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Original Research

Research on Stabilization Strategies for Inter-Enterprise Cooperative Carbon Reduction Behavior under Incentive-Based Environmental Regulation

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Abstract

To effectively mitigate the free-riding phenomenon prevailing in inter-enterprise collaborative carbon emission reduction behavior, this paper establishes an evolutionary game model for cooperative carbon emission reduction based on the spatial public goods game. By introducing incentive-based environmental regulations, the equilibrium solution of the game model is derived and analyzed. Numerical simulations are conducted to examine the impact of three types of incentive-based environmental regulations on the strategic choices of inter-enterprise cooperative carbon emission reduction in China. The research conclusions are presented as follows: (1) when two enterprises both opt for cooperation in carbon reduction, each party can obtain higher benefits compared with adopting non-cooperative strategies. In addition, when the synergistic benefits of cooperative emission reduction exceed the sum of the benefits from one enterprise cooperating while the other does not, and when this sum surpasses the sum of non-cooperative emission reduction benefits and external effects, the optimal choice for both enterprises is to adopt a cooperative emission reduction pattern; (2) incentive-based environmental regulation acts as an implicit incremental cost. Among these, an increase in carbon tax rates will inhibit enterprises from carrying out collaborative emission reduction activities. On the contrary, an increase in carbon emission trading prices and input subsidy coefficients can effectively incentivize enterprises to implement joint carbon emission reduction. This study reveals the dynamic evolutionary path and degree of influence of enterprises' cooperative carbon reduction under incentive-based environmental regulation, providing theoretical foundations and practical references for facilitating inter-enterprise collaboration on carbon reduction initiatives.

Keywords: cooperative carbon emission reduction, incentive-based environmental regulation, evolutionary game

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Introduction

China's industrialization process has consumed enormous volumes of fossil fuels, leading to a dramatic surge in CO_2 emissions. The Global Energy Review 2025 reveals that total carbon dioxide emissions in 2024 rose by 0.8% year-on-year, reaching a record high of 37.8 billion tons. China's contribution stood at 12.6 billion tons, unchanged from 2023, accounting for approximately one-third of global emissions. The environmental degradation caused by excessive energy consumption seriously restricts the sustainable development of China's economy and society, and has also attracted considerable attention from the Party and government. In September 2020, China pledged at the United Nations General Assembly to "adopt more robust policies and measures, striving to peak carbon dioxide emissions before 2030 and endeavoring to achieve carbon neutrality before 2060". This fully demonstrates China's commitment and resolve towards carbon reduction efforts. In the 20th National Congress report, it was also proposed to actively and prudently promote carbon peaking and carbon neutrality.

Enterprises have made significant contributions to economic development and social progress, but the carbon dioxide produced during their production processes is the main source of greenhouse gases. Therefore, promoting enterprises' emission reduction has become the most pressing task in environmental pollution control. The uncertainty of resource and environmental property rights, the public good nature of carbon emission space, and the negative externalities brought by carbon emissions indicate that relying solely on internal carbon reduction measures within enterprises to achieve the dual carbon goals is becoming increasingly difficult. It has become imperative to strengthen carbon reduction efforts through cross-enterprise collaboration. Scholars have proposed that the higher the proportion of corporate cooperation in pollution control, the more conducive this is to the optimization of public environmental resources (Ma and Deng, 2024) [1]. However, owing to the existence of perfectly rational actors, most enterprises will opt for a defection strategy (i.e., non-cooperation), ultimately leading to the depletion of public environmental resources. This phenomenon is known as the 'tragedy of the commons' (Hardin, 1968) [2], representing a cooperative dilemma. Accordingly, exploring effective ways to maintain and promote cooperative behaviors within such social dilemmas has long been a core research topic among scholars. Environmental regulation constitutes a necessary response to environmental impact issues (Jaffe et al., 2005) [3]. It is typically regarded as a suite of policy instruments formulated and implemented by governments to address environmental pollution and carbon emissions. These policies impose constraints on the emission activities of enterprises, guiding them to adjust their production methods and technology choices within the policy framework, thereby achieving pollution reduction, carbon reduction, and environmental quality improvement (Zhao, 2024; Pu et al., 2024) [4, 5]. Globally, governments also internalize environmental externalities through environmental agreements and related policy frameworks to compensate for market failures in allocating ecological and environmental resources (Güçlü and Korkmaz Tumer, 2024) [6]. Therefore, how to effectively drive enterprises to reduce carbon emissions through environmental regulations has become a focus of attention for all sectors of society.

