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Reduction Effect and Mechanism Analysis of Carbon Trading Policy on Carbon Emissions from Land Use

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Abstract: The reduction of carbon emissions from land use (CELU) is critical for China to achieve carbon neutrality, which may be greatly facilitated by carbon trading policies. Previous studies of the emission reduction effects of carbon trading policies focused mostly on the reduction of carbon source emissions, and there is a lack of research from the comprehensive perspective of carbon sources and carbon sinks. Understanding the effect of carbon trading policies on emission reduction from the perspective of CELU may help to improve the evaluation system of carbon trading policies, as well as provide important implications for the construction of China’s carbon trading market in the context of global carbon neutrality. Here, based on China’s current carbon-trading pilot areas, quasi-natural experiments were conducted by using the CELU data from 2005 to 2017, the synthetic control method (SCM) and the mediation effect model, aiming to empirically study the reduction effect and mechanism of carbon trading policies on CELU. The following main findings were obtained. (1) Carbon trading policies have had a significant reduction effect on the average CELU of the pilot areas by at least four million tons per year during the study period. (2) The carbon emission reduction effect of carbon trading policies has certain regional heterogeneity. (3) Carbon trading policies reduce CELU through the intermediate effect of energy structure, whose contribution rate reaches 30.433%. (4) Carbon trading policies did not achieve the Porter effect of technological progress during the study period, and technological progress has no significant intermediate effect on the reduction of CELU by carbon trading policy. Based on the above findings, the following policy implications can be proposed. Carbon trading and carbon offset should be studied from a comprehensive perspective of land use; regional heterogeneity should be considered when promoting the carbon emission trading system nationwide; and the energy structure should be optimized continuously.

Keywords: carbon trading policy; carbon emissions from land use; emission reduction effect; synthetic control method; mediation effect model

1. Introduction

Carbon emissions exacerbate global warming and cause increasingly severe environmental problems. The reduction of carbon emissions and the promotion of sustainable development have achieved an international consensus. As the world’s largest country of carbon emissions, China declared it would adopt more effective emission reduction policies, and strive to reach emission peak by 2030 and carbon neutrality by 2060 at the General Debate of the 75th Session of the United Nations General Assembly, which means that China will reduce its annual net carbon emissions from 16 billion tons to zero in 40 years [1]. As a coupling system of human society, the economy and the natural ecological environment, the land is the reservoir of carbon source and carbon sink in terrestrial ecosystems. Carbon emissions from land use (CELU) refer to the release of carbon into the atmosphere from land that is interfered with by human production, ecological or social activities [2,3]. CELU depends on the balance between the carbon source and the carbon sink. Carbon source is reflected by the carbon emission intensity, and carbon sink is determined by the carbon
storage and cumulative rate of absorption [4,5]. Carbon sources and carbon sinks in a terrestrial ecosystem can be matched with different land use types. Among the major types of land use, cultivated land and construction land are carbon sources, while woodland and grassland are carbon sinks [6–8].

In this study, CELU includes direct and indirect carbon emissions [3]. The former mainly refer to carbon emissions caused by land use and land use change, such as farming, wetland drying, forest logging, construction land expansion, and the latter mainly refer to anthropogenic carbon emissions that have occurred on the individual land use types earlier, such as energy consumption, industrial and transportation carbon emissions. CELU is an important approach for measuring and reporting the inclusive land-use emissions in China. It has been estimated that between 1850 and 1998, direct and indirect CELU accounts for about 1/3 and 2/3 of the total carbon emissions from human activities, respectively [9,10]. Therefore, reduction of CELU in consideration of both carbon source and carbon sink is critical for China to achieve the final target of carbon neutrality.

Carbon emission trading is considered as an effective policy tool to reduce carbon emissions and address climate change issues. The carbon trading market can internalize external costs [11], improve the utilization efficiency of environmental resources [12], and promote the development of carbon sinks [13]. Since the release of the Kyoto Protocol, many countries have established carbon trading markets. The Chinese government officially launched a pilot project of local carbon emission trading in 2011, which covered the areas of Beijing, Tianjin, Shanghai, Hubei, Guangdong, Shenzhen and Chongqing, and the government sets out to establish the national carbon trading market in 2021, which will be the world’s largest carbon trading market [14].

China’s carbon trading market can be divided into the market based on the cap of allowances and the carbon credit market based on the project system (mainly Chinese Certified Emission Reduction, CCER) [15]. Carbon trading policies aim to achieve carbon emission reduction at lower costs through a reasonable allocation and a virtuous circle in terms of reducing carbon sources and increasing carbon sinks. CELU provides a new perspective for studying the effectiveness of the carbon trading policies. However, it remains unknown whether carbon trading policies can effectively alleviate CELU and what is the underlying mechanism. A targeted analysis of the reduction effect of carbon trading policies on CELU and the related mechanism will provide empirical reference for the national promotion of carbon trading policies and the path optimization of carbon emission reduction in China, and finally achieve emission peak and carbon neutrality on the premise of ensuring high-quality and sustainable development of the economy.

Since the pilot project of local carbon emission trading was launched in 2011, some research has been conducted to assess the impact of carbon trading policies with different methods from various perspectives and at different scales. First, diverse methods were used to evaluate the impact of carbon trading policies at different scales, including micro level companies, energy sectors, macroeconomics and environment. For example, Liu et al. [16] sampled the A-share listed companies in China from 2009 to 2018 and adopted the difference-in-difference (DID) method to investigate the effect of the carbon emission trading on corporate financial performance from the micro level. Wang et al. [17] analyzed the economic impacts of carbon trading policies among different energy intensive sectors in Guangdong Province with a two-region dynamic computable general equilibrium model (CGE), finding that carbon trading policies could significantly reduce the mitigation cost for the whole economy. Zhang et al. [18] applied a robust econometric method DID estimation on city-level panel data in China, and found that the emission trading policies adopted in pilot regions could reduce carbon emissions by approximately 16.2%, and such an effect is particularly prominent in eastern areas of China where the economy is better developed. Based on the propensity score matching (PSM) and DID, Fan et al. [19] found that carbon trading could reduce the total carbon emissions to a certain extent, but has a weak impact on economic output. Zhang et al. [20] evaluated the emission reduction effect and carbon
market efficiency of carbon emission trading policies, and revealed that the polices could cobenefit the economy and the environment in the seven pilots of China.

