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Domestic Regional Synergy in Achieving National Climate Goals—The Role of Comparative Advantage in Emission Reduction

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Abstract: Domestic regional synergistic emission reduction is important in achieving national climate goals. This study constructed a game theory-based model for regional synergistic emission reduction, modified the Basic Climate Game using the exact-hat algebra method, and expanded the game model using a general spatial equilibrium model to incorporate cross-regional economic impacts generated by emission reduction actions through factors and product flows. The formation of regional comparative advantages in emission reductions and their impact on synergistic emission reductions were revealed through regional characteristics such as emission elasticity, sectoral structure, regional trade shares, and green total factor productivity. A form of synergy was then proposed that utilizes the comparative advantages of different regions, allowing for synergistic emission reductions across different income regions and engagement with regions that are still at the carbon-peaking stage in cooperation. Moreover, the model was created to be as close to the economic reality as possible to provide a trade, industry, and economic growth policy that complements emission-reduction policies.

Keywords: regional synergy; carbon neutrality; comparative advantage; emission reduction; regional economic growth; regional trade; scenario analysis

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1. Introduction

Domestic regional synergy is an effective mechanism for achieving national emission reduction goals (in this paper, "emissions" specifically refers to CO_2 emissions) [1]. An imbalance between regional economic development and emission characteristics leads to varying tradeoffs between mitigating climate change and promoting economic growth in different regions [2]. This requires a reasonable emission reduction path and policy design to avoid economic development constraints resulting from achieving climate goals [3]. Thus, to achieve national emission reduction goals, the interests of different regions must be coordinated, and appropriate regional cooperation paths must be identified to achieve the dual goals of economic growth and emission reduction [4]. Regions with different levels of economic development and resource endowments should have different timelines for achieving climate goals. Leveraging the unique advantages of each region based on their development for regional synergistic emission reduction is necessary. The formation of these unique advantages does not solely depend on geographical proximity but also on the economic interdependence between regions, including factors such as technological level [5], industrial structures [6], carbon emission characteristics, and regional trade relationships [7]. These factors cannot be ignored in regional synergistic emission reduction.

Similar to international cooperation on climate change, regional synergy within a country to reduce emissions faces issues of public good attributes of climate change and trade-offs between emission reduction benefits and costs. In national climate governance, local government actions determine the achievement of climate change targets [8]. Due to the short-term economic losses caused by climate policies [9], non-exclusivity of emission reduction benefits, and emission reduction costs borne by regions, free-riding is widespread in climate change, creating resistance to unilateral emission reduction actions by regions [10]. Climate change is an environmental and developmental problem and different stages of regional development result in different emission reduction costs. Independent emission-reduction actions lead to higher emission reduction costs for regions with lower emission-reduction potential. Therefore, regional synergy is required to reduce overall emission reduction costs [11]. Cooperation not only achieves emission reduction goals but also generates economic benefits, mainly reflected in the promotion of economic growth. Some studies have quantified the environmental benefits and gross domestic product (GDP) impacts of cooperative actions in the Paris Agreement [12,13]. In this process, regional spillover effects caused by trade cannot be ignored [14]. Under the flow of factors and products between regions, emission reduction costs, and economic losses and benefits caused by emission reduction constitute a comparative advantage of emission reduction in regions. Policies aimed at regional trade should be the primary method of promoting regional climate cooperation [15–17].

Regional synergistic emission reduction in a country exhibits unique characteristics that differ from those of international climate cooperation, as the actions of different regions can be managed by the national government [18], which faces less resistance than international cooperation. Furthermore, under a tighter flow of factors and products, regional cooperation on carbon reduction is more vulnerable to the influence of inter-regional trade. The current resource mismatch in regional factors and product markets limits the achievement of climate goals in some countries [19]. Therefore, regional synergy is needed to optimize the flow of factors and products among regions and promote emission reduction. Local governments are concerned with short-term economic growth and tend to develop high-carbon emission sectors with high output values [20]. Therefore, regional synergistic emission reduction needs to consider the differentiated climate goal realization paths and coordinate policies, industries, technologies, energy, and ecology among regions.

Game theory and its modeling methods could explain regional cooperation issues related to climate change [21,22]. DeCanio and Fremstad [23] analyzed 25 basic game theory models for climate cooperation and provided a theoretical foundation for analyzing regional cooperation issues related to climate change. Subsequent research has extended the formalism of models, including incorporating irreversible environmental degradation into participant payoffs [24], using N-player bargaining games based on learning dynamics to test international climate agreements [25], adding climate disaster risk to bargaining games to analyze the possibility of cooperation [26], constructing game models with foresight alliances [27], allowing multi-round negotiations and using dynamic games to explain the formation of large coalitions [28], proposing a dynamic differential game to model the transboundary pollution control between two asymmetric regions [29], and incorporating international leadership, domestic energy security, domestic economy, and domestic environment in games to explain participants' strategic choices [30]. Although these model forms are diverse, the core problem is the trade-off between regional development and emission reduction. The most intuitive model is the Basic Climate Game, which defines the payoffs of regions in climate cooperation as the benefits and harms of carbon emissions [31]. Although these game models provide a refined description of the theoretical mechanism of regional climate cooperation, their strict assumptions limit their explanatory power, whereas overly simple models are unable to provide useful policy recommendations [32]. In particular, when analyzing synergistic emission reduction among various regions within a country, cross-regional flows of goods and factors must be considered. Some studies have introduced trade models and new economic geography theories into game models to examine the relationships between carbon tariffs, trade barriers, and climate cooperation alliances [33–35]. These studies simulate and analyze cooperative behavior using assumed parameters, which cannot provide accurate characterizations of cooperative behavior based on real data; however, they provide support for studying regional synergistic emission reduction from a trade perspective.

This study aimed to make several contributions to existing research. First, current theories on climate change cooperation mainly analyze cooperative emission reduction behaviors between countries, whereas research on regional synergistic emission reduction under the guidance and coordination of the state is scarce. Regional synergistic emission reduction should consider the process of achieving climate goals through regionally graded and orderly measures. This requires a new explanation of the relationship between the local and global optima in regional synergistic emission reduction. This study constructed a game model for regional synergistic emission reduction and used the exact-hat algebra method to construct the payoff function of game subjects. This method appropriately described the changes in emissions and their growth rates while achieving climate change targets and explained the differences in emission reduction actions between regions in different stages of development.

Second, although some studies on regional climate cooperation have considered trade issues, considerations of cross-regional economic impacts of factors and product flows of regional emission reduction are scarce. This study drew on the payoff function construction method of the Basic Climate Game proposed by Molina et al. [31] and used changes in economic growth and damage caused by emission reduction to characterize regional payoffs. The general spatial equilibrium model was incorporated into the game model to analyze the changes in regional economic growth caused by emission reduction, reveal the formation of regional comparative advantages in emission reduction, and investigate the impact of these advantages on regional synergistic emission reduction.

Third, achieving regional synergy requires the formation of multifaceted policy efforts; however, current simplified game models do not effectively support policy combinations. The general spatial equilibrium model is an extension of that used by Caliendo et al. [36], which uses conclusions derived from data on carbon emission elasticity [37,38], sectoral structures, trade shares, trade costs, and green total factor productivity (TFP) to support policies.

This study aimed to answer the following questions:

(1) What type of regional synergistic emission reduction meets the phased climate-change mitigation targets for different regions within a country?
(2) Considering the cross-regional impacts of emission reduction actions caused by regional economic interdependence, how can the comparative advantages of emission reduction among regions be utilized to achieve effective regional synergistic emission reduction while maintaining economic growth?
(3) What factors influence the formation of comparative advantages in emission reduction among regions? What insights do these factors provide for policies that promote synergistic regional emission reduction?

2. Model Construction

2.1. Assumptions of the Regional Synergistic Emission Reduction Game Model

2.1.1. Strategy and Payoff

Based on the Basic Climate Game, a regional synergistic emission reduction game model was constructed, and trade relations between regions were incorporated as factors affecting regional strategy based on a general spatial equilibrium model. Assuming that there are N regions, as is common in regional cooperative game models, the focus is on the strategy between two regions, denoted as Regions 1 and 2. The emission level of each region is denoted as e_n, and negative net emissions are allowed for each region (e.g., carbon capture from the atmosphere) [39].

