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Research article

The impact of carbon trading on the “quantity” and “quality” of green technology innovation: A dynamic QCA analysis based on carbon trading pilot areas

Haodong Chang [a,*], Yipeng Zhao [b]

[a] College of Mathematics and Physics, Chengdu University of Technology, Chengdu, China
[b] College of Management Science, Chengdu University of Technology, Chengdu, China

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ABSTRACT

To study the multi-factor linkage effect of carbon trading on green technology innovation, this paper employs the dynamic QCA analysis method and uses panel data from China’s carbon trading pilot areas. The aim is to explore the causal path considering the time effect. Additionally, the Kruskal-Wallis rank sum test is applied to investigate the provincial coverage difference of the configuration and reveal the variation in configuration preferences between regions from a spatial dimension. The results indicate that a single factor alone does not constitute the necessary conditions for the “quantity” and “quality” of high-green technology innovation. However, the necessity of carbon trading price exhibits a declining trend over the years, demonstrating the presence of a time effect. Regarding the sufficiency analysis of conditional configuration, it mainly includes a “price-market scale” dual effect model and a single market scale effect model, with three configuration paths for each model. Among them, the “price-market scale” dual effect model can drive the increase in the quantity of green technology innovation through carbon trading price, market scale, government intervention degree, and other factors. The single market scale effect model can promote the high-quality development of green technology innovation, but the impact of carbon trading price on the quality of green technology innovation is relatively insignificant. In terms of the time dimension, the three configurations still maintain good applicability to green technology innovation under normal conditions. However, when considering the spatial dimension, the coverage distribution of the three configurations exhibits evident regional differences. This study introduces the dynamic panel QCA method into the research field for the first time. It addresses the limitations of the traditional QCA method, which is constrained by cross-section data and lacks the ability to explore the linkage effect between factors over time. Additionally, the study analyzes the effects of carbon trading price and market size on the “quantity” and “quality” of green technology innovation, considering both time and space dimensions, from a configuration perspective.

1. Introduction

The intensification of global warming has led to an increase in extreme phenomena such as droughts, floods, and rising sea levels.

* Corresponding author.
E-mail address: changhd1998@163.com (H. Chang).

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As a result, environmental issues have gained significant attention and have become a focal point of discussions worldwide. Given the seriousness of the global climate problem, there is a general consensus to promote low-carbon development [1,2]. In response, the United Nations Intergovernmental Negotiating Committee issued the United Nations Framework Convention on Climate Change in 1992, urging collaborative efforts from all nations to reduce greenhouse gas concentrations. The Kyoto Protocol, established in 1997, introduced three cooperative emission reduction mechanisms to address the global climate crisis: the joint implementation mechanism, the clean development mechanism, and the international emission trading mechanism, which marked the beginning of the carbon trading mechanism. In 2002, the United Kingdom (UK) pioneered the world's first national carbon trading market. Subsequently, the European Union (EU) Emissions Trading System (ETS) was officially launched in 2005. Currently, the EU ETS is the longest-running and most extensive carbon trading market globally, accounting for 45 % of EU carbon emissions and achieving the EU's 2020 carbon reduction target of 20 % four years ahead of schedule [3]. According to the International Carbon Union, as of 2020, there were 31 carbon emission trading systems worldwide, collectively covering 22 % of global greenhouse gas emissions. These systems had a trading scale of 229 billion euros and a total trading volume of 10.3 billion tons.

Since the 1990s, China has gradually become the world's largest new carbon emitter, surpassing the United States as the largest carbon emitter in 2009 [4]. In order to actively participate in international environmental governance and shoulder the international responsibility of building a community with a shared future for mankind, China has taken initiatives. Notably, during the "12th Five-Year Plan" period, China began efforts to establish a carbon emission trading ("carbon trading") system and explore the use of market mechanisms to achieve energy conservation, emission reduction, and green development. Starting from 2013, eight carbon trading pilot projects have been launched successively in Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, Shenzhen, and Fujian [5]. As of February 2021, China's carbon trading market officially commenced operations, making it the largest carbon trading market worldwide.

In 2020, China officially incorporated the 'double carbon' goal into its ecological civilization construction system and established a leading group for carbon peak and carbon neutrality. The "14th Five-Year Plan" period is a critical phase for China's ecological civilization construction, with carbon reduction as the key strategic direction. Currently, China is less than 10 years away from achieving the carbon peak goal and only 30 years away from carbon peak to carbon neutrality. Compared with Western countries, China faces greater pressure, tighter timelines, and higher reduction targets. Therefore, effectively promoting the realization of the "double carbon" goal during the "14th Five-Year Plan" will directly determine the completion of the carbon peak before 2030 [6]. In October 2021, the "Notice on the Action Plan for Carbon Peak before 2030" emphasized the establishment and improvement of market-oriented mechanisms, including the role of carbon emission trading markets. The "14th Five-Year Plan" of China highlights the importance of supporting green technology innovation, promoting clean energy production, developing the environmental protection industry, and facilitating the green transformation of key industries and important areas. As a result, green technology innovation has become increasingly crucial for green and low-carbon development. Under the carbon trading framework, enterprises will choose technological innovation and improve production processes to achieve carbon reduction and emission reduction goals. Additionally, enterprises can purchase carbon emission trading volume in the carbon trading market to overcome the constraints of carbon trading. Therefore, carbon trading not only serves as a pivotal market tool in achieving the "double carbon" objective but also significantly influences enterprises' green technology innovation [7]. Despite the significant scale of China's carbon trading market, it is still in the early stages of development. Several challenges persist, such as low carbon trading prices and limited market activity [7].

Under the constraint of carbon trading, enterprises may face a crucial decision between purchasing carbon emission credits or investing in green technology innovation. This paper aims to comprehensively study the multi-factor linkage effect of carbon trading on green technology innovation from both temporal and regional perspectives. To achieve this, the dynamic QCA analysis method is adopted to explore the causal path under the time effect, bridging the gap between panel data and QCA method. Additionally, the Kruskal-Wallis rank sum test is used to investigate the provincial coverage difference of the configuration and reveal the regional variation in configuration preference from a spatial dimension. This study seeks to address several key questions: Does carbon trading impact green technology innovation? In the temporal dimension, is the carbon trading price and market size the sole factors necessary to influence the quantity and quality of green technology innovation? Furthermore, which combination of factors influences the quantity and quality of green technology innovation, and do these factors exhibit time effects? In the spatial dimension, does the provincial coverage of the configuration exhibit regional differences? Providing scientific answers to the above questions will facilitate a deeper understanding of the intrinsic relationship between carbon trading and enterprise innovation behavior. This research holds important academic value and practical significance for implementing an innovation-driven strategy, achieving the goal of "double carbon", optimizing the implementation and planning of carbon trading policies, and realizing green and low-carbon transformation development.

