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# Emissions Reduction Effects and Carbon Leakage Risks of Carbon Emissions Trading Policy: An Empirical Study Based on the Spatial Durbin Model

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**Abstract:** China's carbon emissions trading policy represents a significant institutional innovation designed to advance the country's economic and social development towards sustainability and low-carbon growth. This study investigates the effects of China's carbon emissions trading policy by employing the difference-in-differences model and spatial Durbin model, using provincial panel data spanning from 2005 to 2020. We find that the carbon emissions trading policy can inhibit per capita carbon emissions in the pilot areas. This work is primarily driven by green technological innovation and the upgrade of industrial structure. Furthermore, the carbon emissions trading policy exhibits a positive spatial spillover effect, inhibits per capita carbon emissions in the areas adjacent to the pilot through demonstration effect and competition effect, and does not cause carbon leakage. These findings reveal the policy's effectiveness in emissions reduction, and may be useful reference for promoting sustainable economic and social development. This is of great practical significance for exploring how to optimize environmental governance measures, avoid carbon leakage, and achieve balance and fairness in responsibilities in achieving low-carbon sustainable development. Our study proposes policy recommendations for synergizing the national trading market in China.

**Keywords:** carbon emissions trading policy; carbon emissions reduction; carbon leakage; sustainability; difference-in-differences; spatial Durbin mode; spatial spillover effect

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## 1. Introduction

The increase in greenhouse gas emissions has led to climate deterioration, posing a threat to social, economic, and environmental sustainability [1]. While numerous studies suggest that natural causes may contribute to global warming [2], alternative perspectives suggest that the cause of global warming may be attributed to the emissions of greenhouse gasses caused by human activity [3]. Reducing carbon emissions is essential to controlling global warming, requiring the joint efforts of all countries worldwide. In the context of rapid economic and trade globalization, China is facing increasingly prominent environmental pollution and climate change problems, of which carbon dioxide emissions pollution is particularly serious [4]. By the end of 2022, China's total carbon emissions reached approximately 13.9 billion tons, making up 27% of global emissions [5]. China has historically been one of the world's largest greenhouse gas emitters [6]. China's ecological civilization construction is still facing many challenges.

Addressing climate change relies on low-carbon development. China is committed to implementing green, low-carbon, and recycling strategies, playing a vital role in global climate pollution management. China joined the Paris Climate Change Agreement in 2016, and it implemented some of its commitments three years ahead of schedule. China piloted the carbon emissions trading policy (hereafter CETP) to utilize market mechanisms' role in lowering greenhouse gas emissions, as well as transiting to a low-carbon economic

model. The General Office of the National Development and Reform Commission (NDRC) approved pilot carbon emissions trading programs in 2011 and implemented them in seven provinces starting in 2013. In 2024, the State Council clarified the trading system of the carbon emissions trading market in the form of an administrative regulation for the first time, providing a legal guarantee for creating a more effective, more dynamic, and more internationally influential system.

CETP serves as a critical policy instrument for enhancing ecological civilization construction and fulfilling international carbon emissions reduction commitments. In 2005, EU-ETS was established, it has been proven effective in reducing emissions without causing carbon leakage. However, China's system and national conditions are quite different from those of EU countries, raising questions about the effectiveness of CETP in China. Some studies suggest that China's CETP covers a limited number of pilot areas and is vulnerable to carbon leakage due to enterprise relocation [7]. Therefore, the effect of China's CETP may have been overestimated by some researchers [8], leaving its true impact uncertain. Moreover, this will increase the cost of carbon emissions reduction [9], and reduce public support for environmental regulatory policies [10].

This raises important questions: Does the CETP effectively control carbon emissions in the pilot regions? What is the policy impact in the time dimension? Furthermore, as a regional policy, what role does the CETP play in the national dimension? Does it lead to carbon leakage, or does it curb carbon emissions in neighboring regions? Answering these questions and clarifying the mechanisms involved is crucial in realizing the dual-carbon goals, promoting low-carbon economic development, and building a Green China. It is worth mentioning that the implementation of the policy will affect the overall economy, and that this paper focuses primarily on the impact of the CETP on carbon emissions.

Therefore, we first explore CETP's influence on carbon emissions, using the difference-in-differences (DID) model with provincial panel data from 2005 to 2020. Secondly, we utilize the spatial Durbin model (SDM) to empirically clarify the spatial spillover of the CETP and discuss whether this policy will cause carbon leakage. Finally, based on the empirical findings, this paper proposes policy recommendations to provide useful references for advancing the effective operation of the national carbon emissions trading market and for promoting a low-carbon economy.

There are three primary highlights of this research. Firstly, it employs the DID model and dynamic DID model to assess how the CETP affects carbon emissions. Secondly, it uses Arc-GIS 10.2 software to visualize the time change track of per capita carbon emissions on a map of China so as to analyze the index characteristics more clearly. Finally, it adopts the SDM to explore cross-boundary carbon emissions so that the policy's spillover effects are thoroughly considered, which could otherwise lead to erroneous conclusions. This approach offers new perspectives for the study of carbon trading policies.

## 2. Literature Review

The CETP originates from the sewage rights policy, a market-driven environmental regulation policy designed to address pollution externalities. Excessive carbon emissions are characterized by a negative externalities. Coase [11] suggested that defining property rights, rather than relying on government regulation, could resolve externality issues and achieve Pareto optimality in resource allocation. In practice, Dales [12] was the first to apply 'emission rights' to pollution control by limiting the amount of emissions rights to an increasing price so that enterprises would choose to reduce pollution when facing the increasingly high costs of emissions. This type of emissions rights policy has been proven to be effective in reducing sulfur dioxide and acid rain in the United States [13]. Further supporting evidence comes from Segura et al. [14], who used a copulas methodology to find that the EU-ETS, based on emissions rights, has a significant reduction effect in Spanish firms. Laing et al. [15] also affirmed the mechanism's contribution to EU-ETS in reducing carbon emissions.

More and more scholars in China are examining whether the CETP has effectively helped carbon emissions reductions as well as producing additional outcomes. These studies have examined through theoretical analysis and empirical evidence whether the CETP can affect total carbon emissions [16,17], per capita carbon emissions [18], carbon intensity [19], carbon emissions reduction efficiency [20], energy efficiency [21,22], urban green transformation [23], and agricultural eco-efficiency [24] in pilot regions. According to [25], the CETP helps a decrease in the total amount of carbon emissions and green economic development. However, in the time dimension, scholars are controversial about the effect played by this policy. Some scholars, based on empirical evidence, conclude that the CETP can inhibit carbon emissions during the year of its implementation, with a lasting effect [26]. However, some researchers have also found that the policy exhibits a time lag, meaning that its impact on carbon emissions is more pronounced over the long term [27,28]. Moreover, because of differences in economic conditions as well as resource endowments among the pilot regions, the effects of the policy's implementation differ from one region to another [29].