Each region's strategy is a Synergistic Action (SA) or Unilateral Action (UA). Molina et al. [31] found that the difference in payoffs for different strategies depended on regional emissions. The Basic Climate Game sets the total payoff for region n as $G_n(e_n) - D_n(e)$, where $G_n(e_n)$ and $D_n(e)$ represent the benefits and damages of emissions, respectively. The benefits of emissions for a region come primarily from economic growth driven by emissions, which is a function of regional emissions, e_n. However, the damage of regional emissions is a function of the total emissions, e, which represents the damages caused by climate change resulting from total emissions. This study improved this assumption by introducing the exact-hat algebra method, which expresses changes in x after an economic and environmental change as $\hat{x} = x'/x$, where x' denotes the new value of x after the change. We assumed that the regional payoff function, denoted as Π_n, is the difference between the changes in GDP and damages caused by emissions. In other words, when a region chooses a strategy, it focuses on the impact of emission-reduction actions on economic growth and the reduction in damage caused by emissions. The payoff function is expressed as:

$$\Pi_n = \widehat{G}_n - \widehat{D}_n \quad (1)$$

Improving the model using the exact-hat algebra method has four advantages. First, it can better reflect the actual emission reduction behavior of regions in response to climate change. The variable $\hat{e}$ can describe changes in the growth rate and quantity of emissions and accurately represent the stage of regional emission reduction. The goals of emission reduction in the second half of this century under the Paris Agreement for all countries are a long-term process that considers a decrease in total emissions and emission growth rate; a typical case is China's carbon peaking and carbon-neutral targets. Second, this method can eliminate the numerical differences between G_n and D_n and effectively reflect the tradeoff between economic growth and climate change mitigation in a region. The calculation methods and units of measurement for G_n and D_n differ. A large difference between the two can cause an excessive emphasis or underestimation of their impact. Third, this method is more appropriate for GDP change caused by emission changes in the general spatial equilibrium model, highlighting the role of key variables more accurately by simplifying the model. Fourth, considering only the change in damage caused by emissions, $\widehat{D}_n$, it ensures a more concise model analysis, relaxing the research assumptions regarding damage caused by emissions. Calculating damage caused by emissions is complex. General damage includes negative economic effects represented by GDP loss and the loss of the ecological environment and social welfare.

2.1.2. Comparative Advantage in Regional Synergistic Emission Reduction

The overall change in emissions in the two regions is expressed as $\hat{e}_{1+2} = (e_1/e)\hat{e}_1 + (e_2/e)\hat{e}_2$. The relationships between regional and aggregate emissions indicate that, in the process of achieving the overall goal of reducing emissions or decelerating emissions growth, regional emissions and trends may be in different stages. Therefore, allowing for regional differences in emission reduction efforts is key to achieving overall climate change targets through regional synergy.

We assume that when two regions achieve synergy in mitigating climate change, changes in total emission reduction, denoted as ($\hat{e}_{1+2}$), are lower than the emission reduction resulting from each region acting unilaterally. This can be divided into two scenarios. If $\hat{e}_{1+2}$ decreases, $\hat{e}_1$ and $\hat{e}_2$ may both decrease (Scenario 1), or $\hat{e}_1$ may decrease while $\hat{e}_2$ increase (Scenario 2). Scenario 1 is the basic form of regional cooperation for emission reduction in previous studies, where Regions 1 and 2 are required to reduce $\hat{e}_n$ in synergy. Conversely, Scenario 2 considers the comparative advantage of regional synergistic emission reduction. In regional synergistic emission reduction, if Region 2 does not have an absolute advantage in emission reduction over Region 1, increasing $\hat{e}_2$ in Region 2 provides both regions better overall payoffs than decreasing $\hat{e}_2$. This increase in total payoffs is due to the higher overall economic growth in both regions, caused by the increase in $\hat{e}_2$, including regional economic growth and cross-regional economic impact through trade. Furthermore, a decrease in $\hat{e}_1$ in Region 1 reduces damage caused by emissions more than an increase in $\hat{e}_1$, providing both regions with better overall payoffs.

2.2. Impact of Emission Reduction on Economic Growth in Payoff

2.2.1. Emissions and Economic Growth in General Spatial Equilibrium Models

According to the Environmental Kuznets Curve [40], an inverted U-shaped relationship between emissions and economic growth determines the complexity of connections with government payoff. Changes in emissions and economic growth depend on the level of economic development in the region. However, the flow of factors and products between regions creates regional spillover effects on the impact of emission changes on economic growth. A general spatial equilibrium model is an effective method to address this issue.

Following the methods proposed by Duan et al. [37] and Shapiro and Walker [38] to incorporate emissions into a trade equilibrium model, the government controls the emissions of sector j in region n, denoted as e_n^j, through emission reduction policies, denoted as t_n (including environmental taxes and emission penalties), where $e_n = \sum_{j=1}^{J} e_n^j$. Changes in regional emissions, denoted as $\hat{e}_n$, are determined by changes in the intensity of environmental regulations, denoted as $\hat{t}_n$, where an increase in $\hat{t}_n$ represents an increase in the level of emission reduction efforts, resulting in a decrease in emissions. Changes in the intensity of regional environmental regulations may affect the economic growth of another region due to regional trade. This further specifies government action compared with the Basic Climate Game, making it more realistic. Let α_n^j be the emission elasticity. The relationship between emissions and environmental regulation is given by

$$e_n^j = \frac{\alpha_n^j}{t_n} Y_n^j \tag{2}$$

In contrast to general equilibrium models in international trade, examining regional economic relations in a country requires consideration of labor mobility and transfer payments. Caliendo et al. [36] made pioneering efforts in this field, and this study extended their model.

2.2.2. Production of Intermediate Goods with Emissions as a Byproduct

Following the approach of Copeland and Taylor [41], we introduced emissions as a byproduct of the production function of intermediate goods. The potential output function is expressed as:

$$y_n^j\left(z_n^j\right) = z_n^j \left[T_n^j \left[h_n^j\left(z_n^j\right)\right]^{\beta_n} \left[l_n^j\left(z_n^j\right)\right]^{(1-\beta_n)} \right]^{\gamma_n^j} \prod_{k=1}^{J} \left[M_n^{jk}\left(z_n^j\right)\right]^{\gamma_n^{jk}} \tag{3}$$

where the productivity level, z_n^j, follows the Fréchet distribution, T_n^j is the fundamental productivity, $h_n^j(\cdot)$ and $l_n^j(\cdot)$ denote the demand for land and labor, respectively, $M_n^{jk}(\cdot)$ is the demand for final material inputs by firms in sector j from sector k, $\gamma_n^{jk} \geq 0$ is the share of sector j goods spent on materials from sector k, and $\gamma_n^j \geq 0$ is the share of value added to the gross output. We assume that the production function has constant returns to scale, namely that $\gamma_n^j + \sum_{j=1}^{J} \gamma_n^{jk} = 1$. Based on potential output, a producer can allocate a fraction ϵ_n^j of $y_n^j\left(z_n^j\right)$ to emission-reduction activities to reduce payments. The remaining $1 - \epsilon_n^j$ fraction is the net output. We denote the net production after abatement investment using $q_n^j\left(z_n^j\right) = \left(1 - \epsilon_n^j\right) y_n^j\left(z_n^j\right)$. We assume that the emissions are also affected by z_n^j. Advanced production technologies can improve resource utilization efficiency, leading to positive externalities in emission reduction. Research on the technology list for China's response to climate change supports this assumption [42]. Under this assumption, emissions from output at different technological levels differ. Let α_n^j denote the emission elasticity of sector j in region n. Then, the relationship between emissions and potential output can be expressed as:

$$e_n^j\left(z_n^j\right)=\left(\frac{1}{z_n^j}\right)\left(1-\epsilon_n^j\right)^{\frac{1}{\alpha_n^j}}y_n^j\left(z_n^j\right) \tag{4}$$

The net production of intermediate goods is obtained, where z_n^j includes the technical level of potential output ${z_n^j}^{1-\alpha_n^j}$ and the technical level of emission reduction ${z_n^j}^{\alpha_n^j}$:

$$q_n^j\left(z_n^j\right)=z_n^j\left(\left[T_n^j\left[h_n^j\left(z_n^j\right)\right]^{\beta_n}\left[l_n^j\left(z_n^j\right)\right]^{(1-\beta_n)}\right]^{\gamma_n^j}\prod_{k=1}^J\left[M_n^{jk}\left(z_n^j\right)\right]^{\gamma_n^{jk}}\right)^{1-\alpha_n^j}\left[e_n^j\left(z_n^j\right)\right]^{\alpha_n^j} \tag{5}$$