Second, the research perspectives have been widely broadened to be beyond the direct impact of carbon trading policies, involving various fields such as green development, forest carbon sinks and CELU. For instance, Wu et al. [14] studied the impact of China’s carbon emission trading pilot markets on carbon emissions and regional green development and found that carbon trading policies can achieve green development through synergistic SO\textsubscript{2} emission reduction. Zhou et al. [21] focused on how the forest carbon trade affects the management decision of forests such as the optimal forest rotation age. Yi et al. [22] proposed that the market-based ecosystem payments, especially carbon financing, are potential tools to prevent further forest loss in China. They also compared different land-use scenarios, and found that the conservation-oriented scenario could maintain the highest level of natural forest area and sequester 57\% more carbon than an economic-oriented scenario. Chen et al. [23] investigated the influencing factors of the decoupling relationship between CELU and economic growth, and proposed that the guidance of macro-environmental policy plays a fundamental role in the decoupling relationship between CELU and economic growth. The implementation of carbon trading policies and the improvement of energy-saving and emission-reduction technologies contributed to the optimal decoupling of CELU and economic growth in Guangdong from 2011 to 2015. Li et al. [24] studied the effects of carbon trading policies from the perspective of interprovincial differences on carbon emission intensity of construction land, and found that carbon trading policies could significantly reduce the carbon emission intensity of construction land in the pilot areas. Zhao et al. [25] believed that land science has advantages in comprehensive research on regional carbon emissions, and proposed that CELU should be further combined with resource utilization and economic regulation to study land use carbon trading and carbon offset. Dong et al. [26] suggested that the allocation of emission reduction responsibilities is crucial in the construction of the carbon trading system. From the perspective of regional differences in CELU, they studied the allocation of carbon emission reduction responsibilities in the Wuhan urban agglomeration and verified its feasibility, laying a foundation for studying the relationship between CELU and macro carbon-trading policies.

In summary, the existing literature provides a theoretical basis for exploring the reduction effect of carbon trading policies on CELU. However, there are two major limitations in the research on the effect of carbon trading policies. First, since China’s carbon trading market is still in its infancy, there is still a lack of empirical research on the emission reduction effect, regional heterogeneity and the mechanism of carbon trading policies on CELU. Secondly, DID and PSM are the most often used methods to evaluate the effect of carbon trading policies. These two methods have certain disadvantages in several aspects. On the one hand, due to the short implementation time of carbon trading policies and few pilot areas, there are not many samples available for observation, which affects the choice of the reference group and to a certain extent influences the reliability of the estimation results. On the other hand, systemic differences between pilot areas and nonpilot areas will cause endogenous problems of the policy. Thus, direct use of DID or PSM may lead to estimation errors [27]. The synthetic control method (SCM) proposed by Abadie and Gardeazabal [28] constructs a “synthetic control area” through the linear combination of areas not subjected to policy intervention. The optimal weight of the linear combination is driven by data, which can effectively avoid estimation bias caused by subjective arbitrary selection of the control group [29]. SCM has been widely applied to policy evaluation such as tobacco control laws [27], electricity price limit policies [30], and the establishment of free trade zones [31].

Therefore, this paper conducts quasi-natural experiments based on China’s current carbon trading pilot areas with the panel data of CELU from 2005 to 2017, and uses SCM to explore the reduction effect of carbon trading policies on CELU, and the mediation effect model, a relatively mature method, to analyze the mechanism underlying the effect [32].
2. Theoretical Analysis and Hypothesis

To determine whether carbon trading policies have any reduction effect on CELU, we first attempted to understand the relationship between land use and carbon trading considering both the carbon emissions from social economic activities in carbon source (mainly construction land and cultivated land) and the carbon absorption in carbon sink (mainly woodland and grassland). In Figure 1, the carbon trading market is at the core of reconciling social economic carbon sources and natural ecological carbon sinks, which can promote carbon balance and achieve sustainable development. The carbon trading market links CO\textsubscript{2} concentration, land use, social economy and natural ecosystems through information feedback [33]. Specifically, there are currently two types of basic products in China’s carbon trading market. One is government-assigned carbon allowances, and the other is carbon credit of CCER. The carbon allowance is mainly determined by industrial production carbon sources, and carbon credit is mainly associated with forest carbon sink. Carbon allowances and carbon credits circulate in the carbon trading market to form carbon prices, and the price mechanism in turn regulates social and economic activities. Appropriate carbon prices will contribute to a decline of industrial production carbon emissions, and encourage afforestation or reforestation to generate more carbon sinks. All carbon sources and carbon sinks are inseparable from land use. The main types of land use, including cultivated land, construction land, grassland and woodland, play fundamental roles in carbon emissions, the social economy and natural ecosystems.

![Figure 1. Relationship between land use and carbon trading. (Note: land use types, including cultivated land, construction land, grassland and woodland, are linked to carbon trading system).](image)

Second, we analyzed how carbon trading promotes the reduction of CELU by controlling the emissions from carbon source and increasing carbon absorption in carbon sinks (Figure 2). The original intention of carbon trading is based on the Coase theorem to clarify the emission rights, giving economic value to resources and the environment, internalizing pollution costs through market functions, and finally reducing total carbon emissions [34]. There are two types of enterprises belonging to carbon source: high-emission enterprises and low-emission enterprises. High-emission enterprises are the main buyers in the carbon trading market. The carbon allowance directly leads to an increase in the production cost of the enterprise. When an enterprise chooses to reduce the production scale to decrease production costs, the emissions from the carbon source will be directly decreased, and when the enterprise chooses to buy carbon allowance or carbon credit to maintain its production scale, the emissions will remain unchanged in the short term. However, since carbon prices in the market may fluctuate, the enterprises may consider the risks of rising carbon prices and a possible further increase in production costs. In order to reduce expected risks in the long term, they may choose to optimize the energy structure and develop or adopt...
low-carbon production technologies, which can help to finally achieve the reduction of emissions from carbon source.

![Diagram: Framework for the reduction of CELU by carbon trading policies.](image)

Figure 2. Framework for the reduction of CELU by carbon trading policies.

Low-emission enterprises are the main sellers in the carbon trading market. Carbon emission rights have become a salable resource, and directly bring premium returns to low-emission enterprises. When an enterprise chooses to maintain low-carbon production to obtain the premium returns, the emissions from the carbon source land will remain unchanged in the short term. Under the influence of the price mechanism, the enterprise may also face the opportunity of rising carbon prices and a further increase in revenue. At this time, the enterprise may choose to further develop low-carbon production technologies so as to obtain more sellable carbon allowance, which may contribute to the reduction of emissions from the carbon source as well.

The carbon sink operators are mostly agricultural and forestry operators, who are also the main sellers in the carbon trading market. Carbon credit trading can directly bring benefits to forest managers beyond the benefits of timber, and encourage them to increase the area of carbon sink forests, reduce logging, extend the rotation age, and adopt more professional forest management and protection activities [35], so as to create more carbon credit available in the trading market. This process will directly enhance the carbon absorption effect of the carbon sink. Therefore, carbon trading policies can play some roles in coordinating carbon allowance and carbon credit, to reduce carbon source emissions, increase carbon sink absorption, improve resource allocation efficiency, and finally reduce total CELU.