2. Literature review

The Industrial Revolution resulted in the integration of natural resources and machine production, leading to rapid economic development through new production methods. However, this development model focused on economic growth has caused significant depletion of natural resources and a sharp increase in environmental pollution. To effectively reduce carbon emissions, the Kyoto Protocol introduced the carbon trading system, allowing countries, regions, and enterprises to trade carbon emission rights. Carbon trading involves the government setting a carbon emission target for a specific period based on the region's environmental capacity. The government then grants or sells carbon emission credits to enterprises and establishes a trading market where they can engage in direct carbon emission rights trading [8]. As global warming intensifies, carbon trading has become a prominent research topic in the fields of climate economics and energy, including studies on the impact of carbon trading on green technology innovation.

The achievement of the goal of "double carbon" through industrial green and low-carbon transformation requires all industries to change their production modes, achieve coordinated development of economy and ecology, and improve green total factor productivity [9]. A key aspect in improving green total factor productivity is to focus on innovation-driven and strengthen green technology innovation. Many scholars have recognized that technological innovation plays a crucial role in influencing the green and low-carbon transformation of industries and achieving carbon emission reduction [10]. Economic growth theory emphasizes that long-term economic growth is driven by technological progress. Throughout history, technological progress has led to a reduction in material and energy consumption during the production process. Therefore, in order to achieve both greenhouse gas emission reduction and sustained economic growth, it is imperative to rely on technological progress, particularly in the field of environment [10].

The concept of "Porter's hypothesis" suggests that environmental regulations can drive technological innovation, leading to improved corporate performance and a competitive advantage. Expanding on this concept, the "Strong Porter hypothesis" further suggests that reasonable environmental regulations such as carbon trading and carbon tax can effectively stimulate technological innovation in enterprises and offset the costs associated with environmental regulations [7]. Many research studies support both the "Porter hypothesis" and the "Strong Porter hypothesis" [11–14]. However, it is important to acknowledge the complexity of this matter, as some investigations reveal a more nuanced perspective. In certain cases, these two hypotheses are valid, while in others, empirical evidence does not support them [15–17]. This indicates that there is a complex and unexplored mechanism and path of action between the carbon trading mechanism and innovation. Additionally, this mechanism and path are influenced by various factors, leading to significant uncertainty in the results [10]. Existing studies suggest that an increase in carbon trading prices can raise transaction costs for enterprises, compelling them to engage in technological innovation [18]. Moreover, the expansion of the carbon trading market can also drive the development of technological innovation [19]. Furthermore, factors such as economic level [20], urbanization [21], energy use [22], openness to the outside world [23–25], and others also have an impact on environmental development and green technology innovation to some extent.

In fact, carbon trading plays a crucial role in the ecological economy. By implementing policies that limit carbon emissions, we can effectively reduce the negative impact of ecological disasters on the social economy. According to theory, when faced with carbon emission restrictions, enterprises have two options: either innovate their technology to improve production processes or purchase carbon emission credits in the trading market to surpass the limit [26]. As the price of carbon trading increases, enterprises are confronted with the decision of either buying carbon emission credits or investing in technological innovation. Therefore, as the price of carbon trading continues to rise, the need for enterprises to innovate becomes more urgent. This is because innovations in the production process help reduce carbon emissions, thus saving on carbon trading costs. With an increase in research and development efforts, the total carbon emissions will decrease accordingly [27].

In general, when the carbon trading price is low, enterprises are more likely to purchase carbon emission rights instead of investing in technological innovation. This is because the initial capital investment for innovation is large and the outcomes are uncertain. However, when the carbon trading price is high, buying carbon emission rights in the market will result in significant transaction costs. This can reduce profits and negatively impact business performance. In such situations, there is a greater incentive for enterprises to innovate. Advanced technologies can improve production processes, leading to a reduction in carbon emissions and production costs.

The implementation of the carbon emission trading pilot policy has the potential to enhance the research and development (R&D) investment intensity of enterprises, thereby encouraging more enterprises to engage in R&D and innovation activities. However, it is important to note that this policy primarily benefits large-scale enterprises in terms of stimulating innovation investment, while it does not have a significant impact on the R&D and innovation activities of small-scale enterprises. Moreover, the carbon trading system can directly and indirectly influence enterprises' innovation behavior by increasing their cash flow and net return on assets. Additionally, the carbon trading mechanism exerts a notable "reverse force" effect on the regional industrial structure upgrade. It is worth mentioning that the magnitude of this effect varies depending on the specific characteristics of the pilot regions involved.

Through a review of existing studies, it has been acknowledged by scholars that carbon trading has a positive impact on national or regional carbon emission reduction. However, when it comes to the impact of carbon trading on enterprises at a micro level, most studies have focused on analyzing its effect on technological innovation. These studies often utilize policy dummy variables or panel regression models, without considering the actual changes in carbon trading price and market. Additionally, there are limited studies that have examined the impact of carbon trading on both the "quantity" and "quality" of green technology innovation. Therefore, this paper aims to analyze the influence of carbon trading price and market changes on the "quantity" and "quality" of green technology innovation within the constraints of carbon trading, with a specific focus on the 'double carbon' goal. Furthermore, this research introduces the dynamic panel QCA method for the first time in this field. This method overcomes the limitations of the traditional QCA method, which is constrained by cross-section data and unable to explore the temporal linkage between factors. By adopting a configurational perspective, this study analyzes the effects of carbon trading price and market scale on the "quantity" and "quality" of green technology innovation in both temporal and spatial dimensions.