Carbon leakage refers to the phenomenon where, due to the implementation of strict environmental regulatory policies in one region, companies shift their production activities to regions without similar regulations, thereby increasing carbon emissions in those areas. Existing studies indicate that environmental regulations may indeed trigger carbon leakage. For instance, Zhou and Huang [30] pointed out that environmental regulations lead to corporate relocation, which increases emissions in unregulated regions. Yu et al. [31] emphasized that the tightness of economic ties is a key factor driving industrial relocation and subsequent carbon leakage. Beck et al. [32] found that Denmark's carbon tax policy resulted in carbon leakage, and they also highlighted that the EU-ETS produced a "waterbed effect," exacerbating the issue. Additionally, China's carbon emissions trading policy encouraged firms in pilot regions to invest abroad, with the "Belt and Road Initiative" further promoting carbon leakage [33]. Antoci et al. [34] developed a theoretical model showing that while high carbon prices can reduce emissions, rising carbon prices may also exacerbate carbon leakage, weakening the overall effectiveness of the policy. Other studies have discovered the existence of reverse carbon leakage, where carbon emissions shift from unregulated regions to regulated ones. Zhou et al. [35] argued that market participation is the key factor leading to reverse carbon leakage. Some research has also introduced the concept of negative carbon leakage, suggesting that environmental regulatory policies can reduce carbon emissions in non-pilot regions. Sadayuki and Arimura [36], through their study of Japan's emissions trading system, found that the system effectively lowered emissions in unregulated regions.

In summary, existing studies have analyzed the CETP's carbon emissions reduction effects from both theory and empirical perspectives, with most concluding that the CETP effectively inhibits pilot areas' total amount of carbon emissions. However, because of the differences in the construction of the indicators, the complexity and diversity of the regions and industries, and China's unique market and institutional conditions, in the time dimension, there is no consensus on the policy's carbon emissions reduction effect. In addition, studies mainly focus on the pilot regions without fully considering the CETP's broader impact. Carbon pollution is not limited to specific areas, since natural factors as well as economic activities can affect its transformation. Therefore, the CETP's influence in neighboring regions of the pilot areas must also be considered.

## 3. Theoretical Mechanisms and Research Hypotheses

### *3.1. Direct Effect*

The CETP is an environmental regulatory policy that affects corporate profits, leading enterprises to adjust their production behavior, ultimately impacting regional carbon emissions. In short, it directly affects carbon emissions through the 'green paradox' effects, the 'forced emission reduction' effects, and the 'established demand' effects [37]. In the trading market, permits of carbon emissions are given the attributes of a commodity [38,39],

allowing enterprises to trade them. The pricing of carbon emissions rights is affected by supply and demand, which ultimately affects the costs and revenues of enterprises. Therefore, the CETP can influence enterprises' emissions behavior via cost constraints and revenue incentives, thereby impacting regional carbon emissions [40].

The CETP influences the behavior of enterprises. A province's total carbon emissions are set, and regulated firms have a certain number of free allowances. If emissions exceed these allowances, companies must buy additional allowances to offset the excess, or else they will be penalized. This regulation internalizes the pollution externality as a cost to firms [41], placing greater abatement pressure on those that exceed their quotas. Moreover, a carbon trading policy creates a revenue incentive for firms. When firms' valuations of allowances surpasses the profits the firms can earn through production, they are incentivized to reduce emissions, sell their surplus allowances, and benefit financially from the carbon emissions trading market. This promotes emissions reductions through revenue-driven incentives. However, if there is a carbon leakage in the CETP, the carbon emissions reduced by enterprises in one area may be offset by those in other unregulated areas.

In light of the above, this study puts forward hypothesis I: The CETP is effective in promoting carbon emissions reduction.

### *3.2. Indirect Effect*

The CETP can realize carbon emissions reduction by promoting green technological innovation. Through green technology, firms can obtain the same output with lower inputs, thus reducing carbon emissions. Therefore, technological innovation is the main driver [42] and an important channel for emissions reduction [43]. The CETP influences technological innovation in two aspects. Firstly, the CETP directly promotes technological innovation. The carbon emissions trading mechanism enhances technology transfer [44], and this knowledge spillover effect reduces innovation costs for other enterprises. Secondly, the carbon emissions trading system indirectly encourages technological innovation. Carbon emissions rights and green technological innovation have a substitutional connection, and changes in the price of one will influence an enterprise's choice between the two. High prices of carbon emissions licenses in the trading market serve as price signals that encourage firms to spend more on green innovation. This allows firms to reduce emissions costs through green technological innovation and earn revenue through carbon rights sales, thereby incentivizing innovation [45].

In light of the above, this study puts forward hypothesis II: The CETP can promote technological innovation to inhibit carbon emissions.

Moreover, the CETP also can realize it through industrial structure upgrading. A region's industrial structure reflects its local pollution intensity, and the CETP can force the local industrial structure to upgrade, thus lowering regional emissions. Specifically, restrictions on carbon emissions allowances force inefficient enterprises—those that can barely bear the costs of emissions and technological innovation—to reduce production, gradually lose market share, relocate to a 'pollution paradise' for production, or be eliminated by the market, so that inefficient and crude production industries are resisted by the market [46]. This process ensures that industries with low efficiency and crude production methods are resisted by the market, effectively raising the threshold for market access. The 'survival of the fittest' mechanism drives industrial structure to evolve towards a higher level.

In light of the above, this study puts forward hypothesis III: The CETP can realize carbon emissions reduction by promoting industrial structure upgrading.