Carbon trading has a certain impact on energy structure and technological progress [36–38]. According to Figures 1 and 2, the carbon trading policy supports the development and utilization of clean energy such as natural gas, and promotes the transformation of fuel use in agricultural and industrial production from coal and oil to clean energy, which can facilitate the optimization of China’s coal-based energy structure. The optimization of the energy structure will directly help to reduce carbon emissions. Inconsistent conclusions have been drawn about the impact of carbon trading policies on technological progress. (1) According to Porter’s hypothesis, appropriate environmental regulatory policies can encourage enterprises to increase productivity through technological innovation so as to
offset the environmental costs, resulting in an “innovation compensation” effect. Market-oriented carbon trading policies will drive enterprises to weigh the cost of purchasing carbon quota and adopting low-carbon production technologies. If the cost of adopting low-carbon production technology is lower than that of purchasing carbon quota, or it can offset part of the external environmental cost, the enterprise will prefer low-carbon production technologies. In addition, the premium returns from the sale of surplus quota will incentivize the innovation of enterprises in low-carbon production technologies. The “innovation compensation” effect can promote the enterprises to rely on advances in low-carbon production technologies to compensate for internalized emission reduction costs, which can effectively reduce external emissions. (2) Some other scholars hold different views about the dynamic effect of carbon trading on technological progress [39,40]. They believe that with the implementation of carbon trading policies, carbon quota will gradually become a scarce resource, which may lead to a rise in carbon prices and subsequently an increase in production costs, and increase the risk of squeezing research and development costs, making carbon trading policies a factor restricting technological progress. Therefore, carbon trading may have either a positive or negative effect on technological progress, and whether carbon trading can reduce CELU through technological progress remains to be empirically tested.

Based on the above theoretical analysis, we believe that carbon trading can help to reduce CELU, and the mechanism may involve the intermediate effect of energy structure optimization and technological progress. We propose the following hypotheses:

**Hypothesis 1 (H1).** Carbon trading is conducive to the reduction of CELU.

**Hypothesis 2 (H2).** Carbon trading promotes the reduction of CELU through the intermediate effect of energy structure.

**Hypothesis 3 (H3).** Carbon trading promotes the reduction of CELU through the intermediate effect of technological progress.

### 3. Methods, Variables and Data

#### 3.1. Methods

**3.1.1. Synthetic Control Method**

The synthetic control method (SCM) is used to estimate the reduction effect of carbon trading on CELU. The experimental group includes the carbon trading pilot areas, and the control group comprises the nonpilot areas. The virtual control group is constructed by the weighted average of the control group, and is the “counterfactual stand-in” of the experimental group. A quasi-natural experiment of the virtual control group and the experimental group was constructed. The difference in CELU between the virtual control group and the experimental group is the actual carbon emission reduction effect of the carbon trading policy. Suppose that there are $P + 1$ sample areas, the first is the carbon trading pilot area, and the remaining $P$ are nonpilot areas, $T$ is the sample period, and $T_0$ represents the time. When the carbon trading policy began to be implemented, with $1 \leq T_0 \leq T$, $E^I_{it}$ represents the CELU of region $i$ under the carbon trading policy at time $t$, $E^N_{it}$ indicates the CELU of region $i$ where the carbon trading policy was not implemented at time $t$. Then, the effect of carbon trading policy is $\alpha_{it} = E^I_{it} - E^N_{it}$, in which $E^N_{it}$ is an unobservable item and needs to be estimated. The estimation model for $E^N_{it}$ is:

$$E^N_{it} = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \epsilon_{it}$$  \hspace{1cm} (1)

In the formula, $\delta_t$ represents the time trend; $\theta_t$ stands for the unknown parameter; $Z_i$ is the predictor variable not affected by the policy; $\lambda_t$ represents the unobservable common factor; $\mu_i$ indicates the regional fixed effect; and $\epsilon_{it}$ is the disturbance term.
Suppose the weight vector \( W = (w_2, \ldots, w_{p+1}) \) satisfies \( w_p \geq 0 \), and \( w_2 + \ldots + w_{p+1} = 1 \), the virtual synthetic control variable can be expressed as:

\[
\sum_{p=2}^{P+1} w_p E_{pt} = \delta_1 + \theta_1 \sum_{p=2}^{P+1} w_p Z_{p} + \lambda_t \sum_{p=2}^{P+1} w_p \mu_p + \sum_{p=2}^{P+1} w_p E_{pt}
\]  

(2)

Suppose there is a weight vector \( W = (w_2, \ldots, w_{p+1}) \), then:

\[
\sum_{p=2}^{P+1} w_p^* E_{p1} = E_{11}, \quad \sum_{p=2}^{P+1} w_p^* E_{p2} = E_{12}, \ldots, \quad \sum_{p=2}^{P+1} w_p^* E_{pT_0} = E_{1T_0}, \quad \text{and} \quad \sum_{p=2}^{P+1} w_p^* Z_{p} = Z_1
\]  

(3)

If \( \sum_{i=1}^{T_0} \lambda_i^t \lambda_i \) is nonsingular, then the following formula holds:

\[
E_{11}^N - \sum_{p=2}^{P+1} w_p^* E_{p1} = \sum_{p=2}^{P+1} w_p^* \sum_{s=1}^{T_0} \lambda_i^t (\sum_{s=1}^{T_0} \lambda_s^t \lambda_s) \lambda_s^t (\epsilon_{ps} - \epsilon_{1s}) - \sum_{p=2}^{P+1} w_p^* (\epsilon_{pt} - \epsilon_{1t})
\]  

(4)

Abadie et al. [27] have proved that under general conditions, if the time period before the policy implementation is longer than that after the policy implementation, the left side of Equation (4) approaches to 0. Therefore, during the carbon trading pilot period, \( \sum_{p=2}^{P+1} w_p^* E_{pt} \) can be used as the unbiased estimate of \( E_{1t}^N \). Furthermore, the estimated value of policy effect \( \alpha_{it} \) can be calculated as \( \hat{\alpha}_{1t} = E_{1t}^I - \sum_{p=2}^{P+1} w_p^* E_{pt}, \ t \in [T_0 + 1, \ldots, T] \). The weight required for the estimation in this paper is determined according to the method of Abadie et al. The estimation process is carried out in the Synth package of the R software.