3. Model setting and data source

3.1. Dynamic QCA

It is difficult for traditional QCA methods to explore the configuration effect in the time dimension [28], while the carbon trading mechanism has been continuously developed and improved since 2013, which is a continuous event occurring on the timeline. Therefore, sectional configuration alone cannot explain the interaction between cause and effect and time. Based on the dynamic QCA analysis method and the relevant theories and methods proposed by Refs. [28,29], this paper uses R language software to break the barrier between panel data and QCA and explore the configuration relationship under the time effect. Meanwhile, enhanced standard analysis (ESA) is used to improve the configuration accuracy.

Different from traditional QCA, dynamic QCA will be measured from three dimensions: between, within and pooled. Meanwhile, the dynamic QCA use consistency adjustment distance to capture the degree of variation of consistency in time and region. In addition, when using R language software for analysis, it should be noted that the distance obtained by the software is Euclidean distance, and equations (1) and (2) need to be used to convert the Euclidean distance into an adjusted distance.

$$BECONS\ adjusted\ distance = \frac{BECONS\ distance}{\sqrt{\frac{n_1}{n_1^2+3n_1+2}}} \tag{1}$$

$$WICONS\ adjusted\ distance = \frac{WICONS\ distance}{\sqrt{\frac{n_2}{n_2^2+3n_2+2}}} \tag{2}$$

where, *BECONS adjusted distance* represents consistency adjustment distance between groups; *BECONS distance* represents consistency Euclidean distance between groups; *WICONS adjusted distance* represents consistency adjustment distance within groups; *WICONS distance* represents the consistent European distance within the groups; n_1 represents the time dimension. If the panel data from 2014 to 2019 is selected, $n_1 = 6$; n_2 represents the sample size in the region dimension.

3.2. Variable setting and description

3.2.1. Result variables

The Chinese Knowledge Industry Administration classifies Chinese patents into three categories: invention, utility model, and design. These categories have differences in terms of innovation [30]. Invention patents require meeting the requirements of novelty, creativity, and practicality [31], while utility model and design patents only require similar applications that have not been approved before, with relatively relaxed application requirements and examination standards. Currently, many scholars use green patent data to measure the level of green technology innovation. For instance, Yan et al. [32] use the number of green patents as a measurement standard for urban green technology innovation. Similarly, Zheng et al. [33] measure the quality of green technology innovation through the number of patent applications for green inventions.

This paper references previous research findings [32–34] to measure the "quantity" of green technology innovation by considering the total number of three types of green patent applications. Additionally, since invention patents are considered more innovative than the other two types of patents, the number of green invention patent applications is used to measure the "quality" of green technology innovation. Furthermore, the average number of green patent applications is calculated, and the "quality" of green technology innovation is assessed based on the number of green invention patent applications per 10,000 people, while the "quantity" of green technology innovation is determined by the number of green patent applications per 10,000 people.

3.2.2. Condition variables

The core conditional variables adopted in this paper are carbon trading price and carbon trading market scale. The scale of the carbon trading market is calculated by multiplying the logarithm of the total annual turnover by the logarithm of the total annual turnover. In addition, since China's carbon emission trading website only publishes daily data of trading volume, transaction value and transaction average price, this paper mainly uses annual data. The logarithm of the annual mean carbon trading price is used as the index to measure the carbon trading price.

In order to analyze whether other factors will also affect the "quantity" and "quality" of green technology innovation, this paper refers to the existing research on the influencing factors of green technology innovation [35–37]. The following variables are select as other condition variables:

(1) Level of economic development (Pgdp). This variable is expressed using GDP per capita. There is a Kuznitz curve relationship between per capita income level and environmental improvement [38], so economic development level is closely related to regional green technology innovation.
(2) Upgrading of industrial structure (IS). The upgrading of industrial structure can not only optimize resource allocation, but also achieve green economic development while improving production efficiency [39]. Therefore, this paper adopts the ratio between the added value of the secondary industry and the added value of the tertiary industry to measure the upgrading degree of the industrial structure.
(3) Urban size (US). With the advancement of urbanization, industrial replacement will also have a certain impact on green technology innovation [7]. Therefore, this paper uses the total population of the Urban at the end of the year to measure the urban size.
(4) Degree of opening (Open). The "pollution refuge" hypothesis holds that FDI leads to the transfer of polluting industries to the host country, thus increasing the pollution emissions of the host country. The "pollution halo" hypothesis holds that opening to the outside world is conducive to the transfer and spill-over of advanced technologies from developed countries to developing countries, and promotes green technology innovation in developing countries [40]. Therefore, this paper uses foreign direct investment to measure the degree of opening up.

(5) Government intervention (GI). Proper government intervention can alleviate problems such as monopoly and information asymmetry caused by market failure. However, excessive government intervention may lead to waste of resources and affect the "quality" and "quantity" of green technology innovation [41]. Therefore, the government public budget expenditure is used to measure the degree of government intervention.

3.3. Data sources

This paper references the studies conducted by other scholars [32–34]. It uses the total number of green patent applications for invention, utility model, and design as a measure of the "quantity" of green technology innovation. Additionally, the number of green invention patent applications is used as a measure of the "quality" of green technology innovation. The green patent application data used in this study were obtained from the IncoPat patent database (https://www.incopat.com), which is primarily used for patent search based on classification number, city of location, filing time, and other published information in the IPC Green List. To account for population differences and their impact on the quantity and quality of green patents, this paper calculates the average number of green patent applications. The "quality" of green technology innovation is measured by the number of green invention patent applications per 10,000 people, while the "quantity" of green technology innovation is measured by the number of green patent applications per 10,000 people.

This paper preprocesses the data in the following manner: Firstly, to ensure the integrity of carbon trading data, the study focuses on six carbon trading pilot regions, namely Beijing, Tianjin, Shanghai, Hubei, Guangdong, and Chongqing. Secondly, the research samples are selected from the time window of 2014–2019, as China's carbon trading pilot was initiated in 2013. Choosing samples after 2013 helps maintain consistency in the external environment and stability of the domestic system. The data on carbon trading price and market size are obtained from China's carbon emissions network (https://www.cets.org.cn) and Mark data network (https://www.macrodatas.cn), respectively. Other data sources include the "*China Statistical Yearbook (2014–2020)*" (https://www.stats.gov.cn/sj/ndsj/) and the "*China City Statistical Yearbook (2014–2020)*" (https://www.stats.gov.cn). Missing data is addressed through techniques such as linear interpolation. Table 1 provides the definitions of variables and descriptive statistical results.