### *3.3. Spatial Effect*

Spatial factors significantly impact the study of environmental and economic issues, and their influence cannot be ignored. It has been proven that air pollution and environmental protection policies have a spatial spillover effect [47,48]. Environmental issues in a given region inevitably impact neighboring areas due to natural geographic factors and economic factors [49]. Moreover, policies implemented in one region may also impact areas

beyond their jurisdiction [50]. Therefore, traditional studies that assume environmental independence between regions are clearly at odds with reality, meaning that spatial factors that cannot be ignored [51]. Specifically, the CETP has a bidirectional influence on emissions in neighboring regions. First, it can propel emissions reduction in neighboring regions. Environmental quality is a key component of the comprehensive assessments conducted by governments at all levels, driving 'healthy competition' among local governments and enhancing the interactions between subjective 'race to the top' strategies among regions [52,53]. The successful experience of carbon emissions reduction in pilot regions can, through the way of knowledge, spillover to the surrounding areas [54] and into the realm of information sharing, serving as a model to inhibit carbon emissions in those regions. Second, the CETP may increase carbon emissions in neighboring regions and cause carbon leakage. As firms in the pilot regions are restricted from emitting carbon, those unable to bear the high costs of technological innovation and purchasing allowances may move to neighboring regions, which serve as 'pollution paradise', to carry out production activities [8]. The upgrading of industrial structure in pilot regions gives them a locational advantage, attracting high-end industries, while non-pilot regions may take over low-end and high-carbon industries, thus increasing carbon emissions.

In light of the above, this study puts forward hypothesis IV: The CETP exhibits a spatial spillover effect, influencing carbon emissions in the surrounding regions of the pilot areas (Figure 1).

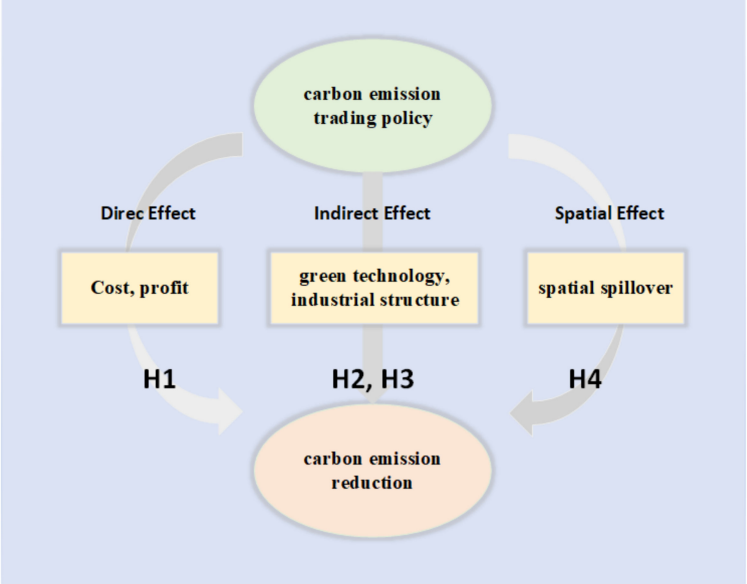



**Figure 1.** Diagram of theoretical mechanisms.

## 4. Research Design and Data

### *4.1. Data Sources and Characterization*

#### 4.1.1. Data Sources

This study selects 30 provinces' panel data from 2005 to 2020 for analysis. The Tibet Autonomous Region (TAR), Hong Kong, Macao, and Taiwan are excluded from this study due to missing data. The data are from the CEADS database [55], the China Energy Statistical Yearbook, the Statistical Yearbooks of individual provinces, the CNRDS database, and the National Bureau of Statistics.

#### 4.1.2. Characterization of the Study Area

(1) Evolution of time patterns.

Figures 2 and 3 analyze the current situation of carbon emissions from the time dimension, and the data source is the same. In Figure 2, the unit is million tons, while in Figure 3, the unit is tons.

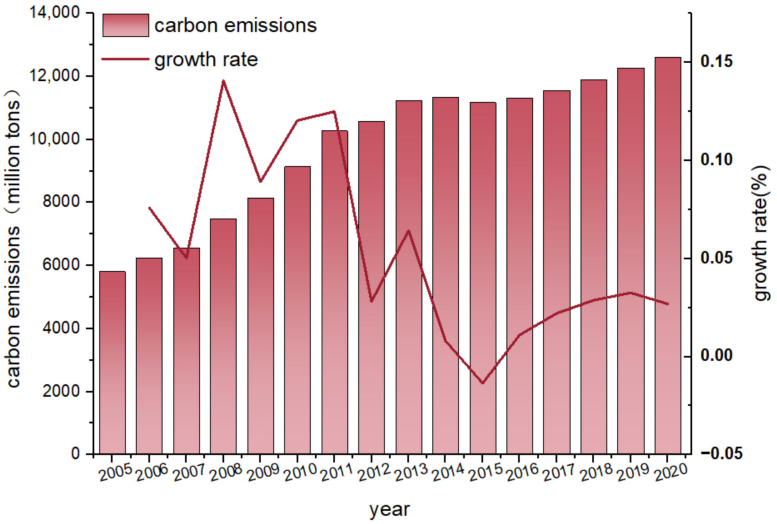



**Figure 2.** Total carbon emissions in China, 2005–2020.

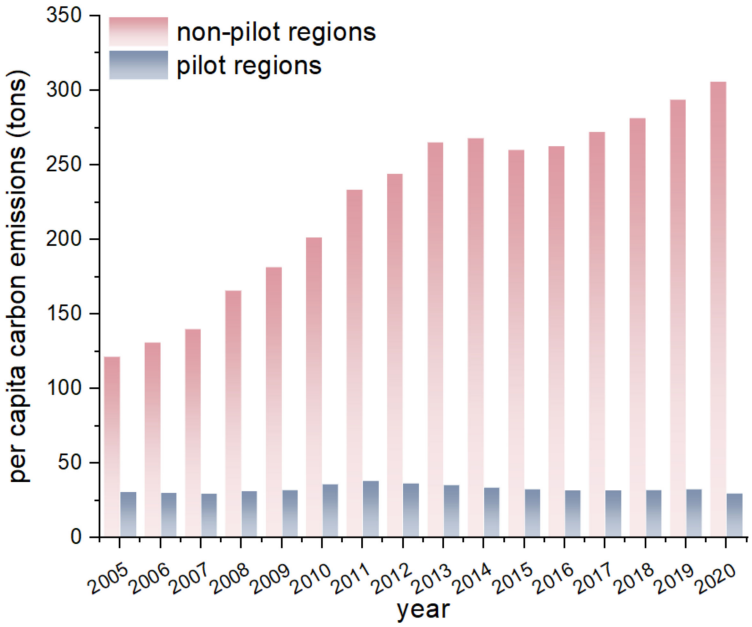



**Figure 3.** Per capita carbon emissions in the pilot region compared with other regions, 2005–2020.

Figure 2 shows the total carbon emissions and the corresponding growth rate in China from 2005 to 2020. From the perspective of the total carbon emissions, it increased annually from 2005, peaking in 2013. The years 2014 and 2015 saw a brief decline, after which carbon emissions stabilized and exhibited a slow upward trend post-2016. An important reason for the rise in emissions between 2005 and 2013 was China's continued economic expansion following its entry into the new century. The country consumed significant amounts of energy without effectively reducing emissions, resulting in a continuous increase in carbon emissions. After 2013, China's economic growth rate slowed down, and environmental policies continued to be promoted, causing a plateau in carbon emissions. From the perspective of the growth rate, it initially increased and then decreased during the sample period. It continued to rise from 2005 to 2011, but after 2011, it displayed an overall fluctuating downward trend, eventually stabilizing at around 3%. This may be because of the policy notice issued in 2011, which allowed regions to make preparations in advance, leading to a slowdown in growth starting in 2012.