2.2.3. Prices of Final Goods, Trade Share, and Transfer Payment

We use x_n^j to denote the cost of the input bundle needed to produce intermediate good varieties. Let $B_{1,n}^j=\left(\alpha_n^j\right)^{-\alpha_n^j}\left(1-\alpha_n^j\right)^{\alpha_n^j-1}$, $B_{2,n}^j=\left[\gamma_n^j(1-\beta_n)^{(1-\beta_n)}\beta_n{}^{\beta_n}\right]^{-\gamma_n^j}\prod_{k=1}^J\left(\gamma_n^{jk}\right)^{-\gamma_n^{jk}}$. Then:

$$x_n^j=B_{1,n}^j(t_n)^{\alpha_n^j}\left(\varsigma_n^j\right)^{1-\alpha_n^j} \tag{6}$$

$$\varsigma_n^j=B_{2,n}^j\left(r_n^{\beta_n}w_n^{1-\beta_n}\right)^{\gamma_n^j}\prod_{k=1}^J\left(P_n^k\right)^{\gamma_n^{jk}}$$

where κ_{ni}^j is the transport cost of intermediate goods. Let $B_3^j=\left[\Gamma\left(1+\frac{1-\eta_n^j}{\theta^j}\right)\right]^{\frac{1}{1-\eta_n^j}}$. We define P_n^j as the unit price of sectoral composite goods:

$$P_n^j=B_3^j\left[\sum_{i=1}^N\left(x_i^j\kappa_{ni}^j\right)^{-\theta^j}\left(T_i^j\right)^{(1-\alpha_i^j)\gamma_i^j\theta^j}\right]^{-\frac{1}{\theta^j}} \tag{7}$$

Let π_{ni}^j denote the share of region n's expenditure on sector j composite goods purchased from region i.:

$$\pi_{ni}^j=\frac{\left(x_i^j\kappa_{ni}^j\right)^{-\theta^j}{T_i^j}^{(1-\alpha_i^j)\theta^j\gamma_i^j}}{\sum_{m=1}^N\left(x_m^j\kappa_{nm}^j\right)^{-\theta^j}{T_m^j}^{(1-\alpha_i^j)\theta^j\gamma_m^j}} \tag{8}$$

We used F_n^j to denote the revenue from emission penalties or carbon taxes received by region n from sector j through environmental regulations; that is, $F_n^j=t_ne_n^j$. The total environmental regulation revenue in region n is $F_n=\sum_{j=1}^J F_n^j$. The term χ represents the return per person from the national portfolio of land and structures in all regions. In particular, $\chi=\frac{\sum_{i=1}^N \iota_i r_i H_i}{\sum_{i=1}^N L_i}$. The income of an agent residing in region n is:

$$I_n=w_n+\chi+(1-\iota_n)r_nH_n/L_n+F_n/L_n \tag{9}$$

2.2.4. Changes in Regional GDP

In the constructed model, the impact of green TFP denoted as A_n^j, is reflected in economic growth. A_n^j incorporates emission elasticity, which allows for the inclusion of non-expected outputs, such as emissions, into the calculation, in contrast to TFP, which only considers expected outputs. The green TFP of sector j in region n can be derived from the equilibrium conditions, as follows:

$$A_n^j = \frac{x_n^j}{P_n^j} \tag{10}$$

As $\hat{\pi}_{nn}^j = \left(\frac{\hat{x}_n^j}{\hat{P}_n^j}\right)^{-\theta^j}\left(\hat{T}_i^j\right)^{(1-\alpha_i^j)\gamma_i^j\theta^j}$, changes in green TFP can be expressed as:

$$\hat{A}_n^j = \frac{\hat{x}_n^j}{\hat{P}_n^j} = \frac{\left(\hat{T}_i^j\right)^{(1-\alpha_i^j)\gamma_i^j}}{\left(\hat{\pi}_{nn}^j\right)^{\frac{1}{\theta^j}}} \tag{11}$$

The GDP in a given region-sector pair is the difference between gross production and expenditure on materials, $\frac{w_n L_n^j + r_n H_n^j}{P_n^i}$. As, in equilibrium, $L_n = \frac{(1-\beta_n) r_n H_n}{\beta_n w_n}$, GDP of sector j in region n is: $GDP_n^j = \left(\frac{1}{1-\beta_n}\right)\frac{w_n L_n}{P_n^j}$. Based on the changes in the price level and green TFP derived from the equilibrium condition, actual GDP changes in sector j in region n can be expressed as:

$$\widehat{GDP}_n^j = \hat{A}_n^j \hat{L}_n^j \left(\frac{\hat{w}_n}{\hat{x}_n^j}\right) \tag{12}$$

Sectors are categorized according to their emission characteristics into carbon-intensive sector j and low-emission sector k, and ψ_n^j and ψ_n^k are used to represent their respective shares of GDP in the region. Thus, changes in regional GDP can be expressed as:

$$\widehat{GDP}_n = \psi_n^j \widehat{GDP}_n^j + \psi_n^k \widehat{GDP}_n^k \tag{13}$$

According to this model, local governments can influence economic growth and emissions by changing the intensity of their environmental regulations, $\hat{t}_n$, and can affect economic growth by changing $\hat{A}_n^j$ and $\hat{\kappa}_{ni}^j$. This process is influenced by regional characteristics, including emission characteristics, which are explained in the model using emission elasticity, α_n^j, sectoral structure, which is explained in the model using the proportion of sector j to the total GDP, ψ_n^j, and trade relationship between two regions, which is explained in the model using the sector trade share between regions, π_{ni}^j.

2.3. Emission Damage in Payoff

As previously mentioned, the impact of global warming caused by climate change on region n is not solely determined by its own emissions, e_n, but also by total emissions. Therefore, damage from emissions is a function of the overall emissions. Considering the complexity of factors and processes involved in the impact of climate change on a region, this study did not aim to construct an exact function to explore these issues. Instead, a simple model was used to elucidate the mechanism, and previous assumptions were leveraged to simplify the analysis using the exact-hat algebra method. This analysis focused on changes in damage caused by emissions rather than on precise emissions. We posited that a linear relationship between damage caused by emissions and emissions would exist. Thus, variation in damage caused by emissions was expressed as:

$$\hat{D}_n = \frac{e_1}{e}\hat{e}_1 + \frac{e_2}{e}\hat{e}_2 + \cdots + \frac{e_n}{e}\hat{e}_n \tag{14}$$

2.4. Data

2.4.1. Numerical Settings of the Payoff Matrix

As with most game model studies, we set values to analyze different Nash equilibrium outcomes. From the perspective of 2 × 2 static games, the model constructed in this study corresponds to the 25 climate cooperation 2 × 2 games proposed by DeCanio and Fremstad [23]. These games can be mainly classified as No-Conflict, Prisoner's Dilemma, Coordination, Chicken, and Unhappy Games. In this study, the game form depended on the numerical values of the payoff matrices. The payoff matrices for the game between the two regions are shown in Table 1, where Π_n^A, Π_n^B, Π_n^C, and Π_n^D represent the regional profits under the four strategy combinations.

Table 1. Payoff Matrix of the 2 × 2 game.

		Region 2	
		Synergistic Action (SA)	Unilateral Action (UA)
Region 1	Synergistic Action (SA)	Π_1^A, Π_2^A	Π_1^B, Π_2^B
	Unilateral Action (UA)	Π_1^C, Π_2^C	Π_1^D, Π_2^D

To clarify the relationship between emissions and economic growth under different strategies, this study used different payoff values, following the analysis method of complete information static games. In this study, game payoffs were ordinal or cardinal. In the studies by DeCanio and Fremstad [23] and Madani [32], ordinal numbers ranging from one to four were used to represent the payoffs of agents in climate games, with the government as a game participant ranking the sequential results. This approach is commonly used in static games with perfect information. Using ordinal values as payoffs in climate change games avoids the comparison of utilities between regions with significantly different income levels, thereby overcoming the shortcomings of traditional cost-benefit analyses. Therefore, we set the payoff values under different strategies to 0.01, 0.02, 0.03, and 0.04. This was consistent with the calculated values of our model, which effectively explained the economic meaning implied in the data, namely, the difference between changes in GDP and damages, both caused by emissions. Furthermore, this setting was similar to ordinal results, representing the utilities of local governments at four levels under different strategies and making the game results more intuitive. Based on these settings, values for emissions, damage caused by emissions, and economic growth were assigned. Although this value setting is only one of many results, it is consistent in interpreting the relationship between different strategies, emissions, and economic growth in models.

For both regions, the numerical settings of emission changes were provided according to the two scenarios assumed above. As shown in Table 2, in Scenario 1, $\hat{e}_n = 0.8$ if the region chose the SA strategy, and $\hat{e}_n = 1$ if the region chose the UA strategy. Regional synergy in Scenario 1 indicated that both players increased their emission reduction efforts to minimize the overall emissions of both regions. In Scenario 2, $\hat{e}_1 = 0.7$ and $\hat{e}_2 = 1.1$ if both regions chose the SA strategy, $\hat{e}_1 = 0.9$ and $\hat{e}_2 = 1$ if Region 1 chose SA and Region 2 chose UA, and $\hat{e}_1 = 1$ and $\hat{e}_2 = 1.1$ if Region 1 chose UA and Region 2 chose SA. The form of regional synergistic emission reduction in Scenario 2 indicated that some regions could increase their emissions appropriately when synergistic, considering the overall decrease in the emissions increase in both regions. According to the model, if changes in emissions are determined, changes in damage caused by emissions can be obtained. If $\hat{e}_{1+2} = 0.8$, $\widehat{D}_n = 0.96$; if $\hat{e}_{1+2} = 0.9$, $\widehat{D}_n = 0.97$; if $\hat{e}_{1+2} = 0.95$, $\widehat{D}_n = 0.98$; if $\hat{e}_{1+2} = 1$, $\widehat{D}_n = 0.99$. The reason for this setting is that while Regions 1 and 2 did not change their emissions, emission reduction actions in other regions reduced total emissions; if $\hat{e}_{1+2} = 1.05$, $\widehat{D}_n = 1$. Thus, the difference in the payoff matrix is mainly determined by the difference in changes in GDP due to abatement actions.