3.1.2. Mediation Effect Model

The previous analysis has indicated that carbon trading policy affects CELU through energy structure and technological progress. Thus, we refer to the three-step mediation effect model of Chinese scholar Wen et al. to verify this hypothesis [32]. The mediation effect model is as follows:

\[
CELU_{it} = \alpha_{it} + \beta_1 public_{it} + \theta_1 control_{it} + \mu_{it}
\]  

(5)

\[
MET_{it} = \alpha_{it} + \beta_2 public_{it} + \theta_2 control_{it} + \mu_{it}
\]  

(6)

\[
CELU_{it} = \alpha_{it} + \beta_3 public_{it} + \phi MET_{it} + \theta_3 control_{it} + \mu_{it}
\]  

(7)

In the formulas, \( CELU_{it} \) represents land use carbon emissions; \( MET_{it} \) means energy structure or technological progress; \( public_{it} \) is a dummy variable of carbon trading policy; \( control_{it} \) stands for the control variable that may affect the CELU; and \( \mu_{it} \) represents the random error term.

The steps to test the mediation effect are as follows. First, land use carbon emissions (\( CELU_{it} \)) were used to perform regression analysis on the dummy variable (\( public_{it} \)) generated by carbon trading policies (model 5). If \( \beta_1 \) is not significant, the mediation effect test is stopped. If \( \beta_1 \) is significantly negative, the carbon trading policy can reduce CELU. Then, the carbon trading policy dummy variable (\( public_{it} \)) was used to perform regression analysis on the mediating variable (\( MET_{it} \)) (model 6). If \( \beta_2 \) is not significant, the test is stopped. If \( \beta_2 \) is significant, the carbon trading policy has a significant effect on the mediating variable. Finally, land use carbon emissions (\( CELU_{it} \)) and the mediating variable (\( MET_{it} \)) were jointly used to regress the carbon trading policy dummy variable (\( public_{it} \)) (model 7). If \( \beta_2 \) and \( \phi \) are significant, the mediating variable plays an intermediate role between carbon trading policy and CELU. If the coefficient of \( \beta_3 \) is significant, the mediation effect is considered as a partial mediation effect, and on the contrary, it is a
complete mediation effect. The value of the mediation effect was calculated as $\beta_2 \times \varphi$. The ratio of the mediation effect to the total effect was calculated as $\beta_2 \times \varphi / \beta_1$. In addition, the direction of the relationship between carbon trading policy, CELU and mediating variables was determined according to the symbol of the regression coefficient.

3.2. Variable Selection

(1) Explained variable and explanatory variable. The explained variable is CELU, and the core explanatory variable is the carbon trading policy dummy variable (public). The year of 2011 when the carbon trading pilot was approved was selected as the starting point for policy evaluation. A region where carbon trading policy was implemented in 2011 and later was assigned with the value of 1, otherwise the value of 0.

Based on the above analysis and the Classification of Land Use Status (GB/T21010-2017), we classified and estimated the carbon emissions of the four main types of land use, including cultivated land, woodland, grassland and construction land. Taking carbon absorption as negative carbon emissions, CELU are the sum of carbon emissions from the four main types of land use. According to the method of IPCC, the calculation formula is $\text{CELU} = \sum \text{Ca} + \sum \text{Ce} = \sum L_i \times \delta_i + \sum \sum e_j \times \varepsilon_j \times \theta_j$, where $\text{Ca}$ is the sum of carbon emissions from cultivated land, woodland and grassland, $\delta_i$ is the carbon emission coefficient of the i-th land use type, $L_i$ is the area of the i-th land use type, and $\varepsilon_j \theta_j$ is the carbon emission coefficient of the i-th land use type. According to existing research results, the coefficient of carbon emissions was taken as $0.422 \text{t/hm}^2$ for cultivated land [4], $-0.581 \text{t/hm}^2$ for woodland [41], and $-0.022 \text{t/hm}^2$ for grassland [4]. Since human production and living activities carried by construction land consume a lot of energy, we used energy consumption carbon emissions to indirectly estimate the carbon emissions from construction land. In the above formula, $\text{Ce}$ is the carbon emissions of construction land; $e_j$ is the carbon emissions from different energy consumptions; $\varepsilon_j \theta_j$ represents the consumption of the j-th energy; $\varepsilon_j$ represents the coefficient of converting various energy sources into standard coal; $\theta_j$ is the carbon emission coefficient of the j-th energy. A total of eight main energy sources of (raw coal, coal char, crude oil, fuel oil, gasoline, kerosene, diesel and natural gas) were chosen for calculation. The coefficient for the conversion of main energy into standard coal was taken from the China Energy Statistical Yearbook, and the carbon emission coefficient was taken from the IPCC Guidelines for National Greenhouse Gas Inventories (2006) (The acronym “tc/tce” is the unit of carbon emission coefficient, which means carbon emission produced by the complete combustion of one ton of standard coal.). The specific values are listed in Table 1.

(2) Control variables and mediator variables. Based on related research results [7,18,42,43], the selected control variables are as follows. 1. GDP per capita (PGDP). GDP per capita is an important indicator for measuring the level of economic development. Economically developed regions tend to have higher carbon emissions, which also means that the region has better resources to support the reduction of carbon emissions. 2. Total population (POP). The population size varies among different regions. An area with a large population has high carbon emissions, and population growth and agglomeration will also increase energy resource consumption and carbon emissions. 3. Proportion of secondary industry (SEC), which is expressed as the proportion of secondary industry in GDP. Enterprises with high energy consumption, high pollution and high emissions are generally concen-
trated in secondary industry. Therefore, a higher proportion of secondary industry usually corresponds to greater carbon emissions. 4. Proportion of the tertiary industry (TER), which is expressed as the proportion of tertiary industry in GDP. The tertiary industry is mostly enterprises with cleaner production, and an increase in the proportion of the tertiary industry can suppress carbon emissions. 5. Energy consumption intensity (ENI), which is expressed as energy consumption per unit of GDP. The decline in fossil energy consumption will lead to a reduction of energy consumption intensity and then reduce the total carbon emissions.

The mediator variables are energy structure and technological progress. 6. Energy structure (ENE) is expressed as the proportion of coal consumption in total energy consumption. For the year 2020, coal consumption still accounted for 56.8% of China’s primary energy consumption structure, and is in a dominant position. The reduction of coal consumption will help to optimize the energy structure and promote carbon emission reduction. 7. Technological progress (TEC) is expressed as the number of domestic patent applications received in each region, which represents the amount of newly developed technologies and is an important indicator for the level of technological progress. The descriptive statistics of the main variables are presented in Table 2.