Evolutionary game theory, first proposed by Maynard and Price (Maynard Smith and Price, 1973) [7], serves as a dynamic theoretical framework and methodology for examining the behavior of groups with bounded rationality. It elucidates the long-term evolutionary game processes among biological species. The selection and evolution of different strategies among individuals within a population undergo a protracted process, yet the system ultimately converges towards a stable equilibrium (Friedman, 1998) [8]. Therefore, evolutionary game theory does not need to consider the effectiveness of contracts and is a widely used tool for analyzing competition and cooperation among rational decision-makers (Ji et al., 2015) [9]. To investigate and resolve cooperation dilemmas, scholars have applied evolutionary game theory to explore mechanisms promoting the evolution of cooperative behavior. At present, research using game theory to analyze cooperative behavior mainly focuses on two decision-making entities: governments and enterprises. One approach is to analyze the evolutionary mechanism of enterprise cooperative behavior from the perspective of enterprises as the main body. Shi et al. (2018) constructed an evolutionary game model to evaluate supplier relationships, analyzing cooperative tendencies among prefabricated component suppliers in large-scale construction projects [10]. Dong et al. (2019) investigated the effects of four representative second-order reputation assessment models (Simple Standing, Stern Judging, Shunning, Image Scoring) in spatial Prisoner's Dilemma games, finding that all four regulatory mechanisms promoted cooperation [11]. Ji et al. (2024) constructed an evolutionary game model between governments and automotive enterprises. Through numerical simulation analysis, they examined the dynamic evolution and influencing factors of corporate production methods (including green production and low-carbon technology adoption) under varying regulatory intensities and incentive mechanisms [12]. Liu (2024) systematically characterized the dynamic interplay between policy risk and carbon emissions within a time-varying framework. At the macro level, this revealed the evolutionary response mechanism of low-carbon behavior to external policy shocks, providing crucial insights into the micro-level mechanisms underpinning corporate low-carbon innovation cooperation [13]. Nwilaty et al. (2023) examined the entrepreneurial pathways of sustainable recycling enterprises, demonstrating that within a rational policy and market incentive framework,

enterprises can achieve the integration of environmental and economic benefits through resource sharing and collaborative network building. This further illustrates the critical role of incentive structures and cooperative mechanism design in environmental governance outcomes [14]. Xue and Wang (2020) adopted evolutionary game theory to analyze the dynamic evolution of cooperative behavior among stakeholders in China's public-private partnership projects for integrated river water environment management. Their study explored how availability payment mechanisms and public participation in performance evaluation influence the evolutionary pathways of behavioral adoption [15]. Guo et al. (2020) built a tripartite evolutionary game model for collaborative innovation among enterprises in industrial parks, exploring the key factors affecting the strategic choices in tripartite collaborative innovation [16]. Zhou and Ren (2021) developed an evolutionary game model for collaborative innovation in low-carbon technology based on public goods games. Introducing the social exclusion mechanism and comprehensively considering the heterogeneity and non-scale characteristics of industrial clusters, they explored the fundamental requirements for the emergence of inter-enterprise collaboration [17].

In terms of institutional incentives and public behavior research, Tirtayasa et al. (2024) demonstrate that heightened green consumerism encourages consumers to choose environmentally friendly products and services, which indicates that changes in the expected benefit structure can guide individual behavioral choices [18]. Kaihatu et al. (2024) similarly found that governmental support significantly enhances corporate sustainable performance, indicating that policy incentives and resource allocation can guide enterprises to adopt greener and more sustainable operational strategies [19]. Nakamura (2019) used the method of evolutionary game dynamics to construct two models. One is a competition model between collaborators and defectors, where defectors may be punished by external authorities. In contrast, there is also a competition model among collaborators, defectors, and cooperative punishers, where defectors may be punished by cooperative punishers. This study investigates the role of third-party punishment in promoting social learning motivation for risk avoidance [20]. Luo et al. (2020) simulated the evolutionary process of enterprise environmental governance cooperation by incorporating governmental oversight actions and reputation evaluation behaviors by environmental social organizations [21].

A comprehensive review of domestic and foreign literature on cooperative behaviors shows that existing studies have laid a foundation for applying game theory to solve social dilemmas; however, further analysis is needed on the dynamic evolution mechanism of carbon emission reduction behavior among enterprises under environmental regulatory constraints. Environmental regulations can be divided into three types: command-based, incentive-based, and voluntary. Compared to command-based and voluntary environmental regulations, incentive-based regulations have unique research value. Command-based environmental regulation relies on administrative enforcement to unify standards for pollution control, resulting in an imbalanced allocation of emission reduction costs and a heavy regulatory burden. Voluntary environmental regulations have no legal binding force, and the participation behavior of enterprises fluctuates greatly. Incentive-based environmental regulation takes market tools such as environmental taxes and emissions trading as the starting point, combining the advantages of an institutional bottom line and flexible adjustment. It relies on economic signals to guide enterprises to differentiate emission reduction and optimize the allocation of pollution control resources throughout society. This type of policy fills the theoretical gap between rigid coercion and autonomous self-discipline, and is a core research carrier that balances ecological protection and stable industrial transformation. Exploring the driving mechanism of incentive parameters on the evolution of the enterprise emission reduction game system can provide a quantitative basis and decision-making support for the government to accurately optimize market-oriented carbon policies and guide spontaneous cooperation in the industrial chain to reduce carbon emissions. Consequently, this paper employs an evolutionary game model to construct a framework for the evolution of collaborative carbon reduction behavior among enterprises under incentive-based environmental regulation. It examines the dynamic evolutionary equilibrium mechanisms for achieving stable cooperative governance, while using numerical simulation to account for the impact of three kinds of incentive-based environmental regulations, including carbon emission taxation, emission trading, and emission reduction subsidies. The research results can help coordinate the interests of enterprises, comprehensively improve the level of cooperative carbon reduction, and enrich the practical experience of collaborative environmental governance.

Materials and Methods

Construction of Evolutionary Game Model for Carbon Emission Reduction Behavior among Enterprises under Incentive-Based Environmental Regulation

This paper explores stable strategies for cooperative carbon emission reduction behavior influenced by three kinds of incentive-based environmental regulations. Cooperative carbon emission reduction refers to addressing free-riding issues through collaboration with other enterprises. Inter-enterprise cooperative carbon emission reduction strategies require certain cooperation costs, and the focus of this study is on how to promote

cooperative carbon emission reduction strategies among enterprises.