Figure 3 compares per capita carbon emissions between Chinese provinces from 2005 to 2020, showing a continuous increase from 2005 to 2012. However, per capita carbon

emissions in the pilot regions decreased with volatility from 2013, whereas non-pilot regions saw a brief decrease in 2015, after which there resumed an upward trend. Figure 3 preliminary suggests that per capita carbon emissions in pilot and non-pilot areas may differ before and after the policy implementation; however, further research is necessary to confirm this.

(2) Evolution of spatial patterns.

China's vast land area and regional disparities in socio-economic development lead to variations in per capita carbon emissions across different provinces. To visualize this, this study used ArcGIS 10.2 software [56] to generate the trajectories of per capita carbon emissions in China for the years 2005, 2010, 2015, and 2020. The results, shown in Figure 4, highlight the pilot regions for the CETP with red-dotted areas.

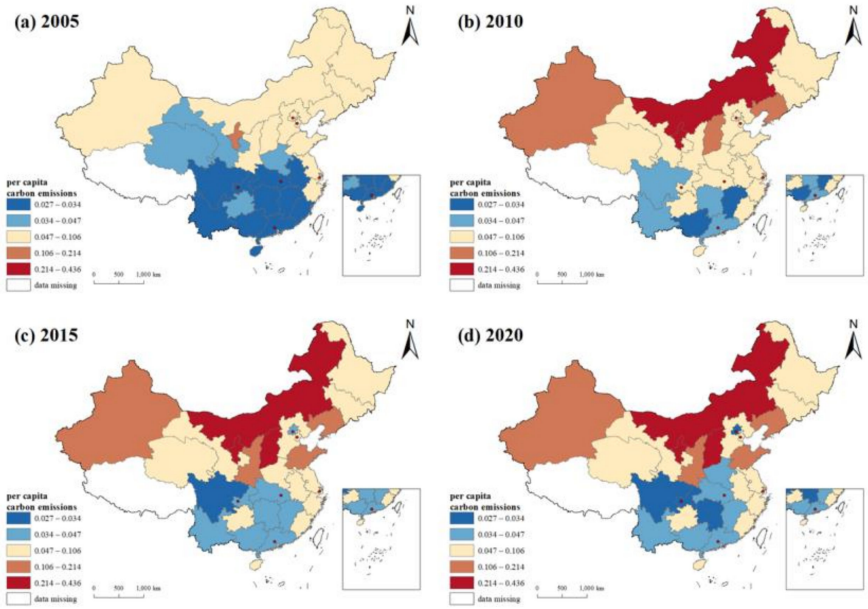



**Figure 4.** Per capita carbon emissions in provinces of China, 2005–2020.

Figure 4 shows that from 2005 to 2020, per capita carbon emissions generally exhibited an upward trend, with larger emissions in the north than in the south. In 2005, ten provinces had per capita emissions below 0.034 hundred tons, while only one province exceeded 0.106 hundred tons. In 2010, the number of provinces with per capita emissions below 0.034 hundred tons decreased to two, and the number of provinces above the level of 0.106 hundred tons increased to four, with Inner Mongolia surpassing 0.214 hundred tons. Inner Mongolia's distance from the ocean may prevent its carbon from being transported to the ocean via erosion and river systems [57], which may explain its significantly higher carbon emissions compared to other provinces. In 2015, the pilot provinces of Tianjin, Chongqing, and Wuhan experienced a reduction in per capita emissions, moving from the range of 0.047 to 0.106 hundred tons down to 0.034 to 0.047 hundred tons. In 2020, Chongqing and Tianjin dropped to below 0.034 hundred tons again. Figure 4 illustrates that before 2013, per capita carbon emissions in China showed a growing trend. After 2013, emissions of the pilot regions and neighboring regions began to decrease. However, whether this reduction is caused by the CETP needs to be further discussed.

### *4.2. Research Methodology Design and Benchmark Modeling*

(1) Research Methodology Design.

Viewing the CETP as a quasi-natural experiment, the use of DID analysis can effectively avoid exogenous problems and explore the causal effect. Therefore, we evaluated the CETP's contribution to carbon emissions using the DID model. Additionally, this study

adopts the moderating effect to further explore the mechanisms through which the CETP reduces emissions. Moreover, in the exploration of environmental issues, spatial factors must not be ignored, and it is necessary to consider spatial factors and assess how the CETP influences neighboring areas. For this purpose, we adopt the SDM to investigate the policy's spillover effects. The overall research methodology design is illustrated in Figure 5.

(2) Benchmark modeling.

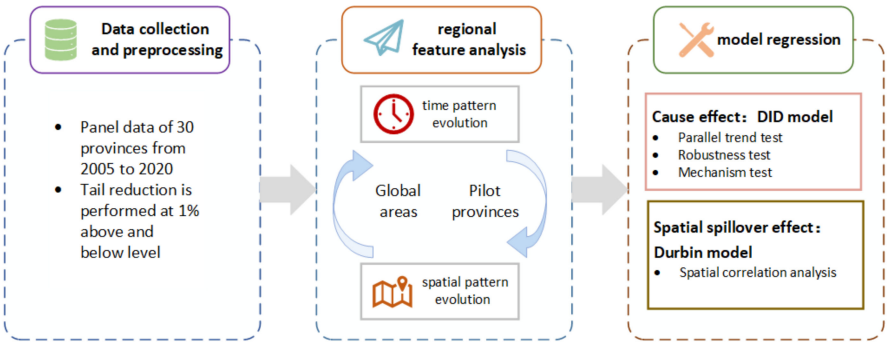



**Figure 5.** Research methodology design.

The DID model is designed to analyze how the CETP influences carbon emissions. Shenzhen, being part of Guangdong Province, is not considered separately. The treatment group consists of the six pilot provinces, while the control group comprises the other regions. Since China began implementing the policy in the latter half of 2013, we set 2013 as the base year. The measurement model 1 is presented below:

$$CE_{i,t} = \alpha_0 + \alpha_1 \times DID_{i,t} + \alpha_2 \times control_{i,t} + \gamma_i + \delta_t + \varepsilon_{i,t}. \quad (1)$$

In Equation (1), $CE_{i,t}$ is the per capita carbon emissions of region $i$ in year $t$. $DID_{i,t}$ denotes as $treated_i \times post_t$, where $treated_i$ denotes that the experimental group take 1 if the *ith* province is the pilot, and 0 otherwise. The variable $post_t$ denotes that when year $t \geq 2013$, $post_t$ is taken as 1, and 0 otherwise. The coefficient $\alpha_1$ then denotes the *DID* estimator, the term $\gamma$ denotes regional fixed effects, and $\delta_t$ denotes year fixed effects. The variable $control_{i,t}$ denotes the control variables, and $\varepsilon_{i,t}$ denotes the error term.