3.4. Data calibration

In order to analyze the consistency and coverage between groups, within groups and as a whole, this paper carried out a unified calibration of data based on existing studies [42]. According to the characteristics of the variables, direct calibration method was adopted in this paper. The quantile of 95 %, quantile of 50 % and quantile of 5 % were set as calibration anchors, representing Completely affiliated, crossing point and Completely unaffiliated respectively. The specific calibration results are shown in Table 2.

4. Empirical analysis

4.1. Necessity analysis of a single condition

In traditional QCA, a conditional variable is considered a necessary condition for the outcome variable when its consistency level is higher than 0.9 [28]. In dynamic QCA panel data analysis, if the adjustment distance is less than 0.1 and the level of summary consistency is high, the condition variable can be considered a necessary condition for the outcome variable [29]. However, if the adjustment distance is greater than 0.1, further exploration is needed to determine its necessity. The necessity analysis results for the single conditions of "quantity" and "quality" of green technology innovation are presented in Table 3 and Table 4 respectively. From Table 3, it can be observed that, in terms of the time dimension, the BECONS adjustment distance of the four conditional variables (Pgdp, IS, US, and GI) is less than 0.1, and the consistency of these variables is less than 0.9. This indicates that these factors are not necessary conditions for influencing the quantity of green technology innovation.

As shown in Table 4, the quality of green technology innovation is not solely dependent on five conditional variables: Pgdp, IS, US, Open, and GI. However, it is worth noting that for other condition variables, the BECONS adjustment distance exceeds 0.1, which necessitates further discussion. In terms of the spatial dimension, except for the BECONS adjustment distance of carbon trading price, which is less than 0.1, the adjustment distance for the remaining condition variables exceeds 0.1. This indicates that spatial differences,

Table 1
Description of main variables and descriptive statistics.

Variables	Meaning of Variables	Sample size	Mean	Standard deviation	Min	Max
Quantity	Quantity of green technology innovation	36	27.97	43.09	0.89	161.98
Quality	Quality of green technology innovation	36	13.88	19.89	0.43	79.40
Price	Price of carbon trading	36	3.34	0.18	3.13	3.73
Scale	Market scale of carbon trading	36	33.94	7.74	16.51	38.37
IS	Upgrading of industrial structure	36	64.67	26.79	19.11	106.34
US	Urban size	36	4514.03	3687.41	1383	12489
Pgdp	Level of economic development	36	90172.82	32681.23	48307	161776
Open	Degree of opening	36	82875.69	195176.30	548.69	1031402
GI	Government intervention	36	6891.04	3716.97	2884.70	17297.85

Table 2
Variable calibration.

Variables		Calibration		
		Completely affiliated	Crossing point	Completely unaffiliated
Result variables	Quantity	145.851	11.611	1.568
	Quality	65.973	6.722	0.717
Condition variables	Price	3.729	3.301	3.130
	Scale	38.366	37.516	17.188
	Pgdp	151494.721	78179.735	51174.500
	IS	98.909	73.133	20.303
	US	12192.750	2762.410	1403.750
	Open	388723.500	9422.749	680.588
	GI	15210.425	6299.165	3200.053

Table 3
Necessary condition analysis of quantity.

Condition variables	High-quantity of green technology innovation				low-quantity of green technology innovation			
	Aggregate consistency	Aggregate coverage	BECONS adjusted distance	WICONS adjusted distance	Aggregate consistency	Aggregate coverage	BECONS adjusted distance	WICONS adjusted distance
High-price	0.642	0.564	0.178	0.09	0.681	0.819	0.169	0.088
Low-price	0.794	0.645	0.148	0.065	0.638	0.709	0.175	0.044
High-scale	0.74	0.561	0.05	0.165	0.678	0.704	0.083	0.164
Low-scale	0.61	0.581	0.125	0.159	0.577	0.752	0.11	0.153
High-Pdgp	0.698	0.587	0.061	0.139	0.596	0.687	0.088	0.19
Low-Pdgp	0.628	0.531	0.096	0.184	0.642	0.744	0.058	0.198
High-IS	0.627	0.54	0.059	0.198	0.593	0.7	0.049	0.229
Low-IS	0.652	0.539	0.052	0.169	0.61	0.691	0.085	0.198
High-US	0.755	0.678	0.014	0.179	0.525	0.645	0.013	0.213
Low-US	0.605	0.482	0.011	0.187	0.738	0.805	0.027	0.149
High-Open	0.472	0.501	0.074	0.24	0.62	0.902	0.057	0.225
Low-Open	0.908	0.636	0.043	0.036	0.657	0.63	0.021	0.174
High-GI	0.877	0.868	0.027	0.142	0.453	0.614	0.102	0.246
Low-GI	0.611	0.449	0.054	0.161	0.903	0.909	0.016	0.05

Table 4
Necessary condition analysis quality.

Condition variables	High-quality of green technology innovation				low-quality of green technology innovation			
	Aggregate consistency	Aggregate coverage	BECONS adjusted distance	WICONS adjusted distance	Aggregate consistency	Aggregate coverage	BECONS adjusted distance	WICONS adjusted distance
High-price	0.631	0.538	0.181	0.097	0.664	0.815	0.171	0.092
Low-price	0.784	0.618	0.149	0.065	0.624	0.709	0.176	0.049
High-scale	0.716	0.527	0.05	0.167	0.667	0.708	0.082	0.165
Low-scale	0.603	0.557	0.129	0.162	0.554	0.738	0.116	0.159
High-Pdgp	0.696	0.569	0.058	0.136	0.577	0.68	0.086	0.193
Low-Pdgp	0.608	0.5	0.1	0.188	0.634	0.75	0.063	0.199
High-IS	0.608	0.508	0.06	0.202	0.586	0.706	0.056	0.233
Low-IS	0.649	0.521	0.048	0.166	0.592	0.685	0.083	0.202
High-US	0.774	0.674	0.009	0.163	0.517	0.649	0.008	0.21
Low-US	0.597	0.462	0.015	0.186	0.74	0.825	0.029	0.151
High-Open	0.479	0.494	0.076	0.229	0.6	0.891	0.051	0.233
Low-Open	0.895	0.608	0.049	0.036	0.66	0.646	0.026	0.174
High-GI	0.901	0.866	0.032	0.12	0.436	0.604	0.096	0.249
Low-GI	0.589	0.42	0.064	0.161	0.903	0.929	0.018	0.051

resulting from variations in development level and population size among regions, play a crucial role in influencing both the "quality" and "quantity" of green technology innovation.