Problem Description

The strategic choices of each enterprise include implementing cooperative carbon reduction (C), not engaging in a cooperative carbon reduction strategy (D), and not participating in cooperative carbon reduction (I). Among them, cooperative enterprises contribute investment *Ce* to cooperative carbon reduction efforts and share the resulting carbon reduction benefits; non-cooperative enterprises do not invest in public goods but can freely benefit from others' investment returns; non-participating enterprises neither engage in cooperative carbon reduction nor share its benefits, earning a fixed income G independent of others' actions. The strategy combination matrix of two enterprises is shown in Table 1. Under unconstrained conditions, when all enterprises in the region choose not to implement carbon emission control, they will suffer losses caused by temperature rise, sea level rise, and abnormal climate due to excessive CO_2 emissions. When one company reduces carbon emissions while the other does not, the reducing party will gain potential economic benefits (manifested as the carbon trading market value of the reduced emissions) and social benefits from the reduction, as well as corresponding reduction costs, short-term economic losses caused by carbon emission reduction, and negative externalities of the non-reducing company. The non-reducing enterprise suffers losses from its emissions. Under environmental regulation, beyond capturing their respective potential reduction benefits, when all enterprises in a region choose not to control carbon emissions, the higher-level government will impose penalties according to specific standards. When one enterprise reduces carbon emissions while another does not, the reducing party receives a certain level of reduction compensation, while the non-reducing enterprise faces penalties from the higher-level government. Under three kinds of incentive-based environmental regulation, when all enterprises cooperate on emissions reduction, they gain synergistic benefits in addition to their individual potential reduction gains, and the government provides incentives. To establish a reasonable evolutionary game model, this paper makes the following assumptions:

Assumption 1: The main entities involved in corporate cooperation to reduce carbon emissions are enterprise A and enterprise B, both of which have bounded rationality with asymmetric information between them.

Assumption 2: The enterprise's emission reduction efforts are assumed to be effective, that is, carbon emissions or emission intensity are controlled;

Assumption 3: The degree of negative externalities among enterprises is the same.

Different Scenarios and Parameter Settings

(1) In a "natural" state without additional interfering factors, each enterprise is equipped with three strategic options: Cooperative carbon reduction, non-cooperative carbon reduction, and non-participation in cooperative carbon reduction. Thus, the set of strategies for each enterprise is {Cooperative Reduction, Non-Cooperative Reduction, Non-Participation in Cooperative Reduction}. Furthermore, no enterprise possesses complete information about the game or can fully predict its outcome; each can only estimate the expected payoffs of both parties with a certain probability. For enterprise A, the probability of cooperative emission reduction is x_1, the probability of non-cooperative emission reduction is x_2, and the probability of non-participation in cooperative emission reduction is $1 - x_1 - x_2$. For enterprise B, the probability of cooperative emission reduction is y_1, the probability of non-cooperative emission reduction is y_2, and the probability of non-participation in cooperative emission reduction is $1 - y_1 - y_2$, where x_1, x_2, y_1, $y_2 \in [0,1]$ are functions of t.

(2) The individual benefit gained by an enterprise when not cooperating in emissions reduction is Rl_i (where $Rl_i>0$, $l = A, B$, representing enterprise A or enterprise B, respectively, as below). The carbon emissions when not cooperating in emissions reduction are W_i.

Table 1. Strategy combination matrix.

No.	Strategy Combination	No.	Combination Strategy
1	Collaborative Carbon Reduction, Collaborative Carbon Reduction	6	Non-Cooperative Carbon Reduction, Non-Participation in Cooperative Carbon Reduction
2	Cooperative Carbon Reduction, Non-Cooperative Carbon Reduction	7	Non-Participation in Cooperative Carbon Reduction, Cooperative Carbon Reduction
3	Collaborative Carbon Reduction, Non-Participation in Collaborative Carbon Reduction	8	Non-Participation in Cooperative Carbon Reduction, Non-Cooperative Carbon Reduction
4	Non-Cooperative Carbon Reduction, Cooperative Carbon Reduction	9	Non-Participation in Cooperative Carbon Reduction, Non-Participation in Cooperative Carbon Reduction
5	Non-Cooperative Carbon Reduction, Non-Cooperative Carbon Reduction		

(3) Assume that the government sets the maximum carbon emission standard for enterprises as $\bar{W}_i$; the carbon tax rate, carbon emission trading unit price, and input subsidy coefficient are σ, ε, μ, respectively.

(4) When enterprises engage in cooperative emissions reduction under three kinds of incentive-based environmental regulations, the synergistic benefits obtained by both parties through complementary advantages can be expressed as Rs_i. These benefits encompass both economic gains and social benefits from optimized climate and environmental outcomes.

(5) Enterprises need to pay a certain transaction cost to achieve cooperative emission reduction targets, which can be expressed as Ce_i. These costs include implementation costs and economic costs: implementation costs refer to government resources (human, material, and financial) invested in air pollution control; economic costs denote restrictions on economic development imposed by environmental constraints during air pollution control. The emission levels of enterprises choosing cooperative carbon reduction are W'_i.

(6) The government provides subsidies $\mu \times Ce_i$ to enterprises actively participating in cooperative emission reduction based on the scale of their reduction investments, while imposing penalties F_i on enterprises that do not engage in cooperative carbon emission reduction.