Table 1 lists the descriptions of each variable, where the *MOORE* index [58] is calculated as follows:

$$MOORE = arccos \frac{\sum_{i=1}^{n} W_{i,t} \times W_{i,t+1}}{\sqrt{\sum_{i=1}^{n} w_{i,t}^2} \times \sqrt{\sum_{i=1}^{n} w_{i,t+1}^2}}. \quad (2)$$

**Table 1.** Variable descriptions.

| Name | Symbol | Measurement Indicator and Explanation |
|---|---|---|
| Per capita carbon emissions | CE | Proportion of total carbon emissions to total resident population |
| Interaction of treat and post | DID | Interaction term of time dummy variables and individual dummy variables |
| Economic development level | PER | GDP per capita |
| Economic development level | PER2 | GDP per capita squared |
| Industrial structure | IS | Ratio of value added of the secondary industry to the total GDP |
| Human capital | EDU | Total number of students attending junior high school or above |
| Energy consumption intensity | ENE | Proportion of total energy consumption to total GDP |
| Population size | POP | Logarithm of total resident population at the end of the year |

**Table 1.** *Cont.*

| Name | Symbol | Measurement Indicator and Explanation |
|---|---|---|
| Openness degree | T | Proportion of total regional imports and exports to total GDP |
| Green utility technology innovation | TEC | Proportion of green utility models to utility model patents authorized |
| Industrial structure upgrading | MOORE | The MOORE index |
| Per capita carbon emissions | CE | Proportion of total carbon emissions to total resident population |
| Interaction of treat and post | DID | Interaction term of time dummy variables and individual dummy variables |

Of these, the $W_{i,t}$ and $W_{i,t+1}$ are the proportion of industry $i$ in period $t$ and period $t + 1$, respectively. The *MOORE* index measures the angle; the larger the angle is, the faster the upgrading speed of industrial institutions.

## 5. Empirical Analysis

### *5.1. Analysis of the DID Regression Results*

This study selects 30 provinces' panel data in China covering the years from 2005 to 2020 and employs the DID model to test the effect of the CETP on carbon emissions. In this study, standard errors are clustered at the provincial level and adjust explanatory variables by trimming the upper and lower 1% of their distributions. The results are presented in Table 2. Column (1) of Table 2 shows the results from the control variables not included and individual–time effect fixed, and column (2) shows the results with control variables included and the individual–time effect fixed. Column (2) demonstrates that the DID coefficient is negative at the 1% level, indicating that the CETP lowers the per capita carbon emissions of the pilot, thus providing preliminary support for Hypothesis 1.

**Table 2.** Results of the DID test for carbon emissions.

| Variable Name | Explained Variable: CE (Per Capita Carbon Emissions) | |
|---|---|---|
| | (1) | (2) |
| DID | −0.042 *** (−3.14) | −0.028 *** (−2.80) |
| PER1 | | −0.007 (−0.47) |
| PER2 | | 0.000 (−0.37) |
| POP | | 0.103 (0.94) |
| IS | | −0.140 (−0.68) |
| EDU | | 0.000 ** (−2.31) |
| ENE | | −0.045 (−1.62) |
| T | | −0.000 (−0.20) |
| Individual Effect | Control | Control |
| Time Effect | Control | Control |
| Control Variables | Not Included | Included |
| $R^2$ | 0.32 | 0.41 |

Notes: **, *** indicate 5%, and 1% significance levels, respectively. T-values are presented in parentheses.

### 5.2. Parallel Trend Test

A critical assumption when implementing the DID method is the parallel trend assumption. To ensure that carbon emissions reduction is caused by the CETP and not by other unseen influences, this study utilizes an event study method. The model is as follows:

$$CE_{i,t} = \alpha_0 + \sum_{t=2005}^{2020} \alpha_t \times DID_{i,t} + \alpha_2 \times control_{1i,t} + \gamma_i + \delta_t + \varepsilon_{i,t}. \quad (3)$$

In this study, the first five periods of the policy are combined into period 5, and the last four periods of the policy are combined into period 4, with 2005 as the base year. Figure 6 presents the dynamic effect of the study outcomes. The treatment effect coefficients before the implementation of the CETP do not pass the 5% significance test, indicating that the treatment and control groups did not differ notably before 2013, thereby passing the assumption. The estimated value of the treatment effect coefficients during and after the policy implementation are significantly less than 0 and exhibit continuity, suggesting that the policy significantly continues to curb per capita carbon emissions.

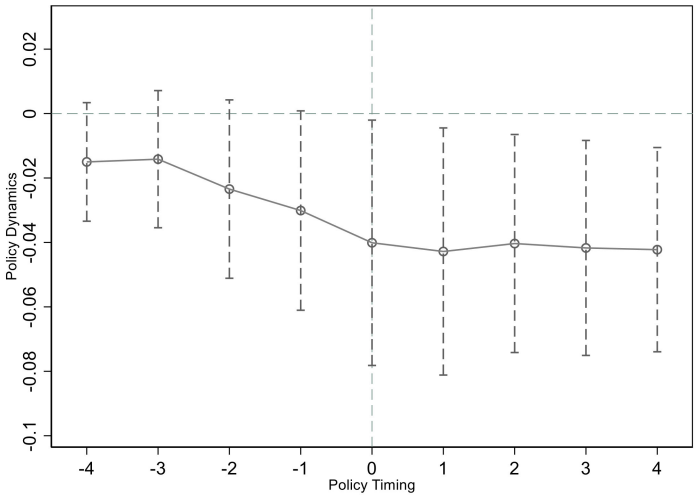



**Figure 6.** Dynamic policy effects.

### 5.3. Robustness Tests

Referring to Zhou Mao et al. [59], Xu et al. [38], He et al. [60], and other scholars' practices, we conducted 500 random regressions on Model 1 to address the influence of key omitted variables. The results, presented in Figure 7, show that most of the random coefficients are centered around 0. Additionally, the number −0.02 marked by the red line is the actual regression coefficient, coefficients obtained from random sampling and the actual regression coefficients are quite different, indicating that the actual regression coefficients are not obtained randomly, confirming the existence of a carbon emissions reduction effect from the CETP.