The variables related to the quantity and quality of green technology innovation are analyzed separately, as shown in Table 5 and Table 6. According to Table 5, the consistency level of each year in terms of the quantity of green technology innovation is less than 0.9, and there is no necessary relationship in situations 6 and 7 [28]. In situation 5, although the consistency is greater than 0.9 in 2013, the coverage is less than 0.5, indicating that it does not constitute a necessary relationship. In the remaining cases, there is a combination

Table 5
The data of BECONS adjust distance is greater than 0.1 in quantity.

Causal combination situation			Years					
			2014	2015	2016	2017	2018	2019
Situation1	High-price and High-quantity	consistency	1	0.952	0.728	0.131	0.49	0.797
		coverage	0.307	0.501	0.743	1	0.772	0.794
Situation2	High- price and Low-quantity	consistency	0.941	0.851	0.659	0.12	0.549	0.827
		coverage	0.749	0.841	0.888	1	0.88	0.796
Situation3	Low-price and High-quantity	consistency	0.182	0.69	0.89	1	0.924	0.795
		coverage	0.541	0.705	0.665	0.51	0.669	0.826
Situation4	Low- price and Low-quantity	consistency	0.129	0.481	0.809	1	0.858	0.786
		coverage	1	0.951	0.797	0.557	0.631	0.789
Situation5	Low-scale and High-quantity	consistency	0.906	0.869	0.48	0.377	0.678	0.538
		coverage	0.389	0.515	0.717	0.656	0.689	0.708
Situation6	Low-scale and Low-quantity	consistency	0.735	0.685	0.364	0.367	0.69	0.553
		coverage	0.821	0.785	0.716	0.697	0.714	0.703
Situation7	Low-GI and Low-quantity	consistency	0.227	0.423	0.529	0.543	0.533	0.559
		coverage	0.704	0.715	0.678	0.603	0.538	0.528

Table 6
The data of BECONS adjust distance is greater than 0.1 in quality.

Causal combination situation			Years					
			2014	2015	2016	2017	2018	2019
Situation1	High-price and High-quality	consistency	1	0.953	0.709	0.136	0.454	0.781
		coverage	0.309	0.5	0.722	1	0.7	0.732
Situation2	High-price and Low-quality	consistency	0.941	0.827	0.653	0.116	0.534	0.776
		coverage	0.747	0.838	0.881	1	0.875	0.793
Situation3	Low-price and High-quality	consistency	0.182	0.668	0.883	1	0.919	0.779
		coverage	0.546	0.65	0.657	0.492	0.65	0.761
Situation4	Low-price and Low-quality	consistency	0.13	0.472	0.794	1	0.817	0.737
		coverage	1	0.955	0.784	0.575	0.614	0.786
Situation5	Low-scale and High-quality	consistency	0.907	0.866	0.487	0.356	0.666	0.524
		coverage	0.393	0.489	0.725	0.596	0.662	0.648
Situation6	Low-scale and Low-quality	consistency	0.734	0.666	0.348	0.343	0.654	0.507
		coverage	0.817	0.781	0.687	0.673	0.691	0.684

of consistency greater than 0.9 and coverage greater than 0.5 in one year. By observing the scatter plot in Fig. 1, it can be seen that the scatter points of Situations 2, 3, and 4 are all concentrated on the right y-axis, indicating that there is no significant trend of relationship change overall, thus failing the necessary condition test [28]. However, by observing the consistent change trend of the four situations, it can be noticed that their necessity has a downward trend. Considering the change curve of carbon trading price and market scale from 2014 to 2019 (Fig. 2), it is observed that China's carbon trading price decreased year by year, while the carbon market scale tended to stabilize. This phenomenon may have made enterprises less enthusiastic about green technology innovation. Since green technology innovation requires significant research and development costs, when the price drops and the market scale remains relatively stable, enterprises are more likely to choose to purchase carbon trading volume or control carbon emissions volume instead. Consequently, the impact of green carbon trading price and market scale on the necessity of the number of green technology innovations has gradually decreased.

From the perspective of "quality" of green technology innovation, it can be seen from Table 6 that there is no necessary relationship in situation 5 and 6. In the remaining cases, there is a combination of consistency greater than 0.9 and coverage greater than 0.5 in one year. Further observation of the scatter plot of situation 1 (Fig. 3) shows that the time effect of carbon trading price on the quality of green technology innovation shows a trend of first decreasing and then increasing, and its necessity decreases first and then increases. This is mainly because after the decline of carbon trading price and the quantity of green technology innovation, enterprises' demand for the quality of green technology innovation is also weakening. As a result, the impact of carbon trading market price on the necessity of green technology innovation quality is weakening year by year, and it reached the lowest point in 2017. However, as the government further standardizes the carbon trading mechanism and emphasizes the green and high-quality development of enterprises, the necessity influence of carbon trading price on the quality of green technology innovation shows an increasing trend under the complete carbon trading mechanism.

4.2. Adequacy analysis of conditional configuration

Configuration analysis is a fundamental aspect of the QCA method. To ensure the explanatory power of the configuration, it is necessary to determine the consistency threshold value. Additionally, the PRI threshold should remain above 0.75 to avoid the issue of "simultaneous subset relationship" [28]. In this paper, a consistency threshold of 0.9, a frequency threshold of 1, and a PRI threshold of