(7) The losses incurred by enterprises due to carbon emissions are $k \times W_i$ (or $k \times W'_i$). These losses reflect the long-term comprehensive impacts of climate change caused by emissions, including damage from extreme weather, global warming, and sea level rise. k represents the climate loss coefficient attributable to carbon dioxide emissions. The positive and negative external benefit coefficient of an enterprise's carbon emissions on surrounding enterprises is a constant θ, and $0<\theta<1$. When all enterprises in the region adopt cooperative emission reduction strategies or all adopt non-cooperative emission reduction strategies, the external effects are insignificant and can be disregarded.

(8) Non-participating enterprises neither engage in cooperative carbon reduction activities nor share in the income from such cooperation. They earn a fixed income independent of others' actions, which can be expressed as G_i.

The specific parameter settings are shown in Table 2.

Research Method

Whether enterprises within a region adopt cooperative carbon emission reduction behavior depends on the costs and benefits of cooperative reduction. Considering the fluidity of carbon and the holistic nature of governance, the benefits of cooperative governance are not only related to one's own decisions but also to the decisions of other enterprises. The game among enterprises within the region is a two-enterprise, three-strategy game.

Payoff Matrix

Derivation of the Dynamic Equation

Based on the game payoff matrix, the expected payoff for company A choosing the cooperative carbon

Table 2. Game parameters for inter-enterprise cooperative carbon reduction behavior.

No.	Factors related to collaborative carbon reduction	Company		No.	Factors related to collaborative carbon reduction	Company	
		A	B			A	B
1	Profit Without Collaboration	Rl_1	Rl_2	8	Synergistic benefits from collaborative carbon reduction	Rs_1	Rs_2
2	Carbon emissions without cooperative carbon reduction	W_1	W_2	9	Transaction Costs When Cooperating on Carbon Emissions Reduction	Ce_1	Ce_2
3	Government-mandated maximum carbon emission standards for enterprises	$\bar{W}_1$	$\bar{W}_2$	10	Carbon emissions during cooperative carbon reduction	W'_1	W'_2
4	Carbon tax rate	σ		11	Climate loss coefficient for corporate carbon emissions	k	
5	Unit Price of Carbon Emission Trading	ε		12	Government penalties for non-compliant carbon reduction enterprises	F_1	F_2
6	Input subsidy coefficient	μ		13	External effect coefficient for each enterprise	θ	
7	Benefits from non-participation in cooperative carbon reduction	G_1	G_2				

Note: All parameters are assumed to be positive, where $0<\theta<1$

Table 3. Payoff matrix for cooperative carbon reduction among enterprises under incentive-based environmental regulation.

		Company B		
		Cooperative Carbon Reduction y_1	Non-Cooperative Carbon Reduction y_2	Non-Participation in Cooperative Carbon Reduction $1-y_1-y_2$
Company A	Collaborative Carbon Reduction x_1	$Rl_1 + Rs_1 + \varepsilon(\overline{W_1} - W'_1) + \mu \times Ce_1 - \sigma \times W'_1 - Ce_1 - k \times W'_1{}^2)$ $Rl_2 + Rs_2 + \varepsilon(\overline{W_2} - W'_2) + \mu \times Ce_2 - \sigma \times W'_2 - Ce_2 - k \times W'_2{}^2)$	$Rl_1 - \varepsilon(W_1 - \overline{W_1}) + \mu \times Ce_1 - \sigma \times W_1 - Ce_1 - k \times W_1{}^2 - \theta \times k \times W_2{}^2$ $Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \sigma \times W_2 - (1-\theta) \times k \times W_2{}^2 - F_2$	$Rl_1 - \varepsilon(W_1 - \overline{W_1}) + \mu \times Ce_1 - \sigma \times W_1 - Ce_1 - k \times W_1{}^2$ G_2
	Non-cooperative carbon reduction x_2	$Rl_1 - \varepsilon(W_1 - \overline{W_1}) - \sigma \times W_1 - (1-\theta) \times k \times W_1{}^2 - F_1$ $Rl_2 - \varepsilon(W_2 - \overline{W_2}) + \mu \times Ce_2 - \sigma \times W_2 - Ce_2 - k \times W_2{}^2 - \theta \times k \times W_1{}^2$	$_1 - \varepsilon\ W_1 - W_1\ - \sigma \times W_1 - k \times W_1{}^2 - F_1$ $Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \sigma \times W_2 - k \times W_2{}^2 - F_2$	$Rl_1 - \varepsilon(W_1 - \overline{W_1}) - \sigma \times W_1 - k \times W_1{}^2 - F_1$ G_2
	Non-participation in cooperative carbon reduction $1-x_1-x_2$	G_1 $Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \mu \times Ce_2 - \sigma \times W_2 - Ce_2 - k \times W_2{}^2$	G_1 $Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \sigma \times W_2 - k \times W_2{}^2 - F_2$	G_1 G_2

reduction strategy is denoted as $u_G{}^{x1}$, the expected payoff for not engaging in cooperative carbon reduction is denoted as $u_G{}^{x2}$, and the expected payoff for the non-participation strategy is denoted as $u_G{}^{x0}$; the expected payoff for company B choosing the cooperative carbon reduction strategy is denoted as $u_G{}^{y1}$, the expected payoff for not engaging in cooperative carbon reduction is denoted as $u_G{}^{y2}$, and the expected payoff for the non-participation strategy is denoted as $u_G{}^{y0}$. From the payoff matrix, the expected payoffs for enterprise A and enterprise B choosing the cooperative carbon reduction strategy, choosing not to cooperate, and choosing not to participate in the cooperative carbon reduction strategy are calculated.

