Song M (2022) The power of innovation diffusion: How patent transfer affects urban innovation quality. J Bus Res 145:414–425. https://doi.org/10.1016/j.jbusres.2022.03.025
Ju JD, Lin JY, Wang Y (2015) Endowment structures, industrial dynamics, and economic growth. J Monet Econ 76:244–263. https://doi.org/10.1016/j.jmoneco.2015.09.006
Kobarg S, Stumpf-Wollersheim J, Schlgel C, Welpe IM (2020) Green together? The effects of companies' innovation collaboration with different partner types on ecological process and product innovation. Ind Innov 27(9):953–990. https://doi.org/10.1080/13662716.2020.1713733
Lee J, Veloso FM, Hounshell DA (2011) Linking induced technological change, and environmental regulation: evidence from patenting in the US auto industry. Res Policy 40(9):1240–1252. https://doi.org/10.1016/j.respol.2011.06.006
Li J, Sutherland D, Ning LT, Wang YD (2014) Firm ownership, industrial structure, and regional innovation performance in China's provinces. Technol Anal Strateg Manag 26(9):1001–1022. https://doi.org/10.1080/09537325.2014.943714
Liao ZJ (2018) Environmental policy instruments, environmental innovation and the reputation of enterprises. J Clean Prod 171:1111–1117. https://doi.org/10.1016/j.jclepro.2017.10.126
Lin BQ, Jia ZJ (2019a) Impacts of carbon price level in carbon emission trading market. Appl Energy 239:157–170. https://doi.org/10.1016/j.apenergy.2019.01.194
Lin BQ, Jia ZJ (2019b) What are the main factors affecting carbon price in Emission Trading Scheme? A case study in China. Sci Total Environ 654:525–534. https://doi.org/10.1016/j.scitotenv.2018.11.106
Lin BQ, Jia ZJ (2019c) What will China's carbon emission trading market affect with only electricity sector involvement? A CGE based study. Energy Econ 78:301–311. https://doi.org/10.1016/j.eneco.2018.11.030
Lin P, Liu ZM, Zhang YF (2009) Do Chinese domestic firms benefit from FDI inflow? Evidence of horizontal and vertical spillovers. China Econ Rev 20(4):677–691. https://doi.org/10.1016/j.chieco.2009.05.010

Liu M, Shan YF, Li YM (2022a) Study on the effect of carbon trading regulation on green innovation and heterogeneity analysis from China. Energy Policy 171:15. https://doi.org/10.1016/j.enpol.2022.113290
Liu MH, Li YX (2022) Environmental regulation and green innovation: Evidence from China?s carbon emissions trading policy. Financ Res Lett 48:9. https://doi.org/10.1016/j.frl.2022.103051
Liu Z, Qian QS, Hu B, Shang WL, Li LL, Zhao YJ, Han CJ (2022b) Government regulation to promote coordinated emission reduction among enterprises in the green supply chain based on evolutionary game analysis. Resources Conserv Recycl 182:15. https://doi.org/10.1016/j.resconrec.2022.106290
Liu ZL, Sun HB (2021) Assessing the impact of emissions trading scheme on low-carbon technological innovation: evidence from China. Environ Impact Assess Rev 89:10. https://doi.org/10.1016/j.eiar.2021.106589
Ma Y, Kong L, Yang X, Lin C (2021) Innovation cooperation network evolution about green building technology with Government Intervention: based on evolutionary game theory. Ieee Access 9:142289–142301. https://doi.org/10.1109/access.2021.3119632
Muhammad B, Khan S (2019) Effect of bilateral FDI, energy consumption, CO2 emission and capital on economic growth of Asia countries. Energy Rep 5:1305–1315. https://doi.org/10.1016/j.egyr.2019.09.004
Narayan PK, Sharma SS (2015) Is carbon emissions trading profitable? Econ Model 47:84–92. https://doi.org/10.1016/j.econmod.2015.01.001
Noni ID, Orsi L, Belussi F (2018) The role of collaborative networks in supporting the innovation performances of lagging-behind European regions. Res Policy 47(1):1–13. https://doi.org/10.1016/j.respol.2017.09.006
Paramati SR, Di M, Huang R (2021) The role of financial deepening and green technology on carbon emissions: evidence from major OECD economies. Financ Res Lett 41:1. https://doi.org/10.1016/j.frl.2020.101794