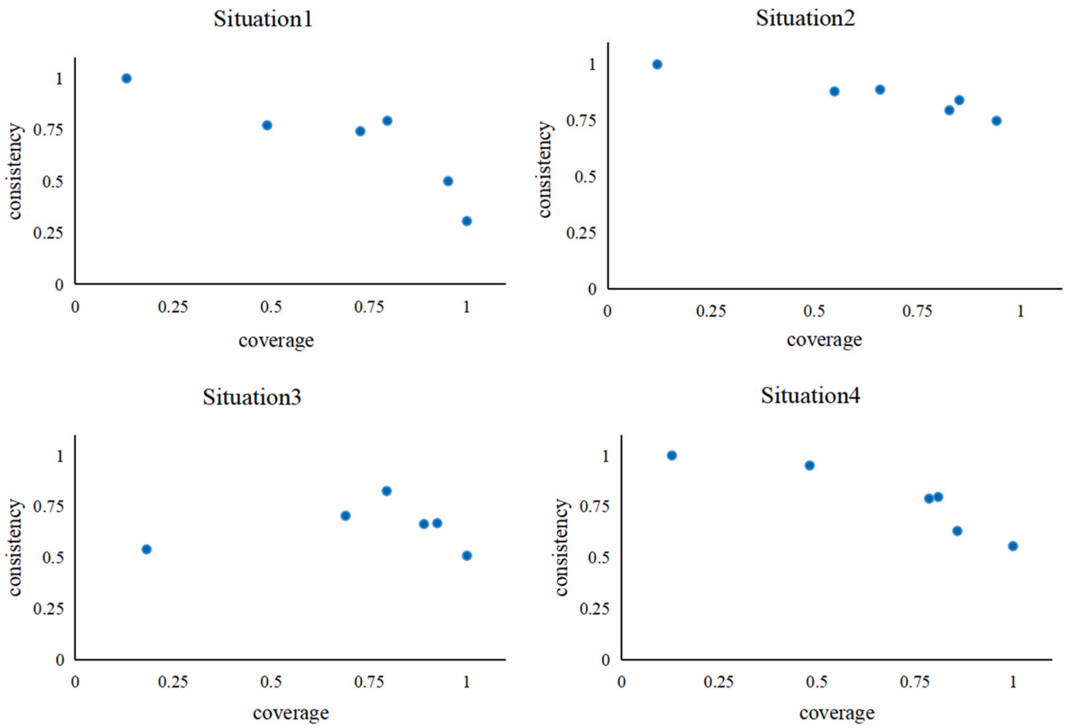

Fig. 1. Scatter plot of the necessary conditions for the quantity.

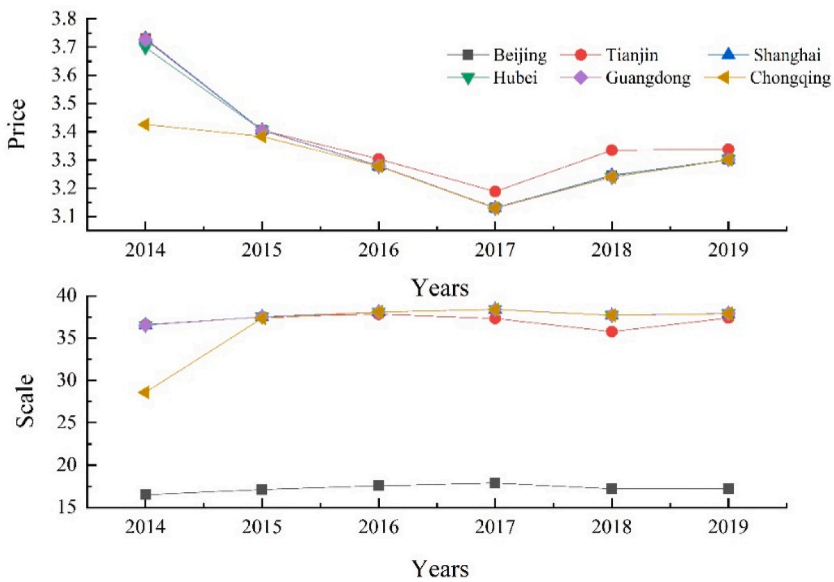

Fig. 2. Trends of price and market scale in 2014–2019.

0.75 are used to assess the significance and effectiveness of the QCA analysis. Once the truth table is constructed, a reinforced standard analysis is employed. Furthermore, in the counter-fact analysis section, the contradictory simplified hypothesis is initially excluded. Due to variations in the development of different provinces, there is no standardized criterion for evaluating the impact of antecedent conditions on the results. Therefore, this paper does not assume a specific direction, but rather considers the "presence or absence" of these conditions. Finally, the study yields enhanced simple solutions, intermediate solutions, and complex solutions.

In this paper, the core and edge conditions are determined by utilizing the improved intermediate solution and the simple solution. Table 7 presents the analysis results of the overall configuration, which includes three different configurations. Configuration 1

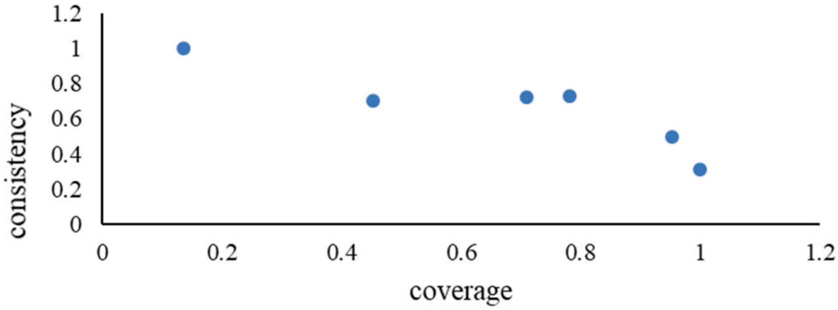

Fig. 3. Scatter plot of the necessary conditions for Situation 1 in "quality".

represents the analysis results of the "quantity" of green technology innovation, while configurations 2 and 3 represent the analysis results of the "quality" of green technology innovation. Based on the influence of carbon trading, two models can be derived: the 'price-market scale' dual effect model and the single market scale effect model.

4.2.1. Pooled results

It can be seen from Table 7 that from the perspective of the number of green technology innovations, the aggregate consistency of the overall solution is 0.957, and the BECONS and WICONS adjustment distances of configuration 1 are both less than 0.1. This indicates that the aggregate consistency has better explanatory power. Therefore, configuration 1 can be considered a sufficient condition for a high-quantity of green technology innovation. From the perspective of green technology innovation quality, the aggregate consistency of the overall solution is 0.908, and the BECONS and WICONS adjustment distance of configuration 1 and 2 are less than 0.1, so the two configurations can be regarded as sufficient conditions for high green technology innovation quality.