$$u_G^{x1} = y_1[Rs_1 + \varepsilon(\overline{W}_1 - \overline{W'}_1) - \sigma \times W'_1 - k \times (W'_1)^2] + y_2[-\varepsilon(W_1 - \overline{W}_1) - \theta \times k \times (W_2)^2] + [Rl_1 - \varepsilon(W_1 - \overline{W}_1) + \mu \times Ce_1 - \sigma \times W_1 - Ce_1 - k \times (W_1)^2] - y_1[-\varepsilon(W_1 - \overline{W}_1) - \sigma \times W_1 - k \times (W_1)^2] - y_2[-\varepsilon(W_1 - \overline{W}_1)]$$
$$= y_1 \times [Rs_1 + \varepsilon \times W'_1 + \sigma \times (W_1 - W'_1) + k \times (W_1^2 - W'_1{}^2)] + y_2 \times [-\theta \times k \times (W_2)^2] + [Rl_1 - \varepsilon(W_1 - \overline{W}_1) + \mu \times Ce_1 - \sigma \times W_1 - Ce_1 - k \times (W_1)^2]$$

$$u_G^{x2} = y_1 \times \theta \times k \times (W_1)^2 + [Rl_1 - \varepsilon(W_1 - \overline{W_1}) - \sigma \times W_1 - k \times (W_1)^2 - F_1]$$

$$u_G^{x0} = G_1$$

$$u_G^{y1} = x_1 \times [Rs_2 + \varepsilon \times W'_2 + \sigma \times (W_2 - W'_2) + k \times (W_2^2 - W'_2{}^2)] + x_2 \times [-\theta \times k \times (W_1)^2] + [Rl_2 - \varepsilon(W_2 - \overline{W}_2) + \mu \times Ce_2 - \sigma \times W_2 - Ce_2 - k \times (W_2)^2]$$

$$u_G^{y2} = x_1 \times \theta \times k \times (W_2)^2 + [Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \sigma \times W_2 - k \times (W_2)^2 - F_2]$$

$$u_G^{y0} = G_2$$

Based on the replicator dynamics equations, let the growth rates of the proportions of enterprises choosing cooperative carbon reduction and non-cooperative carbon reduction strategies be $f_1(x_1)$, $f_2(x_2)$, $f_3(y_1)$, $f_4(y_2)$. Then, the Malthusian equation is:

$$f_1(x_1) = dx_1/dt = x_1 * [u_G^{x1} - x_1 * u_G^{x1} - x_2 * u_G^{x2} - (1 - x_1 - x_2) * u_G^{x0}]$$

$$f_2(x_2) = dx_2/dt = x_2 * [u_G^{x2} - x_1 * u_G^{x1} - x_2 * u_G^{x2} - (1 - x_1 - x_2) * u_G^{x0}]$$

$$f_3(y_1) = dy_1/dt = y_1 * [u_G^{y1} - y_1 * u_G^{y1} - y_2 * u_G^{y2} - (1 - y_1 - y_2) * u_G^{y0}]$$

$$f_4(y_2) = dy_2/dt = y_2 * [u_G^{y2} - y_1 * u_G^{y1} - y_2 * u_G^{y2} - (1 - y_1 - y_2) * u_G^{y0}]$$

Equilibrium Point Solution and Stability Analysis

The equilibrium points of the evolutionary game dynamics can be generated from

$$f_1(x_1)=\frac{dx_1}{dt}=0\ ,\quad f_2(x_2)=\frac{dx_2}{dt}=0\ ,$$
$$f_3(y_1)=\frac{dy_1}{dt}=0\ ,\text{ and }\quad f_4(y_2)=\frac{dy_2}{dt}=0 \qquad (1)$$

The asymptotic stability of equilibrium points is determined using the Lyapunov criterion (indirect method), thus requiring the solution of the Jacobian matrix and its eigenvalues. Taking the first-order partial derivatives of x_1, x_2, y_1, y_2 with respect to $f_1(x_1)$, $f_2(x_2)$, $f_3(y_1)$, and $f_4(y_2)$ yields the Jacobian matrix of this system as follows:

$$J=\begin{bmatrix} df_1(x_1)/dx_1 & df_1(x_1)/dx_2 & df_1(x_1)/dy_1 & df_1(x_1)/dy_2 \\ df_2(x_2)/dx_1 & df_2(x_2)/dx_2 & df_2(x_2)/dy_1 & df_2(x_2)/dy_2 \\ df_3(y_1)/dx_1 & df_3(y_1)/dx_2 & df_3(y_1)/dy_1 & df_3(y_1)/dy_2 \\ df_4(y_2)/dx_1 & df_4(y_2)/dx_2 & df_4(y_2)/dy_1 & df_4(y_2)/dy_2 \end{bmatrix}$$