Table 2. Nash equilibrium, emissions, and economic growth of synergistic emission reduction.

Type of Game		**No-Conflict Game**		**Prisoner's Dilemma Game**		**Coordination Game**		**Chicken Game**		**Unhappy Game**	
Nash Equilibrium		**(SA, SA)**		**(UA, UA)**		**(SA, SA) and (UA, UA)**		**(SA, UA) and (UA, SA)**		**(SA, UA)**	
Region		1	2	1	2	1	2	1	2	1	2
Payoff	Π_n^A	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.03
	Π_n^B	0.02	0.03	0.01	0.04	0.01	0.03	0.02	0.04	0.02	0.04
	Π_n^C	0.03	0.02	0.04	0.01	0.03	0.01	0.04	0.02	0.04	0.01
	Π_n^D	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02
Scenario 1	$\hat{e}_n$	0.8	0.8	1	1	0.8 (1)	0.8 (1)	0.8 (1)	1 (0.8)	0.8	1
	$\hat{e}_{1+2}$	0.8		1		0.8 (1)		0.9		0.9	
	$\widehat{D}_{\mathrm{n}}$	0.96		0.99		0.96 (0.99)		0.97		0.97	
	$\widehat{G}_n$	1	1	1	1	1 (1.01)	1 (1.01)	0.99 (1.01)	1.01 (0.99)	0.99	1.01
	$\widehat{G}_{1+2}$	1		1		1 (1.01)		1 (1)		1	
Scenario 2	$\hat{e}_n$	0.7	1.1	1	1	0.7 (1)	1.1 (1)	0.9 (1)	1 (1.1)	0.9	1
	$\hat{e}_{1+2}$	0.9		1		0.9 (1)		0.95 (1.05)		0.95	
	$\widehat{D}_{\mathrm{n}}$	0.97		0.99		0.97 (0.99)		0.98 (1)		0.98	
	$\widehat{G}_n$	1.01	1.01	1.01	1.01	1.01	1.01	1 (1.04)	1.02 (1.02)	1	1.02
	$\widehat{G}_{1+2}$	1.01		1.01		1.01		1.01 (1.03)		1.01	

2.4.2. Parameter Settings

As the design of the regional economic growth part of the model in this study is based on a general spatial equilibrium model, realistic data can be used for the analysis. To obtain more general findings, we use a range of key parameters and values from existing studies, including trade elasticity [43] and emissions elasticity [37]. The object of our analysis is still assumed to be the two general regions, 1 and 2, and all other regions are grouped into Region 3. We establish a set of parameters based on the current state of the economy as a baseline, where $\theta^j = \theta^k = 4$, $\alpha_n^j = 0.6$, $\alpha_n^k = 0$, $\pi_{11}^j = \pi_{12}^j = \pi_{21}^j = \pi_{21}^j = 0.3$, $\pi_{13}^j = \pi_{23}^j = 0.4$, $\gamma_n^{jk} = \gamma_n^{jj} = \gamma_n^{kk} = 0.1$, $\gamma_n^{kj} = 0.4$, $\gamma_n^j = 0.6$, $\psi_n^j = 0.5$, and $\beta_n = 0.17$. In this baseline, we take two values for each parameter to compare the results and thus analyze the impact of each factor on the comparative advantage of emission reduction. The specific settings are given in the later analysis.

3. Results

3.1. Nash Equilibrium of Regional Synergistic Emission Reduction

3.1.1. Equilibrium Results in the Basic Synergistic Form

The results of the game analysis are presented in Table 2 (a more detailed analysis of the process and results can be found in Appendix A). Changes in the GDP caused by abatement actions determine regional strategies, resulting in different Nash equilibrium outcomes. In Scenario 1, for the No-Conflict Game, when the changes in GDP of the two regions are less affected by the abatement action ($\widehat{G}_1 = \widehat{G}_2 = 1,\ \hat{e}_1 = \hat{e}_2 = 0.8$), unilateral actions of the free-riding regions do not cause an increase in their own GDP but generate a loss of economic growth for regions that choose SA ($\widehat{G}_1 = 0.99,\ \widehat{G}_2 = 1,\ \hat{e}_1 = 0.8,\ \hat{e}_2 = 1$). There was no significant boost to economic growth when both sides maintained their existing emission reduction plans ($\widehat{G}_1 = \widehat{G}_2 = 1,\ \hat{e}_1 = \hat{e}_2 = 1$), and rational players settled on the (SA, SA) strategy pair in Nash equilibrium.

When the payoff of free-riding is greater than the payoff of synergistic emission reduction ($\Pi_1^C = 0.04 > 0.03 = \Pi_1^A$ and $\Pi_2^B = 0.04 > 0.03 = \Pi_2^A$), and benefiting from the overall reduction in emissions from global mitigation actions, two regions taking unilateral action can achieve a decrease in changes in damage from emissions ($\widehat{D}_1 = \widehat{D}_2 = 0.98$). In other words, both regions can benefit from the overall reduction in emissions by choosing the UA strategy ($\Pi_1^D = \Pi_2^D = 0.02$), even if this payoff is smaller than the payoff from the synergistic emission reduction ($\Pi_1^A = \Pi_2^A = 0.03$). In this case, the game falls into a prisoner's dilemma.

Unlike the prisoner's dilemma, although there is an equilibrium outcome (UA, UA) in the Coordination Game, there is also a Pareto-optimal equilibrium for the (SA, SA) strategy pair; that is, when both regions reach a synergistic emission reduction, they gain the highest payoff. When one region chooses SA and the other chooses UA in the Coordination Game, the region loses economic growth to reduce emissions ($\widehat{G}_n = 0.98$) and fails to benefit from the other region's lenient environmental policy. At this point, this region has the lowest payoff ($\Pi_n^B = 0.01$); therefore, this game reflects the nature of collective action in both regions.

In addition, when either player in the game is able to achieve a greater increase in economic growth by free-riding ($\widehat{G}_n = 1.01$) and gaining the highest payoff, a Chicken or Unhappy Game is formed, and it is difficult for the two regions to reach an equilibrium result of synergistic emission reduction.

In summary, the mitigation actions of the two regions impact each other's economic growth, and the extent to which the two regions can achieve synergistic emission reduction depends on the changes in economic growth resulting from emission reduction. Achieving the regional synergistic emission reduction described in Scenario 1 requires both parties to achieve higher economic growth under strict environmental policies while reducing emissions. It is important to avoid high economic growth in a region through free-rider behavior.

3.1.2. Equilibrium Results Considering the Comparative Advantage of Emission Reduction

Unlike Scenario 1, Scenario 2 describes two regions that exploit their respective comparative advantages to reduce emissions. For Region 2, increasing $\hat{e}_2$ rather than decreasing $\hat{e}_2$ allows for more overall economic growth in both regions. For Region 1, decreasing $\hat{e}_1$ compared to increasing $\hat{e}_1$ can reduce the damage from emissions by significantly reducing emissions and does not result in a greater loss of economic growth. Consequently, both regions reap greater overall payoffs.

In Scenario 2, the synergistic emission reduction in the two regions allows one region to increase emissions in the short term. This means that the (SA, SA) Nash equilibrium strategy pair in Scenario 2 is easier to achieve than in Scenario 1, and both players in the game are more likely to form regional synergistic emission reduction. It is easier to form No-Conflict and Coordination Games. When a region has a comparative advantage in emission reduction, the implementation of strict emission reduction policies can still lead to economic growth ($\widehat{G}_1 = 1.01$). Even if another region increases some of its emissions, it is an effective synergistic emission reduction as long as the overall emission change of both regions ($\hat{e}_{1+2}$) decreases. This means that the conditions for achieving regional synergistic emission reduction have been relaxed, allowing regions that are still in the process of reaching their carbon peaks to participate. However, other payoff matrices in Scenario 2 that cannot achieve the (SA, SA) Nash equilibrium strategy pair are less likely to occur in reality than in Scenario 1. To achieve Prisoner's Dilemma, Chicken, and Unhappy Games, regions that do not have a comparative advantage in reducing emissions must achieve higher economic growth ($\widehat{G}_2 = 1$ when $\hat{e}_2 = 1.1$, $\widehat{G}_2 = 1.02$ when $\hat{e}_2 = 1$), which is challenging.