In the "price-market size" dual effect model, carbon trading price, US, Open and GI are the core, market scale is the edge, and IS upgrading is the edge absence, which jointly affects the quantity of green technology innovation. The single market size effect model mainly includes two configurations. In configuration 2, carbon trading market scale, IS, US and GI are the core, Pgdp and Open are the edge, and carbon trading price is the core absence, which constitutes a combination of sufficient conditions for the quality of green technology innovation. In configuration 3, when the carbon trading price is missing, the scale of the carbon trading market, IS and GI as the core conditions can also drive the improvement of the quality of green technology innovation.

In terms of the quantity of green technology innovation, both carbon trading price and market size can promote the improvement of the quantity of green technology innovation, while the absence of carbon trading price has no impact on the sufficiency of green technology innovation quality. Since the scale of China's carbon trading market does not change significantly, and the price of carbon trading gradually shows a downward trend, local governments should pay attention to how to expand the scale of carbon trading market to improve the "quantity" and "quality" of green technology innovation. Meanwhile, the degree of government intervention is also a sufficient condition for promoting green technology innovation. In addition, the continuous improvement of the carbon trading

Table 7
Results of configuration analysis.

Condition variables	Quantity of green technology innovation	Quality of green technology innovation	
	"price-market scale" dual effect model	single market scale effect model	
	Configuration 1	Configuration 2	Configuration 3
Price	●	⊗	⊗
Scale	•	●	●
Pgdp		•	
IS	⊗	●	●
US	●	●	
Open	●	•	
GI	●	●	●
Consistency	0.957	0.901	0.922
PRI	0.883	0.674	0.812
Coverage	0.412	0.224	0.484
Unique coverage	–	0.025	0.285
BECONS adjusted distance	0.014	0.024	0.024
WICONS adjusted distance	0.082	0.094	0.08
Aggregate PRI	0.883	0.781	
Aggregate consistency	0.957	0.908	
Aggregate coverage	0.412	0.509	

Note: ● and ⊗ represent core presence and absence, respectively; • and ⊗ represent marginal presence and absence; Blank space indicates presence or absence.

system and the formulation of corresponding policies and measures will also help to improve the “quantity” and “quality” of green technology innovation. From the perspective of the quality of green technology innovation, the upgrading of industrial structure is accompanied by the green and low-carbon development of the industry, so the quality of industrial structure upgrading and green technology innovation affects each other. Thus, the green and low-carbon transformation of the industry needs strong and high-quality technical support.

4.2.2. Between results

Although the consistency adjustment distance between the three configurations is less than 0.1, it indicates that there is no significant time effect. However, further investigation of its time changes shows that, except for configuration 1, which consistency level is less than 0.75 in 2018, the consistency level of other configurations fluctuates above 0.75 from 2014 to 2019 (as shown in Fig. 4). On the one hand, the results of the inter-group analysis make up for the shortcomings of the existing studies in the longitudinal axis of time. On the other hand, it shows that the three configurations have better explanatory power for the “quantity” and “quality” of green technology innovation during 2014–2019. As for why the impact of configuration 1 on the quantity of green technology innovation decreased in 2018, the possible reason is that China’s carbon emission right management function was transferred to the Ministry of Ecology and Environment in 2018, and all localities were required to strictly verify the carbon emission data of key enterprises in 2016 and 2017. In addition, China has strengthened the excessive speculation and excessive financialization of the carbon trading system, which has made companies pay more attention to policy changes, and government intervention has become a core element in driving the quantity of green technology innovations. By contrast, the power of explanation for other factors inevitably declines. However, since the adjustment distance between groups is less than 0.1, it does not affect the overall interpretation strength, so the research results still have good applicability for green technology innovation under normal conditions.

4.2.3. Within results

As the same as the BECONS adjustment distance, the WICONS adjustment distance of the three configurations is no more than 0.1, which indicates that the interpretation strength of the three configurations is not significantly different among different regions. When the difference of interpretation intensity is small, the analysis of the intra-group coverage of each state can reflect the regional distribution of each state that can explain cases. As the results of normality test show that the three configurations do not conform to normal distribution. Therefore, this paper adopts Kruskal-Wallis rank sum test to explore whether the coverage distribution of each configuration in different regions has significant differences. The test results are shown in Table 8.

As can be seen from Table 8, the influence of the three configurations on different regions is significantly different, that is, configuration 1 has a significant impact on the “quantity” of green technology innovation in different regions, and configuration 2 and 3 have a significant impact on the “quality” of green technology innovation in different regions. From the perspective of “quantity” and “quantity” of green technology innovation, the corresponding cases of the three configurations are mainly distributed in Beijing, Shanghai and Guangdong three first-tier cities, which have relatively perfect carbon trading systems. For example, since the launch of the Beijing carbon trading market, it has established a “1 + 1 + N” legal and policy system and formulated the “Beijing Carbon Emission Trading Management Measures”. Relevant authorities have also formulated and issued supporting policies and technical support documents such as quota verification methods, management measures for verification bodies, implementation rules for over-the-counter trading, management measures for open market operations, and management measures for carbon emission right offsetting. Shanghai adheres to the system first in promoting the carbon trading pilot work, and has built a relatively complete system and management system before the formal launch of carbon trading. Shanghai has continuously formed a complete set of management systems with three levels: the municipal government, the competent department and the exchange. At the same time, Shanghai issued the “Shanghai Carbon Emission Management Trial Measures”, which clearly established the core management systems and corresponding legal responsibilities of the carbon emission trading market, such as the cap and quota allocation system, the enterprise monitoring report and third-party verification system, the carbon emission quota trading system, and the compliance management system. Guangdong Province is the first province in China to launch a carbon trading pilot, and combined with Guangdong characteristics, as far as possible to cover the main emission industries. Guangdong has taken the lead in exploring the feasibility of trading between different regions in the province.

Meanwhile, Beijing, Shanghai and Guangdong are also economically and population-developed provinces in China, which makes their degree of opening up, level of industrial structure upgrading, and policy control are at the forefront of the country. Therefore, under the three different configurations, the “quantity” and “quality” of green technology innovation in developed provinces are significantly higher than those in other regions.