The first-order partial derivatives are as follows:

$$df_1(x_1)/dx_1=(1-2x_1)*u_G^{x1}-x_2*u_G^{x2}-(1-2x_1-x_2)*u_G^{x0}$$
$$df_2(x_2)/dx_2=(1-2x_2)*u_G^{x2}-x_1*u_G^{x1}-(1-2x_2-x_1)*u_G^{x0}$$
$$df_1(y_1)/dy_1=(1-2y_1)*u_G^{y1}-y_2*u_G^{y2}-(1-2y_1-y_2)*u_G^{y0}$$
$$df_2(y_2)/dy_2=(1-2y_2)*u_G^{y2}-y_1*u_G^{y1}-(1-2y_2-y_1)*u_G^{y0}$$

Since x_1, x_2 (or y_1, y_2) cannot simultaneously be equal to 1, according to Equation (1), the system has a total of 3×3 = 9 pure-strategy internal equilibrium points. Substituting these into the Jacobian matrix yields the corresponding eigenvalues. According to the Lyapunov criterion, if all eigenvalues of the Jacobian matrix satisfy $\lambda>0$, the equilibrium point is unstable. If all eigenvalues satisfy $\lambda\leq 0$, the equilibrium point is stable. If the eigenvalues include both positive and negative values (non-zero), the equilibrium point is a saddle point. If both the trace condition (the sum of the diagonal elements of the Jacobian matrix is less than 0) and the determinant condition (the determinant is greater than 0) are satisfied, denoted as *trJ* (*trJ*<0) and *detJ* (*detJ*>0), respectively, then the equilibrium point of the replicator dynamics is locally stable, and this equilibrium point constitutes an evolutionarily stable strategy. Integrating the above inequality relationships and constraint conditions yields the stability judgment

Table 4. Stability analysis of equilibrium points.

No.	Pure Strategy Internal Equilibrium Point				Eigenvalue			
	x_1	x_2	y_1	y_2	1	2	3	4
1	0	0	0	0	U_1-G_1	U_2-G_1	V_1-G_2	V_2-G_2
2	0	0	0	1	$-\theta\times k\times(W_2)^2+U_1-G_1$	U_2-G_1	V_1-V_2	G_2-V_2
3	0	0	1	0	$Z_1+U_1-G_1$	$\theta\times k\times(W_1)^2+U_2-G_1$	G_2-V_1	V_2-V_1
4	0	1	0	0	U_1-U_2	G_1-U_2	$-\theta\times k\times(W_1)^2+V_1-G_2$	V_2-G_2
5	1	0	0	0	G_1-U_1	U_2-U_1	$Z_2+V_1-G_2$	$\theta\times k\times(W_2)^2+V_2-G_2$
6	1	0	1	0	$G_1-Z_1-U_1$	$\theta\times k\times(W_1)^2+U_2-Z_1-U_1$	$G_2-Z_2-V_1$	$\theta\times k\times(W_2)^2+V_2-Z_2-V_1$
7	1	0	0	1	$G_1+\theta\times k\times(W_2)^2-U_1$	$U_2+\theta\times k\times(W_2)^2-U_1$	$Z_2+V_1-\theta\times k(W_1)^2-V_2$	$G_2-\theta\times k\times(W_2)^2-V_2$
8	0	1	1	0	$Z_1+U_1-\theta\times k\times(W_2)^2-U_2$	$G_1-\theta\times k\times(W_1)^2-U_2$	$G_2+\theta\times k\times(W_1)^2-V_1$	$G_2+\theta\times k\times(W_1)^2-V_1$
9	0	1	0	1	$-\theta\times k\times(W_2)^2+U_1-U_2$	G_1-U_2	$-\theta\times k\times(W_1)^2+V_1-V_2$	G_2-V_2

for equilibrium points, as shown in Table 4 below.

Let $U_1 = Rl_1 - \varepsilon(W_1 - \overline{W_1}) + \mu \times Ce_1 - \sigma \times W_1 - Ce_1 - k \times (W_1)^2$ denote the profit of enterprise A when enterprise A participates in cooperative emission reduction and enterprise B does not participate.

$U_2 = Rl_1 - \varepsilon(W_1 - \overline{W_1}) - \sigma \times W_1 - k \times (W_1)^2 - F_1$ denotes the payoff for enterprise A when it does not participate in cooperative emission reduction.

$Z_1 = Rs_1 + \varepsilon \times W'_1 + \sigma \times (W_1 - W'_1) + k \times ({W_1}^2 - {W'_1}^2) > 0$ denotes the synergistic benefit of cooperative emission reduction.

Let $V_1 = Rl_2 - \varepsilon(W_2 - \overline{W_2}) + \mu * Ce_2 - \sigma * W_2 - Ce_2 - k * (W_2)^2$ denote the profit of enterprise B when enterprise B participates in cooperative emission reduction while enterprise A does not.

$V_2 = Rl_2 - \varepsilon(W_2 - \overline{W_2}) - \sigma \times W_2 - k \times (W_2)^2 - F_2$ denotes the benefit to enterprise B when it does not participate in cooperative emission reduction.

$Z_2 = Rs_2 + \varepsilon \times W'_2 + \sigma \times (W_2 - W'_2) + k \times ({W_2}^2 - {W'_2}^2) > 0$ denotes the synergistic benefit from cooperative emission reduction.