### 5.4. Changing the Research Sample

Since Sichuan and Fujian provinces established the carbon emissions trading market after 2013 and began trading in 2016, this might cause the baseline regression results to be incorrect. To address this, this study deletes the samples of Sichuan and Fujian provinces. The results, shown in Table 3, indicate that the DID remains significantly negative after deleting the data from these two provinces, indicating that the effect is robust.

### 5.5. Mechanism Tests

It has been confirmed that the CETP has the ability to lower carbon emissions, but mechanisms through which the policy realizes the emissions reduction effect deserve further exploration. Drawing on the theoretical analysis above and referencing Xu [38], the

variables of the mechanisms are cross-multiplied with the DID, and both the interaction terms and their parallel terms are incorporated into the model. The findings, as shown in Table 4, demonstrate that the cross-multiplication terms have a statistically significant negative impact at 10% level. This indicates the positive moderating role that green innovation and industrial structure upgrading play. The CETP can enhance the inhibiting effect on per capita carbon emissions by enhancing these two mechanisms.

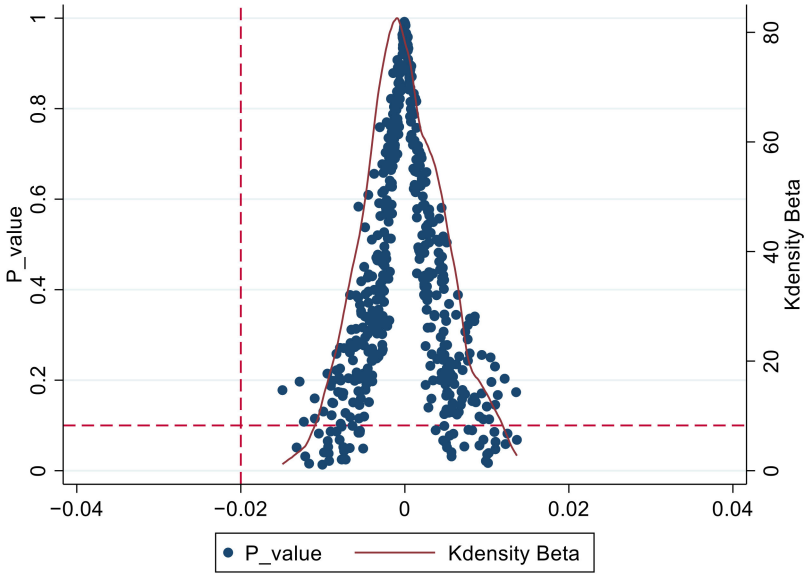



**Figure 7.** Placebo test.

**Table 3.** Results of DID test for carbon emissions of changing study samples.

| Variable Name | Explained Variable: CE (Per Capita Carbon Emissions) | |
|---|---|---|
| | (1) | (2) |
| DID | 0.044 *** | −0.029 ** |
| | (−3.10) | (−2.61) |
| PER1 | | −0.007 |
| | | (−0.40) |
| PER2 | | −0.000 |
| | | (−0.32) |
| POP | | 0.110 |
| | | (0.94) |
| IS | | −0.133 |
| | | (−0.62) |
| EDU | | 0.000 ** |
| | | (−2.31) |
| ENE | | −0.048 |
| | | (−1.39) |
| T | | −0.000 |
| | | (−0.20) |
| Individual Effect | Control | Control |
| Time Effect | Control | Control |
| Control Variables | Not Included | Included |
| $R^2$ | 0.33 | 0.41 |

Notes: **, *** indicate 5%, and 1% significance levels, respectively. T-values are presented in parentheses.

**Table 4.** Mechanism tests.

| Variable Name | Explained Variable: CE (Per Capita Carbon Emissions) | |
|---|---|---|
| | **(1)** | **(2)** |
| DID | −0.019 ** (−2.13) | 0.009 (0.46) |
| DID_MOORE | −0.297 * (−1.71) | |
| MOORE | 0.327 * (1.76) | |
| DID_TEC | | −0.456 * (−1.94) |
| TEC | | 0.169 (0.51) |
| PER1 | −0.007 (−0.50) | −0.008 (−0.54) |
| PER2 | −0.000 (−0.33) | −0.000 (−0.14) |
| POP | 0.104 (0.95) | 0.099 (0.84) |
| IS | −0.144 (−0.71) | −0.138 (−0.68) |
| EDU | 0.000 ** (−2.43) | 0.000 ** (−2.36) |
| ENE | −0.045 (−1.68) | −0.046 (−1.63) |
| T | −0.000 (−0.11) | −0.000 (−0.25) |
| Individual Effect | Control | Control |
| Time Effect | Control | Control |
| Control Variable | Included | Included |
| $R^2$ | 0.43 | 0.41 |

Notes: *, ** indicate 10% and 5% significance levels, respectively. T-values are presented in parentheses.

### *5.6. Analysis of Spatial Spillover Effects*

#### 5.6.1. Spatial Correlation Analysis

(1) Global spatial autocorrelation.

Due to the "First Law of Geography" [61], issues of spatial correlation have garnered significant attention. The Global Moran's I index is used to evaluate spatial correlations. Table 5 shows the results of the global autocorrelation test of per capita carbon emissions under the spatial neighboring space matrix setting. The results indicate that the global Moran's I indices are all greater than 0, as well as being significantly positive at the 1% level. This suggests that there is a significant positive correlation of per capita carbon emissions, implying that the correlation is stronger with geographic proximity.

(2) Local spatial autocorrelation.

Local Moran's I index can reveal the location and extent of outliers or clusters. The samples are mainly in the first and third quadrants and far from the origin, reflecting a significant positive correlation in the spatial distribution of carbon emissions (Figure 8).