Petroni G, Bigliardi B, Galati F (2019) Rethinking the porter hypothesis: the underappreciated importance of value appropriation and pollution intensity. Rev Policy Res 36(1):121–140. https://doi.org/10.1111/ropr.12317
Porter ME, Vander Linde C (1995) Toward a new conception of the environment-competitiveness relationship. J Econ Perspect 9(4):97–118. https://doi.org/10.1257/jep.9.4.97
Ramanathan R, Ramanathan U, Bentley Y (2018) The debate on flexibility of environmental regulations, innovation capabilities and financial performance—a novel use of DEA. Omega-Int J Manag Sci 75:131–138. https://doi.org/10.1016/j.omega.2017.02.006
Rosenbaum PR, Rubin DB (1985) Constructing a control-group using multivariate matched sampling methods that incorporate the propensity score. Am Stat 39(1):33–38. https://doi.org/10.2307/2683903
Shang WL, Lv Z (2023) Low carbon technology for carbon neutrality in sustainable cities: a survey. Sustain Cities Soc 92:1. https://doi.org/10.1016/j.scs.2023.104489
Song Y, Zhang X, Zhang M (2021) The influence of environmental regulation on industrial structure upgrading: Based on the strategic interaction behavior of environmental regulation among local governments. Technol Forecast Soc Change. https://doi.org/10.1016/j.techfore.2021.120930
Springer C, Evans S, Lin J, Roland-Holst D (2019) Low carbon growth in China: the role of emissions trading in a transitioning economy. Appl Energy 235:1118–1125. https://doi.org/10.1016/j.apenergy.2018.11.046
Stavropoulos S, Wall R, Xu Y (2018) Environmental regulations and industrial competitiveness: evidence from China. Appl Econ 50(12):1378–1394. https://doi.org/10.1080/00036846.2017.1363858
Steensma HK, Corley KG (2000) On the performance of technology-sourcing partnerships: The interaction between partner interdependence and technology attributes. Acad Manag J 43(6):1045–1067. https://doi.org/10.2307/1556334
Tang L, Wu JQ, Yu L, Bao Q (2015) Carbon emissions trading scheme exploration in China: a multi-agent-based model. Energy Policy 81:152–169. https://doi.org/10.1016/j.enpol.2015.02.032
Tether BS (2002) Who co-operates for innovation, and why—an empirical analysis. Res Policy 31(6):947–967. https://doi.org/10.1016/s0048-7333(01)00172-x
Topalova P (2010) Factor immobility and regional impacts of trade liberalization: evidence on poverty from India. Am Econ J-Appl Econ 2(4):1–41. https://doi.org/10.1257/app.2.4.1
Tzankova Z (2021) Can private governance boost public policy? Insights from public-private governance interactions in the fisheries and electricity sectors. Regul Govern 15(4):1248–1269. https://doi.org/10.1111/rego.12317
Wang H, Chen ZP, Wu XY, Niea X (2019) Can a carbon trading system promote the transformation of a low-carbon economy under the framework of the porter hypothesis?—Empirical analysis based on the PSM-DID method. Energy Policy 129:930–938. https://doi.org/10.1016/j.enpol.2019.03.007
Wang S, Guidice R, Zhou YY, Wang ZM (2017) It's more complicated than we think: The implications of social capital on innovation. Asia Pac J Manag 34(3):649–674. https://doi.org/10.1007/s10490-016-9491-y
Wang X, Wang X, Ren X, Wen F (2022) Can digital financial inclusion affect CO2 emissions of China at the prefecture level? Evidence from a spatial econometric approach. Energy Econ. https://doi.org/10.1016/j.eneco.2022.105966
Wen FH, Wu N, Gong X (2020) China's carbon emissions trading and stock returns. Energy Econ 86:15. https://doi.org/10.1016/j.eneco.2019.104627
Wen W, Zhou P, Zhang FQ (2018) Carbon emissions abatement: Emissions trading vs consumer awareness. Energy Economics 76:34–47. https://doi.org/10.1016/j.eneco.2018.09.019
Williamson OE (1981) The economics of organization: the transaction cost approach. Am J Sociol 87(3):548–577