Results and Discussion

Stability of the Evolutionary Game Model for Inter-enterprise Cooperative Carbon Emission Reduction

Based on evolutionary game theory, this paper focuses on exploring the evolution of inter-enterprise cooperative carbon emission reduction behavior under bounded rationality and identifying behavioral factors influencing the game's evolutionary process. In evolutionary game theory, the Evolutionarily Stable Strategy (ESS) serves as a criterion for determining whether a system has reached equilibrium, playing a crucial role in the game's evolutionary process. By solving the determinant and trace of the Jacobian matrix of the two-dimensional differential equation system, the ESS of the system can be identified. As shown in Table 4:

Scenario 1: When $G_1 > U_1 > U_2$, i.e., when the profit of non-cooperative enterprises exceeds the profits of cooperative and non-cooperative enterprises, the optimal choice for both enterprises is to adopt the non-cooperative emission reduction model. Thus, the system's ESS is (0,0,0,0).

Scenario 2: When $U_1 > G_1$ and $Z_1 + U_1 > U_2 + \theta \times k(W_i)^2$, the profit from one party cooperating while the other does not exceeds the profit from non-participation. Furthermore, the synergistic profit from cooperative carbon reduction plus the profit from one party cooperating while the other does not exceeds the sum of the profit from non-participation and the external effect profit. Thus, the optimal choice for both enterprises is to adopt the cooperative carbon reduction behavior pattern, resulting in the system's evolutionarily stable strategy of (1,0,1,0).

Scenario 3: When $U_2 > G_1$ and $U_2 + \theta \times k(W_i)^2 > U_1 + Z_1$, the payoff from non-cooperation exceeds the payoff from non-participation in cooperation. Furthermore, the sum of the payoff from non-cooperative emissions reduction and externalities exceeds the sum of the payoff from one party cooperating while the other does not and the synergistic benefit from cooperative emissions reduction. Thus, the optimal choice for both enterprises is to adopt a non-cooperative emissions reduction behavior pattern. Consequently, the system's evolutionarily stable strategy is (0,1,0,1).

Numerical Experiments and Simulation Analysis

Based on the theoretical analysis above, numerical simulations of the evolutionary process of cooperative carbon reduction behavior between enterprises were conducted using MATLAB, incorporating the constraint conditions and replicator dynamics equations.

Stability Analysis of Model Equilibrium Points

(1) Scenario 1: When $G_1 > U_1 > U_2$, the system's evolutionarily stable strategy (ESS) is (0,0,0,0). Suppose enterprise A chooses cooperation and non-cooperation strategies, while enterprise B selects cooperation and non-cooperation strategies with initial proportions of (x_1, x_2, y_1, y_2), respectively. With an initial time of 0 and an evolutionary termination time of 20, the initial state is set to (0.2, 0.4, 0.2, 0.3). The parameter values are $Rs_1 = 15$, $\varepsilon = 6$, $W'_1 = 10$, $\sigma = 0.06$, $W_1 = 20$, $k = 0.03$, $\theta = 0.2$, $W_2 = 20$, $RL_2 = 10$, $RL_1 = 10$, $\overline{w}_1 = 15$, $\mu = 1.2$, $Ce_1 = 10$, $F_1 = 10$, $Rs_2 = 15$, $W'_2 = 10$, $Ce_2 = 10$, $F_2 = 10$, $G_1 = 20$, $G_2 = 20$. As shown in Fig. 1, as the number of evolutionary iterations increases, the proportion of cooperation and non-cooperation between enterprise A and enterprise B continuously decreases. The stable mode is that both enterprise A and enterprise B do not participate in cooperation, which verifies Scenario 1.

(2) Scenario 2: When $U_1 > G_1$ and $Z_1 + U_1 > U_2 + \theta \times k(W_i)^2$, the Evolutionarily Stable Strategy (ESS) of the system is (1,0,1,0). With initial state (0.2, 0.4, 0.2, 0.3) and parameter values $Rs_1 = 15$, $\varepsilon = 6$, $W'_1 = 10$, $\sigma = 0.06$, $W_1 = 17$, $k = 0.03$, $\theta = 0.2$, $W_2 = 17$, $RL_2 = 30$, $RL_1 = 30$, $\overline{w}_1 = 15$, $\mu = 1.2$, $Ce_1 = 30$, $F_1 = 10$, $Rs_2 = 15$, $W'_2 = 10$, $\overline{W}_2 = 15$, $Ce_2 = 30$, $F_2 = 10$, $G_1 = 10$, $G_2 = 10$, the above conditions are satisfied. As shown in Fig. 1 of the simulation, as the number of evolutionary iterations increases, the proportion of enterprises A and B adopting the cooperative mode continues to increase. The stable mode is that both enterprises A and B adopt the cooperative mode, which verifies Scenario 2.

(3) Scenario 3: When $U_2 > G_1$ and $U_2 + \theta \times k(W_i)^2 > U_1 + Z_1$, the system's Evolutionarily Stable Strategy (ESS) is (0,1,0,1). Setting the initial state as (0.2, 0.4, 0.2, 0.3)