5. Discussion and conclusions

5.1. Discussion

Based on the existing environmental regulation policy, the level of economic development, and other factors, this paper examines the impact of enterprise green technology innovation. The measurement standards used are the number of green patent applications and the number of green invention patent applications, which represent the “quantity” and “quality” of green technology innovation respectively. The dynamic panel QCA method is employed to analyze the configuration effect of multiple factors driving green technology innovation, and to explore the causal path considering the time effect. Additionally, the Kruskal-Wallis rank sum test is used to investigate the provincial coverage differences in the configuration, revealing the variation in configuration preferences

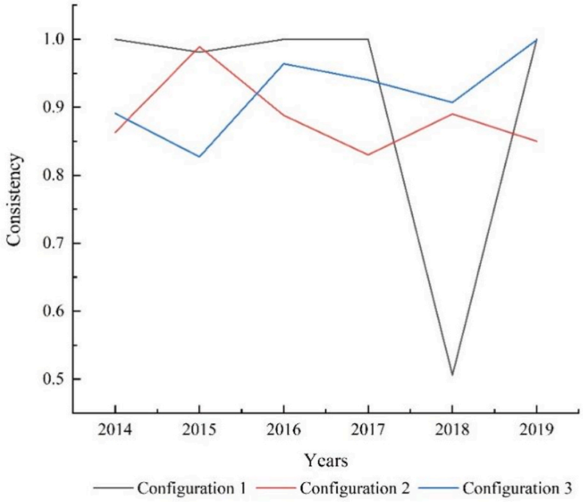

Fig. 4. Consistency change between groups.

Table 8
The result of Kruskal-Wallis rank sum test.

	Mean	SD	Test statistics of Kruskal-Wallis	p-value
Configuration 1	0.705	0.297	28.056	0.000**
Configuration 2	0.692	0.327	22.171	0.000**
Configuration 3	0.683	0.317	22.564	0.000**

Note: ** represents $p < 0.01$.

between regions from a spatial perspective.

Existing research has demonstrated that various factors such as environmental regulation policy, economic development level, industrial structure upgrading, city size, degree of opening, and government intervention significantly influence green technology innovation [34,43,44]. However, previous studies have certain limitations. Firstly, most studies only consider virtual variables for carbon trading policies and fail to account for actual changes in carbon trading price and market scale. Secondly, the application of the QCA method is limited to cross-section data, primarily focusing on consistency and neglecting coverage exploration. Although the impact of environmental regulation policies on green technology innovation and green total factor productivity has been extensively studied [45–47], few scholars have examined the mechanism through which carbon trading policies affect green technology innovation. Furthermore, there is a lack of research exploring the impact of carbon trading policies on the “quantity” and “quality” of green technology innovation from a micro perspective, considering the time and space effects.

This paper addresses a gap in existing research by introducing the dynamic panel QCA method to the research field for the first time. It analyzes the impact of carbon trading price and market scale on the “quantity” and “quality” of green technology innovation in both time and space dimensions, from a configuration perspective. This study contributes to a deeper understanding of the relationship between carbon trading and corporate innovation behavior. Furthermore, it holds significant academic value and practical significance for implementing innovation-driven strategies, achieving the goal of “double carbon”, and optimizing the implementation and planning of carbon trading policies.

5.2. Conclusions

This paper utilizes the dynamic QCA research method to investigate the synergistic effects of carbon trading price, carbon trading market scale, and other conditional variables on the “quantity” and “quality” of green technology innovation. The study focuses on six carbon trading pilots in China conducted between 2014 and 2019. The main findings of the research are as follows:

(1) From the perspective of analyzing the necessity of a single condition, it is clear that no single condition, whether it is a core condition variable or other condition variables, has become a necessary factor for the “quantity” and “quality” of green technology innovation. Additionally, upon further analysis, it is observed that China’s carbon trading price has gradually declined and the market size has stabilized, resulting in a gradual reduction in the influence of price and market scale on the necessity of green technology innovation.
(2) In the analysis of conditional configuration sufficiency, the “price-market size” dual effect model has a significant impact on the quantity of green technology innovation. On the other hand, the single market scale effect model has two ways of influencing

the quality of green technology innovation. Configuration 1, characterized by carbon trading price, urban size, degree of opening, and government intervention, along with carbon trading market scale, promotes an increase in the quantity of green technology innovation. Configuration 2, on the other hand, promotes the enhancement of the quality of green technology innovation through a combination of multiple factors such as carbon trading market scale, upgrading of industrial structure, urban size, and government intervention. Configuration 3 relies on the carbon trading market scale, upgrading of industrial structure, and government intervention to achieve high-quality green technology innovation.

(3) From a temporal perspective, it can be observed that the aggregate consistency in time series does not exhibit a significant time effect. However, the consistency level of the three configurations remained above 0.75 between 2014 and 2019. This suggests that the three configurations effectively explain the "quantity" and "quality" of green technology innovation during this period.

(4) Through the use of Kruskal-Wallis rank sum test, it has been determined that there are noticeable regional disparities in the intra-group coverage of the three configurations. The cases associated with these configurations are predominantly concentrated in the three first-tier cities of Beijing, Shanghai, and Guangdong. This suggests that the developed provinces exhibit significantly higher levels of both the "quantity" and "quality" of green technology innovation compared to other regions.

5.3. Practical enlightenments

This study provides practical insights for the carbon trading mechanism and the development of green technology innovation. Firstly, there are variations in the factors influencing the quantity and quality of green technology innovation, and the driving forces behind quality are diverse. Therefore, carbon trading pilot areas should explore their own development paths based on their specific conditions, while also considering the potential impact of different approaches. Secondly, increasing the quantity of green technology innovation requires a combination of factors such as carbon trading prices, market scale, and government intervention. However, the declining carbon trading prices have reduced their impact on the quality of green technology innovation. China's carbon trading market still has significant room for growth. By expanding the market scale, promoting the upgrading of industrial structure, and strengthening government intervention, the quality of green technology innovation can be effectively enhanced. However, it is important to avoid excessive government intervention, which may hinder the independent innovation capability of enterprises. In the future, it is crucial to enhance the enthusiasm and initiative of enterprises in pursuing green development.

5.4. Research limitations and prospects

The study still has some limitations. Firstly, while the selected influencing factors in this study encompass variables used in previous studies, there are still some shortcomings. For instance, the analysis does not consider the influence of carbon trading on green technology innovation in terms of specific factors within enterprises. Secondly, this study primarily relies on open data and only examines the topic from a macro level. In the future, it would be beneficial to incorporate interviews and surveys to uncover the impact mechanism of green technology innovation at a micro level.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Haodong Chang: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Yipeng Zhao:** Writing – review & editing, Supervision, Data curation.

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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