**Table 5.** Global Moran index.

| Year | Moran Index I |
|---|---|
| 2005 | 0.461 *** |
| 2006 | 0.400 *** |
| 2007 | 0.408 *** |
| 2008 | 0.400 *** |
| 2009 | 0.355 *** |
| 2010 | 0.393 *** |
| 2011 | 0.384 *** |
| 2012 | 0.397 *** |
| 2013 | 0.330 *** |
| 2014 | 0.323 *** |
| 2015 | 0.328 *** |
| 2016 | 0.336 *** |
| 2017 | 0.317 *** |
| 2018 | 0.323 *** |
| 2019 | 0.338 *** |
| 2020 | 0.346 *** |

Notes: *** indicates 1% level of significance, respectively.

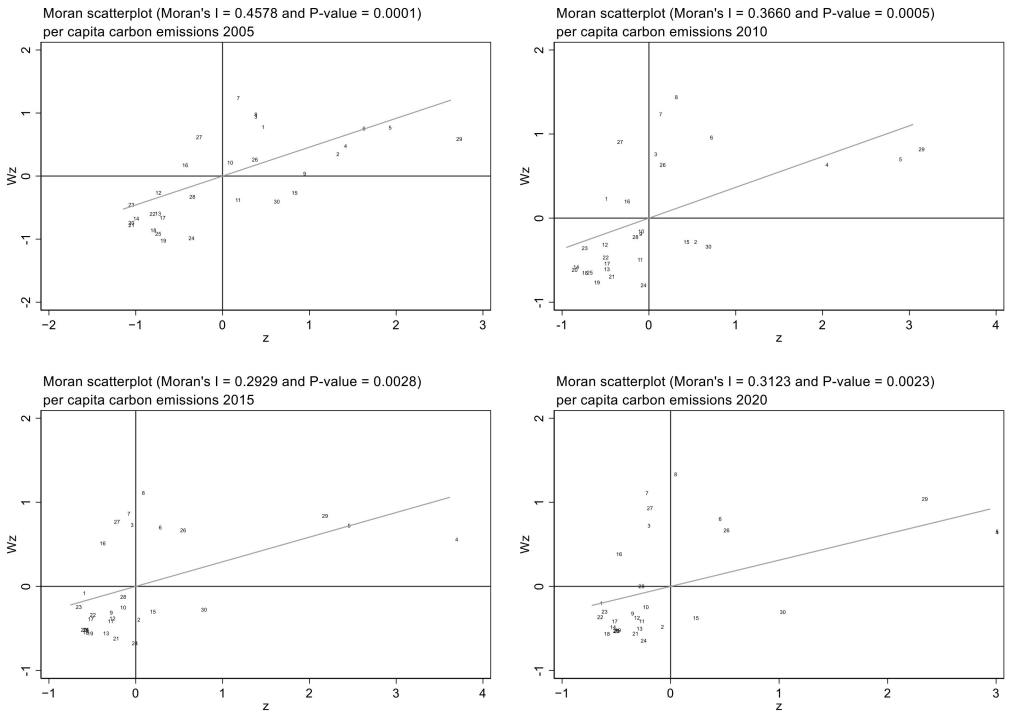



**Figure 8.** Scatterplot of the Moran index.

Table 6 shows the localized Moran's I index in 2005 and 2020. As seen in Table 6, from 2005 to 2020, the areas of high–high clusters have decreased and the areas of low–low clusters have increased, indicating a positive trend toward carbon emissions reduction. In addition, the pilot regions, Beijing and Tianjin, transitioned from high–high clusters to low–low agglomeration clusters, indicating that the policy effectively reduced emissions in these regions. In addition, areas with high per capita carbon emissions are mostly in the northern regions, while areas with low per capita carbon emissions are mostly in the Yangtze River Basin. This may be because the northern regions are mostly dominated by heavy industry, such as the three northeastern provinces, which are mainly industrial bases, and the three northeastern provinces and Shanxi Province, which are limited by resource endowment. Energy production and consumption in these provinces rely heavily on coal, which leads to higher per capita carbon emissions. Conversely, in the Yangtze

River Basin, the tertiary industry occupies a dominant position, and the more developed the economic development of the Yangtze River Economic Belt, the more advanced the low-carbon technology, and thus the lower the per capita carbon emissions.

**Table 6.** Localized Moran index.

| | 2005 | 2020 |
|---|---|---|
| High-High Clusters | Shanxi, Inner Mongo, Liaoning, Jilin, Heilongjiang, Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Shannxi, Ningxia | Shanxi, Inner Mongo, Liaoning, Shannxi, Ningxia |
| Low-High Clusters | Henan, Gansu | Hebei, Jilin, Heilongjiang, Henan, Gansu, Qinghai |
| Low-Low Clusters | Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Qinghai | Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang |
| High-Low Clusters | Zhejiang, Shandong, Xinjiang | Shandong, Xinjiang |

5.6.2. Analysis of Spatial Measurement Models

(1) Spatial measurement model selection.

The LM test shows that both the spatial error model test and the spatial lag model test rejected the null hypothesis of no spatial autocorrelation. The WALD test indicates that the SDM cannot be reduced to either the SAR or the SEM. Additionally, the LR test and the time–individual fixed effects test shows that the model with both time and individual fixed effects is more effective when applying the SDM. Consequently, this study selects the SDM with double-fixed effects for analysis (Table 7).

(2) SDM regression results.

**Table 7.** Spatial measurement model tests.

| Spatial Panel Model Testing | | Value | *p*-Value |
|---|---|---|---|
| LM Test | Moran's I | 2.081 | 0.037 |
| | LM-Lag | 64.203 | 0.000 |
| | Robust—LM-lag | 12.875 | 0.000 |
| | LM-Lag | 65.687 | 0.000 |
| WALD Test | Robust—LM-error | 14.360 | 0.000 |
| | WALD-SDM/SEM | 23.10 | 0.0016 |
| | WALD-SDM/SAR | 19.53 | 0.0067 |
| LR Test | LR-SDM/SEM | 46.70 | 0.000 |
| | LR-SDM/SAR | 36.24 | 0.000 |
| Time-Individual Fixed Effects Test | LR-both/TIME | 573.70 | 0.000 |
| | LR-both/IND | 28.54 | 0.03 |

Based on the confirmation of spatial correlation among the per capita carbon emissions, the static spatial econometric model is constructed as follows:

$$CE_{i,t} = \eta_0 + \rho_{11} WCE_{i,t} + \eta_1 \times DID_{i,t} + \rho_{12} WDID_{i,t} + \eta_2 \times control_{1i,t} + \rho_{13} Wcontrol_{2,t} + \gamma_{1i} + \delta_{1t} + \varepsilon_{1i,t} \quad (4)$$

To examine the regional spatial effects of per capita carbon emissions, the model set in Equation (1) serves as the foundational framework, with Equations (3) and (4) set for

further analysis. Here, $CE_{i,t}$ denotes per capita carbon emissions, $\eta_1$ denotes a coefficient to be estimated for the DID, and where $\rho_{11}$ and $\rho_{12}$ denote the coefficients to be estimated for spatio-temporal lagged variables, and $control_{1i,t}$ denotes control variables, and $\varepsilon_{1i,t}$ and $\varepsilon_{2i}$ denote the random perturbation terms.