Table 2. Descriptive statistics of the main variables.

| Variable Type          | Variable Name                        | Variable Symbol | Obs | Mean   | Std. Dev. | Min   | Max   |
|------------------------|--------------------------------------|-----------------|-----|--------|-----------|-------|-------|
| Explained variable     | Land use carbon emissions CELU       |                 | 390 | 99.730 | 72.730    | 5.962 | 355.600 |
| Explanatory variables  | Carbon trading policy public         |                 | 390 | 0.108  | 0.310     | 0.000 | 1.000 |
| Control variables      | GDP per capita PGDP                  |                 | 390 | 38.690 | 23.890    | 7.835 | 118.200 |
|                        | Total population POP                 |                 | 390 | 445.000| 266.600   | 55.400 | 1072.000|
|                        | Proportion of secondary industry SEC |                 | 390 | 46.390 | 7.980     | 21.310 | 57.690 |
|                        | Proportion of tertiary industry TER  |                 | 390 | 42.690 | 8.896     | 29.670 | 77.950 |
| Mediator variables     | Energy consumption intensity ENI      |                 | 390 | 127.200| 70.520    | 42.840 | 369.200 |
|                        | The level of technological progress TEC |                 | 390 | 53.910 | 88.620    | 0.431  | 505.700 |

3.3. Data Sources

The research data comprise land use data, energy consumption data and socioeconomic data of 30 provincial administrative regions (except for Tibet, Hong Kong, Macao and Taiwan) from 2005 to 2017. As a pilot area, Shenzhen belongs to Guangdong Province, and all other areas are at the level of provincial administration. Hence, Shenzhen is merged into Guangdong Province. The data of cultivated land, woodland and grassland areas are from the Statistical Yearbook of Land and Resources of China. The data of construction land area are from the China Urban Construction Statistical Yearbook and China City Statistical Yearbook. The energy consumption data and socioeconomic data come from the new version of the National Bureau of Statistics of China database. All the socioeconomic data are based on the year of 2005 as the base period for price deflation.

The reason for using 2005 as the starting time point of research is that the Kyoto Protocol with legal constraints on carbon emissions came into effect in 2005. In addition, the target for the reduction of China’s carbon emission intensity per unit of GDP and the existing emission reduction results usually take 2005 as the base year. The pledge at the Paris Climate Conference was that carbon emission intensity in China will be reduced by
60~65% in 2030 relative to that in 2005. Besides, the year of 2017 was set as the end of the study period considering the availability of data.

4. Empirical Analysis

4.1. Changing Trend of CELU

CELU were calculated using the formula published by the IPCC. In order to preliminarily observe the changes of CELU in the pilot areas before and after the implementation of the carbon trading policy, we plotted the trends of CELU in each pilot area in Excel, and compared the average of CELU between the pilot areas and nonpilot areas (Figure 3). The changing trends of CELU are as follows. 1. The average value of CELU in the pilot areas rises first and then falls, with the peak appearing in 2011; while that in the nonpilot areas shows a consistently rising trend all the time. The gap is gradually widened, with the value of the nonpilot areas being significantly higher than that of the pilot areas. Therefore, it can be preliminarily judged that the carbon trading policy has a reduction effect on carbon emissions. 2. The peak of CELU in all pilot areas appeared in 2011, except for that in Shanghai, which occurred in 2013, indicating a lagging of the policy effect. 3. Guangdong and Beijing had the highest and lowest CELU, respectively, and only Guangdong and Hubei had CELU above the average level. 4. The overall CELU in the pilot areas showed a trend from convergence to divergence, and the gap gradually widened after 2011, indicating regional heterogeneity in the effect of carbon trading policies. 5. Some areas showed a slight decline around 2008. A possible reason is that when the global financial crisis broke out in 2008, energy consumption decreased along with the decline in the level of economic development, which in turn reduced the total carbon emissions.

![Figure 3. CELU in pilot and nonpilot areas of carbon trading.](image)

Figure 3 shows that after the implementation of the carbon trading policy in 2011, the CELU dropped significantly in the pilot areas, and the trends were no longer parallel between pilot areas and nonpilot areas. However, it was still not enough to indicate the emission reduction effect of the carbon trading policy. Hence, SCM was used to further explore whether the reduction of CELU in the pilot areas was due to the carbon trading policy and the specific effect of the policy in the following analysis.

4.2. Effect of Carbon Trading Policy on CELU

The principle of SCM is to obtain the weight of the synthetic area by minimizing the mean square error between the pilot and nonpilot areas before policy implementation, and then construct counterfactual synthetic objects for each pilot area through the weighted algorithm. Finally, an analogy between the pilot area and the corresponding counterfactual area is established to evaluate the effect of carbon trading policies. The weight of the synthetic area is calculated through the synth function of R software. Table 3 lists the
weights obtained when each pilot area was used as a synthetic object, and the forecast variables such as economy, population and energy from 2005 to 2017 were used to construct a counterfactual synthetic object. Taking Chongqing as an example, the regions with significant contributions to the synthesis of Chongqing include Fujian, Jiangxi, Hainan, Shaanxi and Qinghai. The CELU of these regions were added up according to the corresponding weights to estimate CELU in Chongqing before the implementation of the carbon trading policy.

Table 3. Weights of the virtual control group of the synthetic carbon trading pilot areas.

| Pilot Area | Synthetic Province | Weights | Synthetic Province | Weights | Synthetic Province | Weights | Synthetic Province | Weights |
|------------|-------------------|---------|-------------------|---------|-------------------|---------|-------------------|---------|
| Beijing    | Hainan            | 0.493   | Guizhou           | 0.507   |                   |         |                   |         |
| Shanghai   | Shanxi            | 0.057   | Liaoning          | 0.027   | Guizhou           | 0.916   |                   |         |
| Guangdong  | Jiangsu           | 0.553   | Shandong          | 0.045   | Sichuan           | 0.402   |                   |         |
| Hubei      | Hebei             | 0.012   | Shanxi            | 0.008   | Inner Mongolia    | 0.006   | Liaoning          | 0.014   |
|            | Jilin             | 0.006   | Heilongjiang      | 0.007   | Jiangsu           | 0.272   | Zhejiang          | 0.008   |
| Anhui      | Henan             | 0.005   | Fujian            | 0.049   | Jiangxi           | 0.003   | Shandong          | 0.006   |
|            | Guizhou           | 0.084   | Huan              | 0.026   | Guangxi           | 0.457   | Sichuan           | 0.005   |
|            |                   |         | Yunnan            | 0.007   | Shaanxi           | 0.005   | Gansu             | 0.007   |
| Tianjin    | Shanxi            | 0.115   | Fujian            | 0.290   | Guizhou           | 0.005   | Qinghai           | 0.434   |
|            |                   |         |                   |         |                   |         | Ningxia           | 0.154   |
| Chongqing  | Fujian            | 0.309   | Jiangxi           | 0.250   | Hainan            | 0.068   | Shaanxi           | 0.119   |
|            |                   |         |                   |         |                   |         | Qinghai           | 0.254   |

Note: Synthetic provinces are nonpilot areas, and the sum of combined weights of each pilot area is 1.