Different comparative advantages of emission reduction between two regions form a differentiated pattern of regional emissions and economic growth. The Nash equilibrium that achieves regional synergistic emission reduction has the lowest overall emissions of the two regions ($\hat{e}_{1+2} = 0.8$) compared to the other equilibrium strategy pairs, enabling faster achievement of the carbon neutrality target while maintaining economic growth. However, Scenario 1 has better reduction results than Scenario 2 ($0.8 < 0.9$), whereas the economic growth of the two regions under Scenario 2 is better than that of Scenario 1 ($1.01 > 1$). Although reducing emissions as quickly as possible is an important pathway to achieving carbon-neutrality goals, for some regions, the pursuit of faster emission reduction comes at a higher cost in terms of lost economic growth. Therefore, regional synergistic emission reduction requires a trade-off between economic growth and emission reduction and the pursuit of a global optimum rather than a local optimum.

3.2. Factors Influencing the Comparative Advantage of Emission Reduction in Regional Synergy

The game analysis demonstrated that effective regional synergy relies on the ability of a region to form a comparative advantage in emission reduction, mainly in terms of the impact of different emission reduction actions on local and other regions' economic growth. This avoids a sharp decline in economic growth when implementing strict environmental regulations and exchanges a lower increase in emissions for faster economic growth in both regions. Therefore, we analyzed the effects of various factors on the formation of a comparative advantage in emission reduction, including the regional characteristics determined by the emission elasticity, α_1^j, the GDP of sector j in region n as a share of the total regional GDP, ψ_n^j, and the trade share, π_{ni}^j. Local governments increase economic growth by changing green TFP, $\hat{A}_n^j$, and trade costs, $\hat{\kappa}_{ni}^j$, and reduce the recession in economic growth from changes in the intensity of environmental regulations, $\hat{t}_n$.

3.2.1. Emission Elasticities

First, in carbon-intensive sectors, low emission elasticities attenuate the impact of changes in the intensity of environmental regulations on economic growth, whereas high emission elasticities amplify the loss of economic growth from abatement. In Figure 1a, the horizontal axis represents the change in the intensity of environmental regulations in Region 1, $\hat{t}_1$, which indicates regional efforts to mitigate climate change. The vertical axis represents the GDP change in Region 1, $\widehat{GDP}_1$. According to Duan et al. [37], who estimated the emission elasticity of sectors in major countries, most of the values of α_n^j range from 0.01 to 0.11. When $\alpha_1^j = 0.01$, an increase in $\hat{t}_1$ causes a smaller decrease in $\widehat{GDP}_1$, whereas when $\alpha_1^j = 0.11$, an increase in $\hat{t}_1$ causes a larger decrease in $\widehat{GDP}_1$. This is because high emission elasticity means that manufacturers in carbon-intensive sectors produce more emissions as by-products when producing intermediate products, which entails higher production costs and results in higher prices for products in carbon-intensive sectors.

Second, when sectors in a region have higher emission elasticity values, the impact of emission reduction actions on economic growth spills over to other regions. As shown in Figure 1b, when $\alpha_1^j = 0.01$, the curves of $\hat{t}_1$ and $\widehat{GDP}_2$ are close to horizontal, which means that changes in the intensity of environmental regulations in Region 1 have little effect on the changes in GDP in Region 2. In contrast, when $\alpha_1^j = 0.11$, an increase in $\hat{t}_1$ causes a decrease in $\widehat{GDP}_2$, which means that the implementation of more stringent environmental regulations in Region 1 causes a loss of economic growth in Region 2. This is because under the trade linkage of carbon-intensive products between the two regions, Region 2 faces the same product price increase owing to strict environmental regulations when purchasing products from Region 1's carbon-intensive sectors. In addition, as shown in Figure 1c, the value of the emission elasticity of another region had little effect on the relationship between $\hat{t}_1$ and $\widehat{GDP}_1$ in this region.

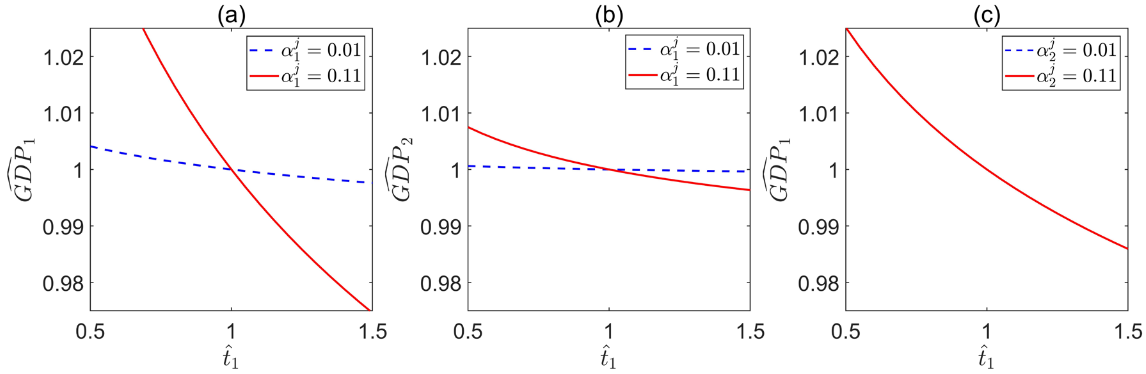

Figure 1. Relationship between $\hat{t}_n$ and $\widehat{GDP}_n$ under different α_n^j. (**a**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_1$ under different α_1^j; (**b**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_2$ under different α_1^j; (**c**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_1$ under different α_2^j.

Third, the value of the emission elasticity portrays the emission characteristics of the sector. When the emission elasticity tends to zero, carbon-intensive sectors gradually transform into low-emission sectors, generating fewer emissions during production. Therefore, the emission elasticity of carbon-intensive sectors is reduced by upgrading technology to decrease the share of byproducts produced effectively in intermediate goods to achieve economic growth under emission reduction constraints.

3.2.2. Sectoral Structures

First, the sectoral structure of a region determines the extent to which changes in environmental regulations affect its economic growth. When a region's sectors are predominantly carbon intensive, enhanced efforts to reduce emissions through strict environmental regulations can lead to a significant decline in economic growth in the region. As shown in Figure 2a, when the share of carbon-intensive sectors in the region is $\psi_1^j = 0.7$, $\hat{t}_1$ increases, causing a larger decrease in $\widehat{GDP}_1$, whereas when $\psi_1^j = 0.3$, $\hat{t}_1$ increases, causing a smaller decrease in $\widehat{GDP}_1$. Regions with a low-emission sectoral structure will not bear a disproportionate economic loss from significant emission reduction compared to regions with carbon-intensive sectors as their mainstay.

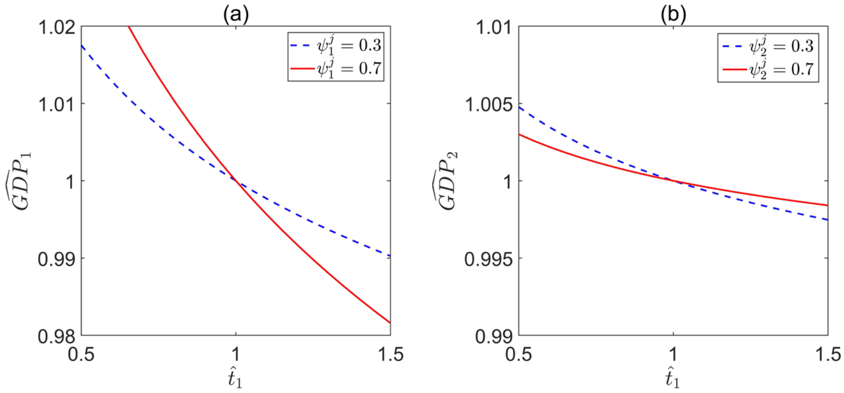

Figure 2. Relationship between $\hat{t}_n$ and $\widehat{GDP}_n$ under different ψ_n^j. (**a**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_1$ under different ψ_1^j; (**b**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_2$ under different ψ_2^j.

Second, regions with low-emission sectoral structures are more vulnerable to changes in the strength of environmental regulations in other regions. As shown in Figure 2b, comparing the values of different ψ_2^j, when $\psi_2^j = 0.3$, an increase in $\hat{t}_1$ causes a greater decrease in $\widehat{GDP}_2$. This suggests that when the sectoral structure of Region 2 has a low share of carbon-intensive sectors, its economy is more vulnerable to the cross-regional impacts of the environmental regulations in Region 1. This is because Region 2 has fewer carbon-intensive sectors, and its demand for carbon-intensive products is more likely to be met by the supply from Region 1. When Region 1 enforces strict environmental regulations, it raises the price of the products produced by its carbon-intensive sectors, which in turn increases the cost of production in Region 2. A specific example is the inter-regional transmission of electricity, where increased environmental regulations in the power-exporting location increase the cost of electricity production, raising the price of purchased electricity in the power-importing location and further increasing the production costs of other industries in the power-importing location, thereby affecting economic growth.