The findings of the static SDM are shown in Table 8; $\rho$ is positive at the 1% level, suggesting that per capita carbon emissions have clustering characteristics at the spatial level, and a rise in per capita carbon emissions will trigger higher emissions in nearby regions. Additionally, the DID coefficient is negative at 5%, showing that the CETP can inhibit the per capita carbon emissions. The spatial term is also significantly negative at the 5% level, suggesting that the implementation of the CETP in neighboring regions can lower carbon emissions in local regions. The direct, indirect, and total effects of DID are negative, demonstrating that the policy decreases per capita carbon emissions in the pilot regions and that there exists a geographical spillover effect. This spillover effect fosters both competitive and demonstrative effects in neighboring regions. It plays a role in reducing per capita carbon emissions in the adjacent regions of the pilot areas, and thus the effect is strengthened in the spatial dimension.

**Table 8.** SDM results.

| Variable Name | Explained Variable: CE (Per Capita Carbon Emissions) | | | | |
|---|---|---|---|---|---|
| | **(1) Main** | **(2) WX** | **(3) Direct Effect** | **(4) Indirect Effect** | **(5) Total Effect** |
| DID | −0.032 ***<br>(−4.04) | −0.043 ***<br>(−2.58) | −0.035 ***<br>(−4.21) | −0.064 ***<br>(−2.69) | −0.098 ***<br>(−3.66) |
| PER1 | 0.007<br>(0.96) | −0.037 ***<br>(−2.84) | 0.004<br>(0.61) | −0.045 ***<br>(−2.60) | −0.041 **<br>(−2.16) |
| PER2 | −0.000<br>(−1.29) | 0.001 *<br>(1.67) | −0.000<br>(−1.03) | 0.001<br>(1.41) | 0.001<br>(0.88) |
| POP | 0.177 ***<br>(3.74) | −0.024<br>(−0.23) | 0.178 ***<br>(4.05) | 0.034<br>(0.25) | 0.212<br>(1.64) |
| IS | −0.149 ***<br>(−2.60) | 0.172<br>(1.36) | −0.140**<br>(−2.39) | 0.168<br>(1.00) | 0.029<br>(0.14) |
| EDU | 0.000 ***<br>(−4.53) | 0.000<br>(0.82) | 0.000 ***<br>(−4.50) | 0.000<br>(0.15) | 0.000 *<br>(−1.84) |
| ENE | −0.032 ***<br>(−3.81) | 0.012<br>(0.61) | −0.032 ***<br>(−3.54) | 0.003<br>(0.13) | −0.029<br>(−1.00) |
| T | 0.001<br>(0.53) | 0.000<br>(0.00) | 0.001<br>(0.59) | 0.000<br>(0.13) | 0.001<br>(0.34) |
| rho | 0.247 ***<br>(3.61) | | | | |

Notes: *, **, *** indicate 10%, 5%, and 1% significance levels, respectively. Z-values are in parentheses.

## 6. Conclusions and Recommendations

### *6.1. Conclusions*

Regarding the CETP as a quasi-natural experiment, this study uses the DID model and the SDM to empirically explore this policy's carbon emissions reduction effect in Chinese provinces. Additionally, this research explores mechanisms through which the policy promotes carbon emissions reductions. The following conclusions are drawn: Firstly, the CETP can significantly lower per capita carbon emissions. Since the CETP's implementation, Chinese provinces have exhibited a positive trend in emissions reduction, with inter-regional differences gradually diminishing. This reduction primarily works through the two mechanisms of green technological innovation and industrial structure upgrading. Secondly, per capita carbon emissions have distinct spatial distribution characteristics, with the majority of high–high clusters situated in northern areas and the low–low clusters

largely within the Yangtze River Basin. Finally, the CETP exhibits a significant spatial spillover effect, which is strengthened in the spatial dimension by generating competition and demonstration effects on the neighboring regions. This spillover effect effectively reduces the per capita carbon emissions of the pilot neighboring regions.

### *6.2. Research Limitations and Prospects*

This study offers a reference for future research in this area. However, this study has some limitations. First, data limitations confine the mechanism analysis to just two pathways of green technological innovation and industrial structure upgrading. China's unique system may also affect the effects of the CETP through both marketization and administrative regulation, factors not considered in this analysis. Second, the decrease in carbon emissions may be attributed to both the economic activities' deceleration and the improvement in economic efficiency. This study ignores the fact that the impact of the CETP on the economy may affect the assessment of the policy's effectiveness. Therefore, in subsequent studies, we will address these limitations by exploring additional pathways through which the CETP lessens carbon emissions and by examining the policy's effects on economic efficiency in greater depth.

### *6.3. Policy Recommendations*

Drawing from the paper's conclusions and China's specific context, we offer the following political proposals:

(1) Enhance carbon emissions trading infrastructure: Given the significant emissions reduction impact of the CETP, the government should refine carbon emissions trading regulations and enhance the infrastructure support system. In addition, the government should foster inter-regional coordination to escort the effective functioning of the national carbon emissions trading market and promote unified national carbon reduction efforts.

(2) Accelerate green technological innovation: To maximize the function of green technological innovation, the government should precisely direct financial resources toward it through monetary and financial policies. The central bank needs to accelerate improvements in structural monetary policy and meet the financing needs of green technological innovations in enterprises through the green technology loan policy. Moreover, the Ministry of Finance should refine the green tax system, strengthen the financial support for green technological innovation, and foster Public–Private-Partnership (PPP) in environmental protection.

(3) Promote industrial transition: Considering local industrial characteristics, the government should implement industrial policies that facilitate the shift from carbon-intensive to green industries and help upgrade the local industrial structure so that the CETP and industrial policy can complement each other and bring into play the synergistic effect of "1 + 1 > 2". For example, they can support low-carbon sectors while reducing support for high-carbon industries, thereby lowering the overall level of carbon emissions.

(4) Foster regional collaboration: Recognizing the spatial spillover effects of the CETP, establishing collaborative mechanisms for low-carbon transformation between regions is crucial. This includes creating networks for information sharing on energy saving and emissions reduction and coordinating efforts to promote the national carbon emissions trading market.

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