It is worth noting that as the political and economic center of China, Beijing is in the leading position in economy, energy structure and technology. However, only two provinces can be used to synthesize Beijing, namely Hainan and Guizhou, with the weights of 0.493 and 0.507, respectively, and they are not economically developed provinces, which may affect the estimation of the real policy effects in Beijing.

4.2.1. Evaluation on the Overall Effect of Carbon Trading Policy

When evaluating the overall effect of carbon trading policy, the average value of each variable in the pilot area was selected as the experimental group of the SCM, and the value of each variable in the nonpilot area was used as the synthetic control group. The estimation process was performed through the Synth package of the R software, and the fitting graph and the effect graph were drawn through the functions path.plot and gaps.plot. Figure 4a presents the evolution path of the average CELU of the six carbon trading pilot areas and the synthetic pilot areas from 2005 to 2017. The vertical dotted line indicates the year of the implementation of the carbon trading policy (2011). The left side of the dotted line shows the fitting between the pilot and synthetic pilot areas before the policy implementation, and the right side of the dotted line is the CELU trends of the pilot and the synthetic pilot areas after the policy implementation. It can be seen from the figure that before 2011, the CELU in the pilot area had a good fitting with that in the synthetic pilot area. The CELU of the pilot areas began to decrease after 2011, while that of the synthetic pilot areas still showed a rising trend, and the actual CELU in the pilot area gradually became lower than that in the synthetic pilot areas, and the gap increased over time.
In view of the good fitting between the pilot and synthetic pilot areas before the policy implementation, the difference in CELU between them after the policy implementation was used to evaluate the effect of the carbon trading policy. A greater difference indicates a more significant effect of carbon trading policy implementation.

Figure 4b shows that before the implementation of the policy, the difference between the pilot and synthetic pilot areas fluctuated around 0, while after the policy implementation in 2011, it was below 0 and continuously declined. Although there may be some kind of rebound of the downward trend, it generally shows that the carbon trading policy had a significant reduction effect on the average CELU of carbon trading pilot areas by at least 4 million tons. Hence, Hypothesis 1 is verified.

4.2.2. Evaluation on the Effect of Carbon Trading Policies in Each Carbon Trading Pilo Area

On the basis of overall effect evaluation, we conducted quasi-natural experiments on the construction of synthetic control areas in each pilot area to analyze regional differences in the effect of carbon trading policies on CELU. The operation of SCM in the R software is the same as the estimation process on the overall effect. Figures 5 and 6 respectively report the fitting effect and policy effect difference of the six pilot areas and their synthetic control areas.
Actual Beijing and synthetic Beijing had a better fitting between 2006 and 2010. Since 2010, the CELU of actual Beijing began to decline, which occurred one year ahead of the implementation of the carbon trading policy. In the previous analysis, only two provinces could synthesize Beijing, which may affect the estimation of the real effect of the policy. However, in the early stage of the SCM, based on the correlation and convergence characteristics of the predictor variables, the iterative method was used to exclude the influence of the control group setting on the composite results, which can ensure good reliability and explanatory power. Therefore, the possibility that the decline of Beijing’s CELU was caused by the carbon trading policy cannot be ruled out. As a national political and economic center, Beijing is more sensitive to policy effects. The significant reduction in CELU in advance is likely due to the early response to the carbon trading policy. Figure 6 shows that the CELU in the Beijing area had decreased significantly. In 2011, the difference between actual Beijing and synthetic Beijing was 8.09 million tons. In 2017, the CELU of actual Beijing fell by 5.26 million tons relative to that in 2011, with an average annual decrease of 3.16%.

![Graphs showing fitting between actual and synthetic areas](image)

**Figure 6.** Policy effect in each pilot area.

The fitting between actual Tianjin and synthetic Tianjin was good before 2011, and both showed an upward trend in CELU without significant difference between the two. The CELU in synthetic Tianjin still showed a slowly increasing trend after 2011, and that in actual Tianjin began to slowly decline, with gradual increases in the differences between the two. The CELU of actual Tianjin was lower than that of synthetic Tianjin, indicating that the carbon trading policy had effectively promoted the reduction of CELU in Tianjin. Compared with that in other regions, the reduction effect of the policy in Tianjin was relatively weaker. In 2011, the difference between actual Tianjin and synthetic Tianjin was 230,000 tons. In 2017, the CELU of actual Tianjin was 4.3 million tons lower than that in 2011, with an average annual decrease of about 0.3%. The possible reasons are that the industrial system in Tianjin is relatively mature; the total carbon emissions are relatively low; and the space for emission reduction is limited.

Actual Shanghai and synthetic Shanghai had a good fitting before 2011. Thereafter, the CELU of synthetic Shanghai maintained a fast growing trend, while that of actual Shanghai began to decline, and the two began to show significant differences from around 2011. The difference between actual Shanghai and synthetic Shanghai in 2011 was 3.06 million tons. The CELU of actual Shanghai in 2017 was 1.01 million tons lower compared with that in
2011, with an average annual decrease of 0.31%. Hence, the carbon trading policy also had a significant effect on the CELU of Shanghai.

Actual Hubei and synthetic Hubei also showed a good fitting before 2011, and had the highest degree of fitting among all pilot areas, which may be ascribed to the large number of regions (a total of 21 regions) to synthesize Hubei in the previous analysis. The CELU of actual Hubei began to decline rapidly after 2011 to be lower than that of the synthetic Hubei, and showed steady decline after 2013, indicating that the implementation of the carbon trading policy played a significant and continuous role in reducing CELU in Hubei. Due to the large base of carbon emissions, the CELU in Hubei was reduced by 13.57 million tons in 2017 compared with that in 2011, with an average annual decrease of 0.38%. In 2011, the difference in CELU between actual Hubei and synthetic Hubei was small (only 150,000 tons).

Actual Guangdong and synthetic Guangdong showed a good fitting before 2011. The CELU first showed a rapid increase before 2011, followed by an extremely slow decline after 2011 with some kind of rebound. Actual Guangdong and synthetic Guangdong showed differences after 2011. The difference in CELU between actual Guangdong and synthetic Guangdong in 2011 was 400,000 tons. In actual Guangdong, the CELU decreased by 3.54 million tons in 2015 but increased by 10.61 million tons in 2017 compared with that in 2011. However, it is worth noting that Guangdong has the highest carbon emission trading volume and trading value among all pilot areas. The reasons may be the largest base of carbon emissions and an extremely complex mechanism of carbon trading policy in Guangdong, which involves economy, energy land and environment; besides, the policy implementation time is relatively short, which would result in a limited and short-term effect on CELU in Guangdong. The rebound of the policy effect may be related to the rebound of energy and the recovery of economic development. Therefore, the effect of carbon trading policy on CELU in Guangdong remains to be observed for a longer period of time.