3.2.3. Trade Shares

First, when regional demand for carbon-intensive intermediate goods is mainly supplied by other regions, changes in the intensity of environmental regulation in the region have less impact on its economic growth. Conversely, when a region purchases a higher share of carbon-intensive intermediate goods from local sources, changes in the intensity of environmental regulations in that region are greater for economic growth.

Figure 3a shows two extreme cases of the trade share of the carbon-intensive sector j. $\pi_{11}^j = 0$ means that all the products of sector j required in the region come from other regions, at which time the increase in $\hat{t}_1$ causes a smaller decrease in $\widehat{GDP}_1$. Moreover, $\pi_{11}^j = 1$ means that all the products of sector j required by the region come from itself, and the increase in $\hat{t}_1$ causes a larger decrease in $\widehat{GDP}_1$. This is because strict environmental regulations increase the price of intermediate products by increasing the production cost of sector j. In the absence of trade in sector j, the region can only buy local intermediate products from sector j at higher prices, which slows economic growth. When the share of intermediate goods purchased from other regions in sector j increases, the demand for local high-priced intermediate goods in sector j gradually decreases and regional economic growth is less affected by environmental regulations.

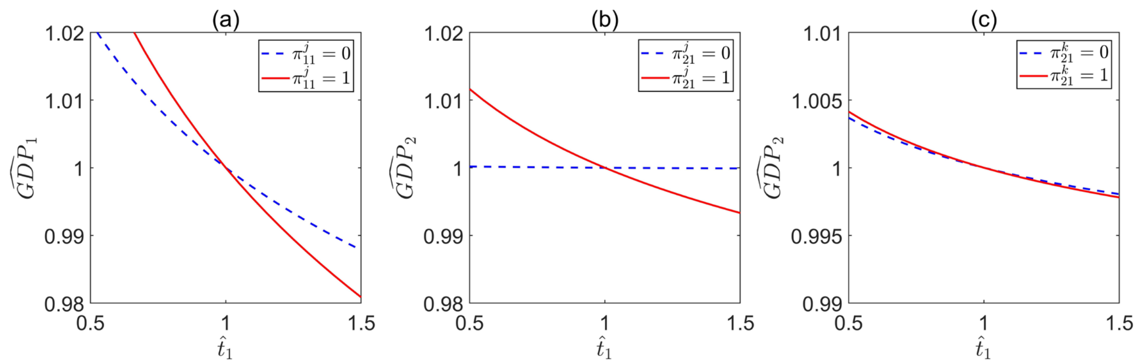

Figure 3. Relationship between $\hat{t}_n$ and $\widehat{GDP}_n$ under different π_{ni}^j. (**a**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_1$ under different π_{11}^j; (**b**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_2$ under different π_{21}^j; (**c**) Relationship between $\hat{t}_1$ and $\widehat{GDP}_2$ under different π_{21}^k.

Second, the cross-regional spillover effects of environmental regulations on economic growth are constrained by trade share. If strong trade links exist between the two regions in carbon-intensive intermediate goods, changes in the intensity of environmental regulations in one region may have a larger impact on economic growth in the other. As shown in the two extreme cases in Figure 3b, $\pi_{21}^j = 0$ indicates that the share of products in sector j purchased by Region 2 from Region 1 is 0. $\hat{t}_1$ has almost no effect on $\widehat{GDP}_2$ in this case. When $\pi_{21}^j = 1$, all the intermediate goods of sector j are purchased by Region 2 from Region 1; at this time, the strengthening of environmental regulations in Region 1 leads to the loss of economic growth in Region 2. In addition, the cross-regional spillover effects of environmental regulations on economic growth are closely related to the emission characteristics of the sectors, as shown in Figure 3c. Changes in the trade shares of the low-carbon sectors in the two regions do not significantly alter the cross-regional economic impact of environmental regulation.

3.2.4. Green Total Factor Productivity

First, an increase in green TFP in carbon-intensive sectors can reduce the negative impact of climate-change mitigation measures on economic growth. As shown in Figure 4a, $\hat{t}_1 = 1.5$ and $\hat{t}_1 = 0.5$ represents the increase and decrease, respectively, in environmental regulations to control the growth of emissions by regional agents. Changes in the intensity of local governments' efforts to control emissions affect the relationship between green TFP and economic growth in carbon-intensive sectors. Achieving the same level of economic growth under strict environmental regulations requires a higher green TFP in carbon-intensive sectors. Although stronger environmental regulations reduce economic growth, $\widehat{GDP}_n$ is greater than 1 when $\hat{A}_n^j$ is higher, which maintains a positive change in GDP.

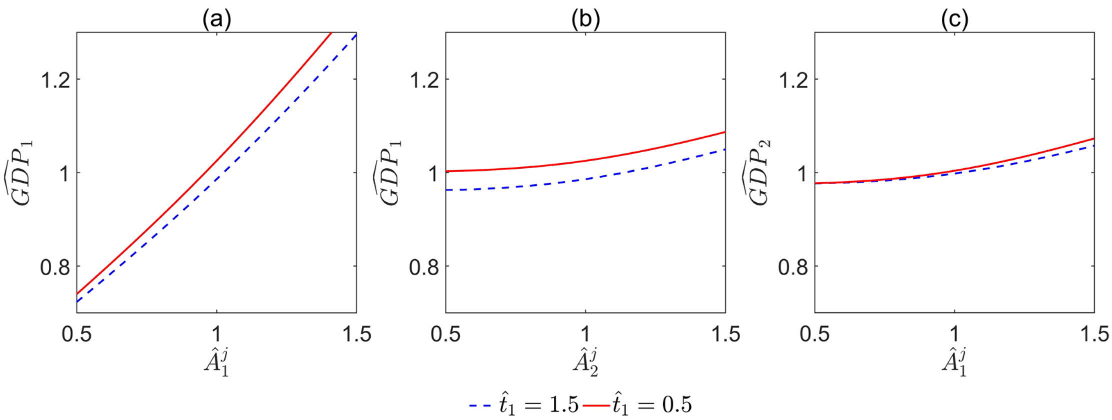

Figure 4. Relationship between $\hat{A}_n^j$ and $\widehat{GDP}_n$ under different $\hat{t}_n$. (**a**) Relationship between $\hat{A}_1^j$ and $\widehat{GDP}_1$; (**b**) Relationship between $\hat{A}_2^j$ and $\widehat{GDP}_1$; (**c**) Relationship between $\hat{A}_1^j$ and $\widehat{GDP}_2$.

Second, the mitigating effect of increased green TFP on the negative impacts of environmental regulations has a regional spillover effect. As shown in Figure 4b, changes in the green TFP $\hat{A}_1^j$ and GDP $\widehat{GDP}_1$ of Region 1 are positively correlated. A higher level of green TFP gains in carbon-intensive sector j leads to a higher level of economic growth. Furthermore, under exact-hat algebra assumptions, the numerical magnitude relationship between the variable and 1 determines the direction of change in the variable. If t_1 is constant, $\hat{A}_1^j > 1$ (or $\hat{A}_1^j < 1$) indicates that an increase (decrease) in green TFP leads to an increase (decrease) in GDP. As can be seen from (b) and (c) in Figure 4, an increase in $\hat{A}_n^j$ positively affects changes in GDP in the other region, $\widehat{GDP}_i$.

3.2.5. Trade Costs

Reducing the cost of trade in carbon-intensive sectors may lead to the relocation of carbon-intensive industries between regions, thereby affecting regional economic growth. According to current spatial economics theory, lower inter-regional trade costs contribute to economic growth. As shown in Figure 5, $\hat{\kappa}_{ni}^j$ has an inverse effect on $\widehat{GDP}_n$. Comparing (a) and (d) with (c) and (f), the impact curve of the change in trade costs on the change in local GDP is steeper than that of the other regions. Lower trade costs result in lower prices for local purchases of intermediate goods from other regions, leading to local economic growth. However, for regions with strict environmental regulations, in which environmental regulations increase the cost of production in local carbon-intensive sectors, lower trade costs imply that carbon-intensive products can be purchased from other regions at lower prices. This reduces the production of carbon-intensive products in the local area and increases those produced in areas with relatively lax emissions regulations. While the relocation of carbon-intensive industries creates carbon leakage problems for the latter, buying higher-emission products from other regions at lower prices allows the former to continue to grow economically under strict environmental regulations. As shown in Figure 5a, although a tendency towards more stringent environmental regulations ($\hat{t}_1 = 1.5$) reduces economic growth, when $\hat{\kappa}^j_{12}$ is lower, $\widehat{GDP}_1$ is greater than 1, and the GDP can maintain its original level of growth. Furthermore, for different industries, comparing (a) and (d) with (b) and (e) in Figure 5, changes in trade costs $\hat{\kappa}^j_{ni}$ for the carbon-intensive sector j has a greater impact on economic growth than changes in trade costs $\hat{\kappa}^k_{ni}$ for other sectors k.