Wu Y, Shen LY, Shuai CY, Jiao LD, Liao SJ, Guo ZH (2021) Key driving forces on the development of low carbon city (LCC) in China. Ecol Ind 124:12. https://doi.org/10.1016/j.ecolind.2021.107379
Xie QJ, Su J (2021) The spatial-temporal complexity and dynamics of research collaboration: evidence from 297 cities in China (1985–2016). Technol Forecast Soc Chang 162:15. https://doi.org/10.1016/j.techfore.2020.120390
Xu X, Jiang M, Zhang Z, Yang J (2022) Does digital finance facilitate improvement in export product quality? Evidence from China. Appl Econ Lett. https://doi.org/10.1080/13504851.2022.2117270
Yan YX, Zhang XL, Zhang JH, Li K (2020) Emissions trading system (ETS) implementation and its collaborative governance effects on air pollution: The China story. Energy Policy 138:13. https://doi.org/10.1016/j.enpol.2020.111282
Yang XY, Jiang P, Pan Y (2020) Does China's carbon emission trading policy have an employment double dividend and a Porter effect? Energy Policy 142:8. https://doi.org/10.1016/j.enpol.2020.111492

Yao SY, Yu XY, Yan S, Wen SY (2021) Heterogeneous emission trading schemes and green innovation. Energy Policy 155:13. https://doi.org/10.1016/j.enpol.2021.112367
Yin S, Zhang N, Li B (2020) Improving the effectiveness of multi-agent cooperation for green manufacturing in China: a theoretical framework to measure the performance of green technology innovation. Int J Environ Res Publ Health 17(9):1. https://doi.org/10.3390/ijerph17093211
Yu HX, Jiang YH, Zhang ZW, Shang WL, Han CJ, Zhao YJ (2022) The impact of carbon emission trading policy on firms' green innovation in China. Financ Innov 8(1):24. https://doi.org/10.1186/s40854-022-00359-0
Yu X, Wang P (2021) Economic effects analysis of environmental regulation policy in the process of industrial structure upgrading: Evidence from Chinese provincial panel data. Sci Tot Environ 753:1. https://doi.org/10.1016/j.scitotenv.2020.142004
Yuan H, Feng Y, Lee C-C, Cen Y (2020) How does manufacturing agglomeration affect green economic efficiency? Energy Econ 92:1. https://doi.org/10.1016/j.eneco.2020.104944
Zhang HT, Sun XM, Ahmad M, Wang XY (2023) Heterogeneous impacts of carbon emission trading on green innovation: firm-level in China. Energy Environ 26:1. https://doi.org/10.1177/0958305x231164690
Zhang J, Kang L, Li H, Ballesteros-Perez P, Skitmore M, Zuo J (2020a) The impact of environmental regulations on urban Green innovation efficiency: The case of Xi'an. Sustain Cities Soc 57:1. https://doi.org/10.1016/j.scs.2020.102123
Zhang WJ, Zhang N, Yu YN (2019) Carbon mitigation effects and potential cost savings from carbon emissions trading in China's regional industry. Technol Forecast Soc Chang 141:1–11. https://doi.org/10.1016/j.techfore.2018.12.014
Zhang YJ, Liang T, Jin YL, Shen B (2020b) The impact of carbon trading on economic output and carbon emissions reduction in China's industrial sectors. Appl Energy 260:13. https://doi.org/10.1016/j.apenergy.2019.114290
Zhang YJ, Peng YL, Ma CQ, Shen B (2017) Can environmental innovation facilitate carbon emissions reduction? Evidence from China. Energy Policy 100:18–28. https://doi.org/10.1016/j.enpol.2016.10.005
Zhao J, Jiang Q, Dong X, Dong K, Jiang H (2022) How does industrial structure adjustment reduce CO2 emissions? Spatial and mediation effects analysis for China. Energy Econ 105:1. https://doi.org/10.1016/j.eneco.2021.105704
Zhao XL, Yin HT, Zhao Y (2015) Impact of environmental regulations on the efficiency and CO2 emissions of power plants in China. Appl Energy 149:238–247. https://doi.org/10.1016/j.apenergy.2015.03.112
Zhou FX, Wang XY (2022) The carbon emissions trading scheme and green technology innovation in China: A new structural economics perspective. Econ Anal Policy 74:365–381. https://doi.org/10.1016/j.eap.2022.03.007

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