The changing trend of actual Chongqing and synthetic Chongqing was similar to that of Hubei, with a certain degree of high fitting before 2011. The CELU in Chongqing declined rapidly and then gradually stabilized after 2011. The CELU of actual Chongqing was lower than that of synthetic Chongqing, and the gap showed a tendency of expansion. In 2011, the difference in CELU between synthetic Chongqing and actual Chongqing was 280,000 tons. In 2017, the CELU of actual Chongqing had decreased by 4.28 million tons compared with that in 2011, with an average annual decrease of 0.95%. These results indicate that the carbon trading policy had a significant impact on the CELU in Chongqing.

In summary, the results of the empirical study reveal that the carbon trading policy has had a significant reduction effect on the overall CELU of the pilot areas, and the effect was heterogeneous among different pilot areas. The policy effect occurred the earliest in Beijing, while was weaker in Tianjin, showed some kind of rebounds in Guangdong in 2016, and continuously became better in Shanghai, Hubei and Chongqing.

4.3. Validity Test

4.3.1. Ranking Test with Hypothetical Pilot Areas

A ranking test method similar to the rank test proposed by Abadie et al. [27] was used to test whether the carbon trading policy reduces the CELU. We randomly selected one from 24 nonpilot areas as a “hypothetical pilot area”, assuming that it had implemented the carbon trading policy in 2011. Following the principle of minimum mean square error, the weights were calculated and counterfactual synthetic objects were constructed, and the difference in policy effect between the real pilot area and the hypothetical pilot area was compared. If the policy effect of the real pilot area is greater than that of the hypothetical pilot area, the carbon trading policy is considered to have a sound reduction effect on CELU. The hypothetical pilot areas were selected by referring to Tan et al. [44]. Taking Chongqing as an example, the areas with a root mean square prediction errors (RMSPE) greater than twice that of the pilot area and the areas with poor early fitting conditions were excluded.
(a poor fitting condition cannot determine whether the emission reduction effect is due to carbon trading policies). Secondly, all regions with contributions and 1–3 regions with no contribution were selected for synthesizing the real pilot area based on the weighted results. Finally, Jiangxi, Fujian, Hainan, Heilongjiang, Hunan and Gansu were selected as the hypothetical pilots for the ranking test (Figure 7).

An ideal value of CELU should be as small as possible. Thus, the difference between the experimental group and the synthetic control group is preferably a negative number. In Figure 7, the real pilot area (solid black line) and hypothetical pilot area (solid gray line) showed convergence in the beginning year, and then gradually diverged after the implementation of the policy. Compared with that of the hypothetical pilot area, the gap in CELU in the real pilot area was below zero after 2011 and showed a continuous decline, and the degree of declining was significantly lower than that in the hypothetical pilot area. Therefore, we believe that it is a small probability event that the CELU reduction of the hypothetical pilot area is attributed to the policy, and the emission reduction effect of the carbon trading policy in the pilot area is robust.

### 4.3.2. Placebo Test Based on Time

An examination of the effect of carbon trading policies on the reduction of CELU in pilot areas can be carried out based on differences in time. By setting the policy implementation time forward or backward a few years as the virtual time point of the policy, if the policy effect is not good at the virtual time point, the effect of carbon trading policies is robust. Still taking Chongqing as an example, assuming that the carbon trading policy was implemented in 2009, SCM was used to estimate the emission reduction effect in the pilot area again. A time-based placebo testing graph was drawn for pilot and synthetic pilot areas. A comparison of Figures 5f and 8 reveals that whether the carbon trading policy was implemented in 2009 or 2011, the synthetic value before the policy implementation is very close to the real value, suggesting that the effect is not significant assuming that the carbon trading policy was implemented in 2009, and the effect of the carbon trading policy in 2011 was robust.
When using the same method to test the validity of other pilot areas besides Chongqing, it was found that except for the unsound ranking test of Guangdong and the unsound placebo test based on the time of Beijing, the effects of carbon trading policy are all robust in other areas. The full figure of results is included in Appendix A.

4.4. Impact Mechanism of Carbon Trading Policies on CELU

The previous analysis has indicated that the carbon trading policy had a significant effect on the CELU in the pilot areas. Then, we used the mediation effect model to explore the impact mechanism. Since the regression coefficient of the mediation effect model represents the effect value, we standardized all the variable data used in previous analyses, and then used Hausmann’s test to determine the applicability of fixed effects and random effects to the regression equation. The results of Hausmann’s test were significant, rejecting the null hypothesis that random effect models were better than fixed effect models. Therefore, fixed effects were used in all models to test the mediation effect. The Stata software was used to run the mediation effect model (Formulas (5)–(7)) and output the results (Table 4). Model 1 was a baseline regression scenario, and the results show that carbon trading policies have a significant negative effect on CELU, which is consistent with the results of the previous SCM analysis. Specifically, the carbon trading policy reduced the CELU in the pilot area by 0.137, which again verified Hypothesis 1.

Table 4. Test results of mediation effect.

| Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|-----------|---------|---------|---------|---------|---------|---------|
| CELU      | −0.137 *** | −0.072 *** | −0.105 *** | −0.118 *** | −0.135 *** | −0.096 *** |
| ENE       | (−7.580) | (0.0235) | (0.0148) | (0.0358) | (0.0184) | (−6.385) |
| CELU      | 0.287 *** | 0.097 **  | 0.243 *** | 0.731 *** | 0.276 *** | 0.192 *** |
| TEC       | (7.895)  | (0.0473) | (0.0296) | (0.0719) | (0.0414) | (5.710)  |
| POP       | −1.554 *** | −0.458   | 1.762 *** | 3.222 *** | 1.505 *** | 1.549 *** |
| SEC       | (5.673)  | (0.356)  | (0.222)  | (0.541)  | (0.288)  | (6.748)  |
| ENI       | 0.010    | −0.110   | 0.060    | −0.146   | 0.012    | 0.072    |
| (0.153)   | (0.085)  | (0.053)  | (0.128)  | (0.065)  | (1.378)  |
| TER       | −0.093   | −0.233 ** | 0.013    | −0.008   | −0.093   | 0.018    |
| (−3.814)  | (0.064)  | (0.040)  | (0.098)  | (0.052)  | (−6.025) |
| ENE       | −0.093   | −0.233 ** | 0.013    | −0.008   | −0.093   | 0.018    |
| (−1.124)  | (0.107)  | (0.067)  | (0.163)  | (0.083)  | (0.266)  |
| TEC       | 0.453 *** | 0.471 *** | (0.033)  | (14.210) |
| R²        | 0.015    | 0.069 *** | (0.027)  | (3.142)  |
| Sobel’s test p value | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

Note: The t statistics are in parentheses; ** and *** represent that the results are significant at the statistical levels of 5% and 1%, respectively.