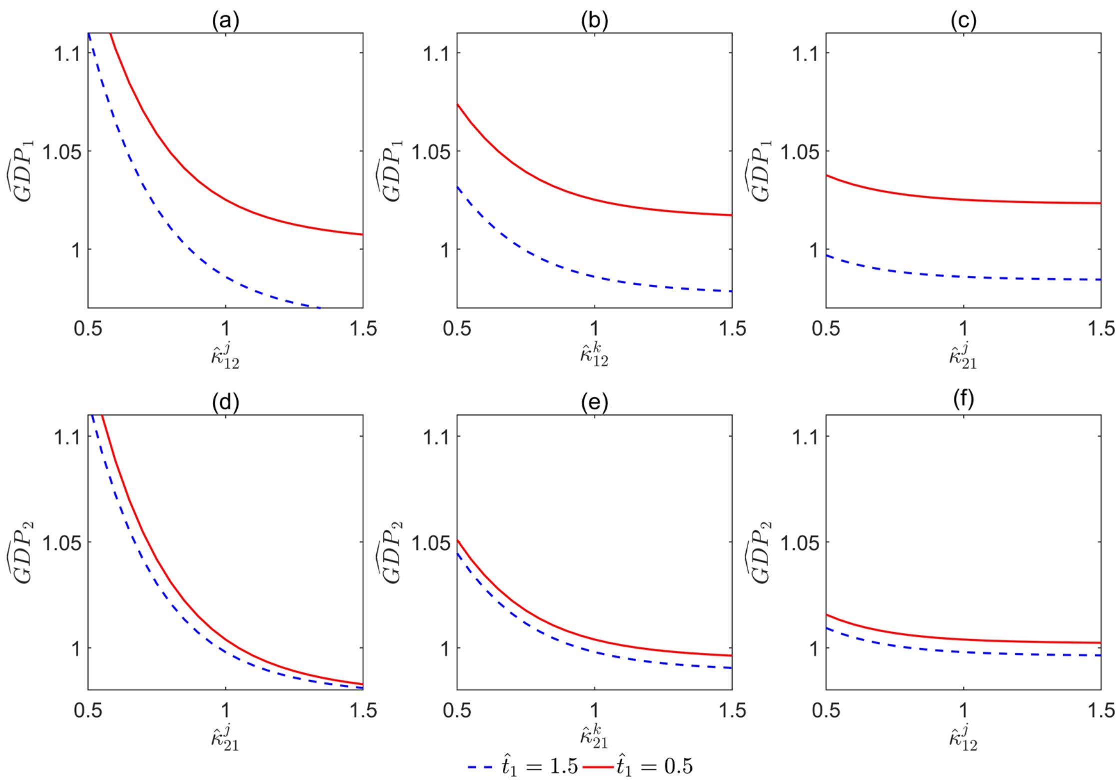

Figure 5. Relationship between $\hat{\kappa}^j_{ni}$ and $\widehat{GDP}_n$ under different $\hat{t}_n$. (**a**) Relationship between $\hat{\kappa}^j_{12}$ and $\widehat{GDP}_1$; (**b**) Relationship between $\hat{\kappa}^k_{12}$ and $\widehat{GDP}_1$; (**c**) Relationship between $\hat{\kappa}^j_{21}$ and $\widehat{GDP}_1$; (**d**) Relationship between $\hat{\kappa}^j_{21}$ and $\widehat{GDP}_2$; (**e**) Relationship between $\hat{\kappa}^k_{21}$ and $\widehat{GDP}_2$; (**f**) Relationship between $\hat{\kappa}^j_{12}$ and $\widehat{GDP}_2$.

4. Discussion

4.1. Discussion of the Case of China

The results of our analysis can explain the current regions where synergistic emission reductions have been developed. China has set the goal of "carbon peaking and carbon neutrality" to mitigate climate change [44]. However, the unique complexity of China's economy as a large country determines the complexity and uniqueness of its regional cooperation in emission reduction [45]. Mitigating climate change is usually assigned to China's administrative regions, and the different resource endowments of each region lead to significant differences in their performance in mitigating climate change [46]. In this context, regional synergistic emission reduction is beginning in some regions of China. A typical example is the collaborative management of air pollution in Beijing, Tianjin, and Hebei. The Action Plan for the Prevention and Control of Air Pollution ("Ten Measures for the Atmosphere") was promulgated in 2013, and the Beijing-Tianjin-Hebei Synergistic Development was elevated to a national strategy in 2014. With the joint efforts between regions, the implementation of "Ten Measures for the Atmosphere" reduced 352.7 Mt of CO_2 emissions in the Beijing-Tianjin-Hebei regions [47]. Although these three regions are in different stages of development, effective synergistic climate change governance has been achieved. Among them, Beijing and Hebei play different roles. Beijing adopts strict environmental regulations to control emissions, while Hebei increases the growth rate of emissions in the short term by taking over some of Beijing's industries [48], with more lenient emission reduction policies to maintain stable economic growth in both regions. According to emissions data published by Carbon Emission Accounts and Datasets [49], the change in Beijing's carbon emissions has decreased from 1.026 in 2013–2014 to 0.937 in 2014–2015 since the enactment of the Air Pollution Control Action Plan in 2013. In contrast, the change in carbon emissions in Hebei saw a brief increase, from 0.95 in 2013–2014 to 1.024 in 2014–2015.

This validates the form of synergistic emission reduction proposed by our model. Compared to Beijing, which has completed industrialization, Hebei has more industries with high carbon emission intensity [50], which means that strict environmental regulations can significantly increase the production costs of firms. The trade link between the two regions is deeper with the industrial transfer, and increasing the emission growth rate in Hebei in the short term will provide better overall returns for both regions than decreasing the emission growth rate. Whether through appropriate regional cost-sharing of emission reductions [51] or horizontal transfer payments from Beijing to Hebei [52], stable synergistic emission reductions must allow Hebei to reap additional gains from cooperative emission reductions. This part of the gains is mainly captured by economic growth in our study.

4.2. Further Discussion of the Findings

Consistent with the findings of Da Zhu [30], Molina et al. [31], and others, the results of our model analysis emphasize the importance of economic growth in the choice of regional synergy strategies. Furthermore, we include changes in GDP caused by changes in emissions in the payoff function and define the formation condition of synergistic emissions reduction as a decrease in changes in total emissions in both regions. This enhancement expands the eligibility for participation in synergistic emission reductions to cover the case of the region reaching peak emissions through synergy.

Recent research on national climate change cooperation concludes that it is difficult to establish stable cooperation between countries with large differences in income levels [24,53]. However, we find that regional synergistic emissions reductions within a country are more flexible in form than cooperation between countries. This allows our model to allow regions with differing incomes to achieve synergistic emissions reductions. Under national-level climate change targets, some regions will appropriately relax constraints on emissions reductions and increase the rate of emissions growth in the short term [46] to ensure smooth economic growth while reaching peak emissions as soon as possible. For such areas, we propose a form of cooperation that exploits the comparative advantages of regional emissions reductions. That is, by increasing the growth rate of emissions, such regions stimulate the economic growth of their own region and the synergistic region, thereby reducing the economic loss of the synergistic region due to emission reduction and helping the two regions to jointly achieve the emission reduction target.

Although game models are considered divorced from policy practice in the analysis of climate cooperation issues [33], as in Carrozzo Magli and Manfredi [24], Verendel et al. [26], and others, more detailed games also strengthen the policy guidance implications of the models. Starting from the base game form proposed by DeCanio and Fremstad [23], our study enriches the current game model in terms of regional characteristics and inter-regional economic relations. By adding a general spatial equilibrium model to the game model, the model is made as close to the economic reality as possible to provide trade, industry, and economic growth policy complement to emissions reduction policy.

The model developed in this study can be used for future analyses. As this study aimed to explain general regional synergistic emission reduction theoretical mechanisms, although a quantitative general spatial equilibrium model was incorporated into the game model, the results of the simulations were derived by assigning values to the parameters in the analysis. Future studies could apply this model to calculate the economic impact of emission-reduction actions using real statistics from specific regions, extend the damage from emissions not analyzed in detail in this study, and make precise calculations. This would allow the analysis of synergistic emission reduction between specific regions and the prediction of synergistic emission reduction potential of different regions. The model is also applicable to other regions and countries, providing methodological support for the analysis of inter-regional cooperation on climate change mitigation. However, the model proposed in this study still has some limitations. First, our model is based on short-term static analyses and is unable to analyze the long-term dynamic problem of stable cooperation. Future research can extend our study with dynamic games and dynamic general equilibrium models. In addition, our model does not focus on socio-political factors and constructs a utility function using only economic gains and climate change damages. Socio-political factors are undeniably critical in climate change cooperation, and issues such as public attitudes toward climate change and environmental issues, mechanisms for the promotion of officials, and the right to development in the region all influence the formation of cooperation. These factors could be used to enrich our model in future research.

5. Conclusions

This study constructed a game model of regional synergistic emission reduction. The Basic Climate Game was modified using the exact-hat algebra method, with changes in GDP and damage caused by emissions included in the payoff function. This allows for a more rational description of changes in emissions during the process of achieving climate change targets and tradeoffs between economic growth and emission reduction by regional agents. A general spatial equilibrium model incorporating emissions and environmental regulations was constructed to extend the game model and analyze the changes in regional economic growth under emission reduction actions to explain the formation of comparative advantages of emission reduction and impact on regional synergistic emission reduction.

Whether synergistic emission reduction can be achieved between regions depends on whether regions can achieve the dual goals of reducing emissions and maintaining economic growth in the process of regional synergistic emission reduction. The synergy between the two regions means that, while maintaining stable economic growth, the overall increase in emissions of the two regions or the total amount of emissions is reduced.

Regional action to reduce emissions using environmental regulations as a policy tool not only impacts local economic growth but also has a cross-regional economic impact in the context of regional trade. Different economic impacts of emission reduction reflect the comparative advantages of regional emission reduction, including faster emission reduction with lower economic growth losses and faster economic growth with fewer incremental emissions.

Pursuing the optimal emission reduction effect locally is difficult and inefficient; the overall optimal emission reduction effect should be pursued to effectively achieve the carbon neutrality target. This requires using the comparative advantage of each region to reduce emissions. Regions where a small increase in emissions can effectively drive the overall economic growth of the two synergistic regions can appropriately increase their emissions. This can lower the threshold for regional participation in synergistic emission reduction and enable more regions to join the synergy. Regions that can maintain economic growth despite significant emission reduction, can undertake more emission reduction in regional synergy. This form of synergy can maintain the overall economic growth of both regions while reducing total emissions.

The formation of a comparative advantage in emission reduction depends on characteristics such as emissions elasticity, sectoral structure, and trade share in a region.

Considering the economic linkages between the two regions, these characteristics affect not only fluctuations in local economic growth due to environmental regulations but also the extent of cross-regional economic shocks due to environmental regulations. Regions must consider these characteristics and choose an appropriate way to participate in collaborative emission reduction.

Regional synergistic emission reduction requires not only emission reduction policies but a combination of policies. Regional trade and economic growth policies should not be neglected in the process of synergistic emission reduction, including improving green TFP, guiding industrial upgrading and inter-regional relocation, and reducing trade costs in key sectors between regions with synergistic emission reduction.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12091723/s1. Title: Supplementary Material—Details of the model.

Author Contributions: Conceptualization, T.M. and D.C.; methodology, D.C.; software, X.C.; validation, D.C., T.H. and T.M.; formal analysis, D.C.; investigation, T.H.; resources, T.M.; data curation, D.C.; writing—original draft preparation, D.C.; writing—review and editing, T.M.; visualization, X.C.; supervision, T.M. and T.H.; project administration, T.M.; funding acquisition, T.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Tables A1–A10 show the game models and the results of changes in emission, damage caused by emissions, and GDP for scenarios 1 and scenarios 2.

Table A1. No-conflict game in scenario 1.

		Region 2	
		Synergistic Action (SA)	Unilateral Action (UA)
Region 1	Synergistic Action (SA)	0.04, 0.04 *	0.02, 0.03
	Unilateral Action (UA)	0.03, 0.02	0.01, 0.01

	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA	0.8	0.8	0.96	0.96	1	1
SA, UA	0.8	1	0.97	0.97	0.99	1
UA, SA	1	0.8	0.97	0.97	1	0.99
UA, UA	1	1	0.99	0.99	1	1

* Nash Equilibrium.

Table A2. Prisoner's dilemma game in scenario 1.

		Region 2			
		SA		UA	
Region 1	SA	0.03, 0.03		0.01, 0.04	
	UA	0.04, 0.01		0.02, 0.02 *	
	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	

	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA	0.8	0.8	0.96	0.96	0.99	0.99
SA, UA	0.8	1	0.97	0.97	0.98	1.01
UA, SA	1	0.8	0.97	0.97	1.01	0.98
UA, UA	1	1	0.98	0.98	1	1

* Nash Equilibrium.

Table A3. Coordination game in scenario 1.

		Region 2	
		SA	UA
Region 1	SA	0.04, 0.04 *	0.01, 0.03
	UA	0.03, 0.01	0.02, 0.02 *

	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA	0.8	0.8	0.96	0.96	1	1
SA, UA	0.8	1	0.97	0.97	0.98	1
UA, SA	1	0.8	0.97	0.97	1	0.98
UA, UA	1	1	0.99	0.99	1.01	1.01

* Nash Equilibrium.

Table A4. Chicken game in scenario 1.

		Region 2	
		SA	UA
Region 1	SA	0.03, 0.03	0.02, 0.04 *
	UA	0.04, 0.02 *	0.01, 0.01

	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA	0.8	0.8	0.96	0.96	0.98	0.98
SA, UA	0.8	1	0.97	0.97	0.99	1.01
UA, SA	1	0.8	0.97	0.97	1.01	0.99
UA, UA	1	1	0.99	0.99	1	1

* Nash Equilibrium.

Table A5. Unhappy game in scenario 1.

		Region 2					
		SA			UA		
Region 1	SA	0.03, 0.03			0.02, 0.04 *		
	UA	0.04, 0.01			0.01, 0.02		
	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$		
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2	
SA, SA	0.8	0.8	0.96	0.96	0.99	0.99	
SA, UA	0.8	1	0.97	0.97	0.99	1.01	
UA, SA	1	0.8	0.97	0.97	1.01	0.98	
UA, UA	1	1	0.99	0.99	1	1.01	

* Nash Equilibrium.

Table A6. No-conflict game in scenario 2.

		Region 2					
		SA			UA		
Region 1	SA	0.04, 0.04 *			0.02, 0.03		
	UA	0.03, 0.02			0.01, 0.01		
	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$		
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2	
SA, SA	0.7	1.1	0.97	0.97	1.01	1.01	
SA, UA	0.9	1	0.98	0.98	1	1.01	
UA, SA	1	1.1	1	1	1.03	1.02	
UA, UA	1	1	0.99	0.99	1	1	

* Nash Equilibrium.

Table A7. Prisoner's dilemma game in scenario 2.

		Region 2					
		SA			UA		
Region 1	SA	0.03, 0.03			0.01, 0.04		
	UA	0.04, 0.01			0.02, 0.02 *		
	$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$		
	Region 1	Region 2	Region 1	Region 2	Region 1	Region 2	
SA, SA	0.7	1.1	0.97	0.97	1	1	
SA, UA	0.9	1	0.98	0.98	0.99	1.02	
UA, SA	1	1.1	1	1	1.04	1.01	
UA, UA	1	1	0.99	0.99	1.01	1.01	

* Nash Equilibrium.

Table A8. Coordination game in scenario 2.

		Region 2					
		SA			UA		
Region 1	SA	0.04, 0.04 *			0.01, 0.03		
	UA	0.03, 0.01			0.02, 0.02 *		
		$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
		Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA		0.7	1.1	0.97	0.97	1.01	1.01
SA, UA		0.9	1	0.98	0.98	0.99	1.01
UA, SA		1	1.1	1	1	1.03	1.02
UA, UA		1	1	0.99	0.99	1.01	1.01

* Nash Equilibrium.

Table A9. Chicken game in scenario 2.

		Region 2					
		SA			UA		
Region 1	SA	0.03, 0.03			0.02, 0.04 *		
	UA	0.04, 0.02 *			0.01, 0.01		
		$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
		Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA		0.7	1.1	0.97	0.97	1	1
SA, UA		0.9	1	0.98	0.98	1	1.02
UA, SA		1	1.1	1	1	1.04	1.02
UA, UA		1	1	0.99	0.99	1	1

* Nash Equilibrium.

Table A10. Unhappy game in scenario 2.

		Region 2					
		SA			UA		
Region 1	SA	0.03, 0.03			0.02, 0.04 *		
	UA	0.04, 0.01			0.01, 0.02		
		$\hat{e}_n$		$\widehat{D}_n$		$\widehat{G}_n$	
		Region 1	Region 2	Region 1	Region 2	Region 1	Region 2
SA, SA		0.7	1.1	0.97	0.97	1	1
SA, UA		0.9	1	0.98	0.98	1	1.02
UA, SA		1	1.1	1	1	1.04	1.01
UA, UA		1	1	0.99	0.99	1	1.01

* Nash Equilibrium.

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