In Table 4, Model 1, Model 2 and Model 3 tested the mechanism for the intermediate effect of energy structure. The policy coefficient in Model 2 was significantly negative, indicating that the carbon trading policy promoted the optimization of energy consumption structure in the pilot area by reducing main energy (coal) consumption. Model 3 added the carbon trading and energy structure variables at the same time, resulting in a regression coefficient −0.105. Compared with the regression coefficient of −0.137 in Model 1, the absolute value dropped by 0.032. The estimated value of the coefficient of energy structure was still significant with a positive sign. The p value of the Sobel test was significant. Therefore, the carbon trading policy is verified to have a mediating effect on CELU through optimizing the energy structure, which accounts for 30.434% by the Sobel test, which verified Hypothesis 2.
Model 4 and Model 5 examined the mechanism for the intermediate effect of technological progress in CELU reduction by the carbon trading policy. In Model 4, the estimated coefficient of carbon trading policy on technological progress was significantly negative, suggesting that during the study period, the carbon trading policy did not promote the technological progress. In Model 5, after adding both the carbon trading pilot policy and technological progress variables, the regression coefficient of carbon trading policy was still significantly negative. Compared with the coefficient in Model 1, the absolute value dropped by 0.002. However, the coefficient of technological progress was not significant, and the P value of the Sobel test was also not significant. Therefore, from the survey samples and observation period of this study, the carbon trading policy seemed to restrict technological progress to some extent. Moreover, the impact of the carbon trading policy on CELU was not related to the intermediate effect of technological progress. Hence, Hypothesis 3 has not been verified.

Model 6 incorporated the energy structure, technological progress and other control variables into the regression model. The results showed that the coefficient of the carbon trading policy was still significantly negative; that of the energy structure was still significantly positive. Interestingly, the coefficient of technological progress became significantly positive, but with a low value. Compared with that of Model 1 ($-0.137$), the estimated coefficient of carbon trading policy ($-0.096$) decreased by 0.041 in absolute value. As a whole, it can be concluded that carbon trading policies reduced CELU mainly through the optimization of the energy structure. However, the Porter effect was not observed for technological progress during the study period. In Model 6, the regression coefficient of the carbon trading policy was still significantly negative, indicating that this paper may have only identified a few impact mechanisms of carbon trading policies to reduce CELU, and other impact mechanisms need to be further explored.

5. Conclusions and Policy Implications

5.1. Conclusions

The reduction of CELU is of great significance for achieving carbon neutrality and green sustainable development. Carbon trading policy is an effective tool for reducing carbon emissions. Previous studies of the emission reduction effects of carbon trading policies focused mostly on the reduction of carbon source emissions, and there is a lack of research from the comprehensive perspective of carbon sources and carbon sinks. This study attempted to comprehensively analyze the effects of carbon trading policies from the perspective of CELU that involves both carbon sources and carbon sink. This study first builds a theoretical analysis framework for carbon trading and CELU, and analyzes the effect mechanism of carbon trading policies from a comprehensive perspective of emissions from carbon source land and absorption in carbon sink land. Then, SCM and the mediation effect model were employed to empirically study the reduction effect and mechanism of carbon trading policies on CELU by using China’s current carbon trading pilot areas as a quasi-natural experiment and based on the provincial CELU data from 2005 to 2017. The main conclusions of the study are as follows. (1) Carbon trading policies can help to significantly reduce CELU in pilot areas, which has been confirmed by the overall effect evaluation of the SCM and the benchmark regression model results of the mediating effect. (2) The carbon emission reduction effects of carbon trading policies on CELU are of regional heterogeneity. The SCM results show that there are differences in the policy effect between different pilot areas: the effect occurred earlier in Beijing, was significant with good sustainability in Hubei, Chongqing and Shanghai, relatively weak in Tianjin, and significant in Guangdong after the initial implementation but rebounded in 2016. (3) Carbon trading policies reduce CELU through the intermediate effect of energy structure, while the intermediate effect of technology progress is not significant. The test results of the mediation effect model show that carbon trading policies can help to optimize the coal-dominant energy consumption structure to promote the reduction of CELU with a contribution rate of 30.433%. The significant negative impact of carbon trading policies on
5.2. Policy Implications

Based on the above conclusions, the following policy implications can be inferred.  
(1) It is feasible to carry out research on carbon trading and carbon offset from a comprehensive perspective of CELU. The carbon trading market can effectively connect land use, economic regulation and optimal allocation of environmental resources. In the future, the carbon emission trading system can control socio-economic carbon emissions and increase natural ecological carbon absorption from a comprehensive perspective of low-carbon use and land management to maximize the potential of carbon emission reduction.  
(2) Regional heterogeneity should be taken into account in the national promotion of the carbon emission trading system. In view of the uneven development of various regions, differences in regional resource endowments, energy structure, industrial systems and land use structure, the degrees of carbon emissions and carbon absorption are also different. Carbon trading derivative products developed according to local conditions will activate the regional carbon trading market.  
(3) Optimization of the energy structure is still of top priority in carbon emission reduction. Increasing the proportion of clean energy and renewable energy and reducing the proportion of high-emission energy sources, such as coal and oil, are the main pathways to optimize the energy structure. Carbon trading can further restrict the carbon emission quotas of high-emission enterprises, encourage carbon sink trading, raise carbon prices relying on market mechanisms, and achieve continuous improvement of the energy structure.  
(4) Although technological progress did not seem to realize the Porter effect during the study period, its emission reduction effect should not be negated. Studies have shown that technological innovation can promote green development [14]. Hence, in the future, the research and development of low-carbon production technologies should be encouraged, so as to promote the application of low-carbon technologies in agricultural production, industrial production and other fields and realize the effect of “innovation compensation”.

Our research has several limitations, which may also be the future directions for our follow-up research. First, CELU only considers carbon equivalence, and does not include carbon emissions from land use changes. Along with the establishment of the national carbon trading market, more and more departments are participating in carbon trading projects. In the future, the research can be extended to the dynamic impact of carbon trading policies on land use changes. Second, the evaluation of CELU only involves four main types of land use, and does not include other land types. Hence, more methods could be developed so as to incorporate other types of land use in the evaluation of the effect of carbon emission trading policies. Additionally, the mechanisms for the effect of China’s carbon trading market are very complicated, and there are many differences in the historical emissions of companies, penalty mechanisms, offset ratios, and the evaluation of forestry carbon sink based on tree species and area. This study only evaluates the emission reduction effect of the carbon trading policy as a whole, while ignores these different factors. Therefore, in future research, the internal differences in carbon trading policies may be taken into account.

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Appendix A

(a) Beijing
(b) Tianjin
(c) Shanghai
(d) Hubei
(e) Guangdong

Figure A1. Validity test: ranking test.
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