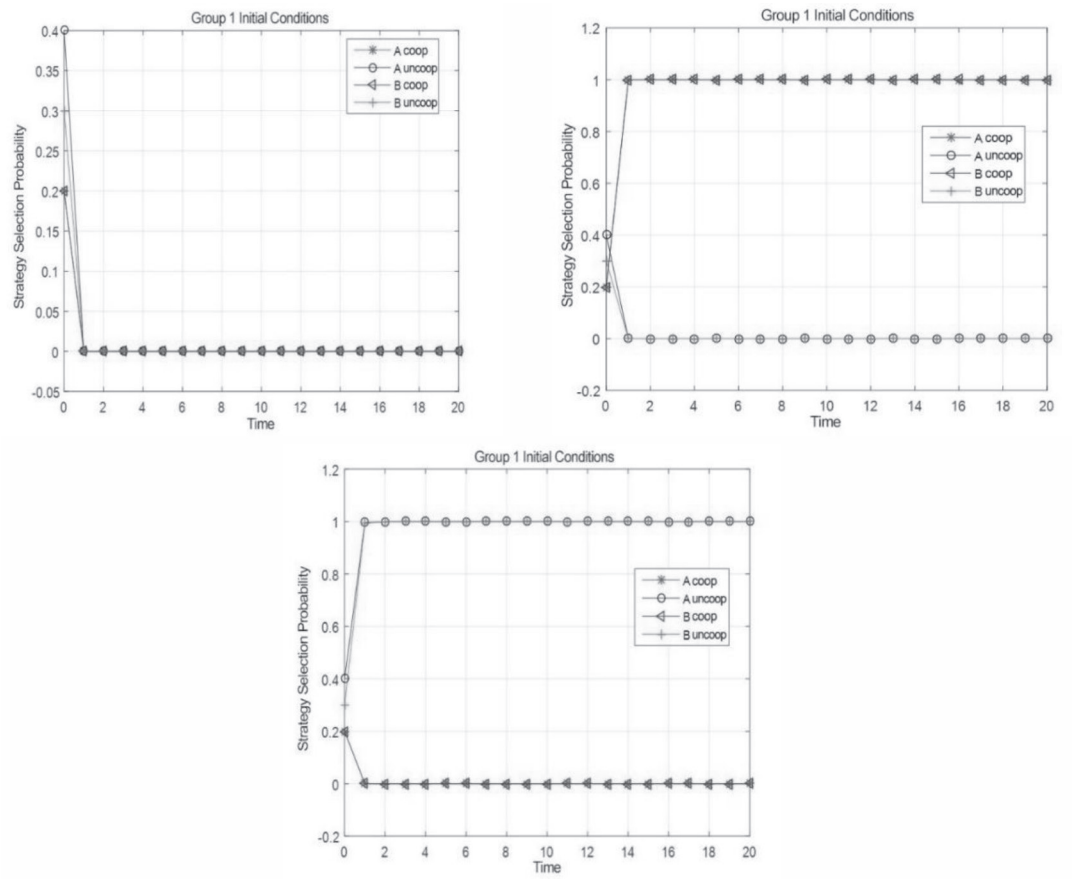


Fig. 1. Simulation results under different scenarios (from left to right: Scenario 1, Scenario 2, Scenario 3).

and the parameter values as $Rs_1 = 15$, $\varepsilon = 6$, $W'_1 = 10$, $\sigma = 0.06$, $W_1 = 17$, $k = 0.03$, $\theta = 0.4$, $W_2 = 17$, $RL_2 = 40$, $RL_1 = 40$, $\bar{w}_1 = 15$, $\mu = 0.8$, $Ce_1 = 100$, $F_1 = 3$, $Rs_2 = 15$, $W'_2 = 10$, $\bar{W}_2 = 15$, $Ce_2 = 100$, $F_2 = 3$, $G_1 = 10$, $G_2 = 10$, satisfies the above conditions. As shown in Fig. 1 of the simulation, as the number of evolutionary iterations increases, the proportion of enterprise A and enterprise B adopting the non-cooperative mode continues to increase. The stable mode is that both enterprise A and enterprise B do not adopt the cooperative mode, which verifies Scenario 3.

Analysis of Factors Influencing Inter-enterprise Cooperative Carbon Reduction Behavior

To assess the importance of basic cooperative emission reduction, this study builds upon existing theoretical analysis. By selecting Scenario 2 (where the evolutionarily stable pattern for enterprises A and B is {Cooperative Emissions Reduction, Cooperative Emissions Reduction}) and adjusting relevant parameters, we observe trends in the evolution of stable behaviors to analyze how different factors influence the cooperative emissions reduction strategies of participating entities.

(1) Impact of carbon tax rates on system evolution

Initial values are set as (0.2, 0.4, 0.3, 0.7), with carbon tax rates of (0.02, 0.1, 0.4), corresponding to the left-to-right progression in Fig. 2. In the scenario where σ takes three carbon tax rates of 0.02, 0.1, and 0.4, the system maintains a long-term steady state, that is, after dynamic evolution, the probability of enterprises A and B choosing a cooperative emission reduction strategy converges to 1, and the probability of the non-cooperative strategy asymptotically approaches 0. Bilateral collaborative emission reduction becomes an evolutionarily stable equilibrium.

The increase in tax rates mainly changes the convergence rate of the system. The increase in carbon tax values significantly accelerates the speed at which corporate strategies move towards cooperative equilibrium. From the perspective of regulatory mechanisms, carbon taxes internalize the external environmental costs of carbon emissions. Raising tax rates will amplify the tax burden cost of non-cooperative strategies, increase the opportunity cost of high-carbon operations for enterprises, and weaken the payoff advantage of non-cooperative strategies. The cooperation model can facilitate the sharing of emission reduction technologies and the allocation of fixed renovation costs and effectively reduce overall carbon tax expenditures. The increase in the marginal intensity of the carbon tax widens the profit difference between the two types of strategies, accelerates the imitation and evolution of group strategies, and thereby strengthens the guiding effectiveness of regulation on enterprises'

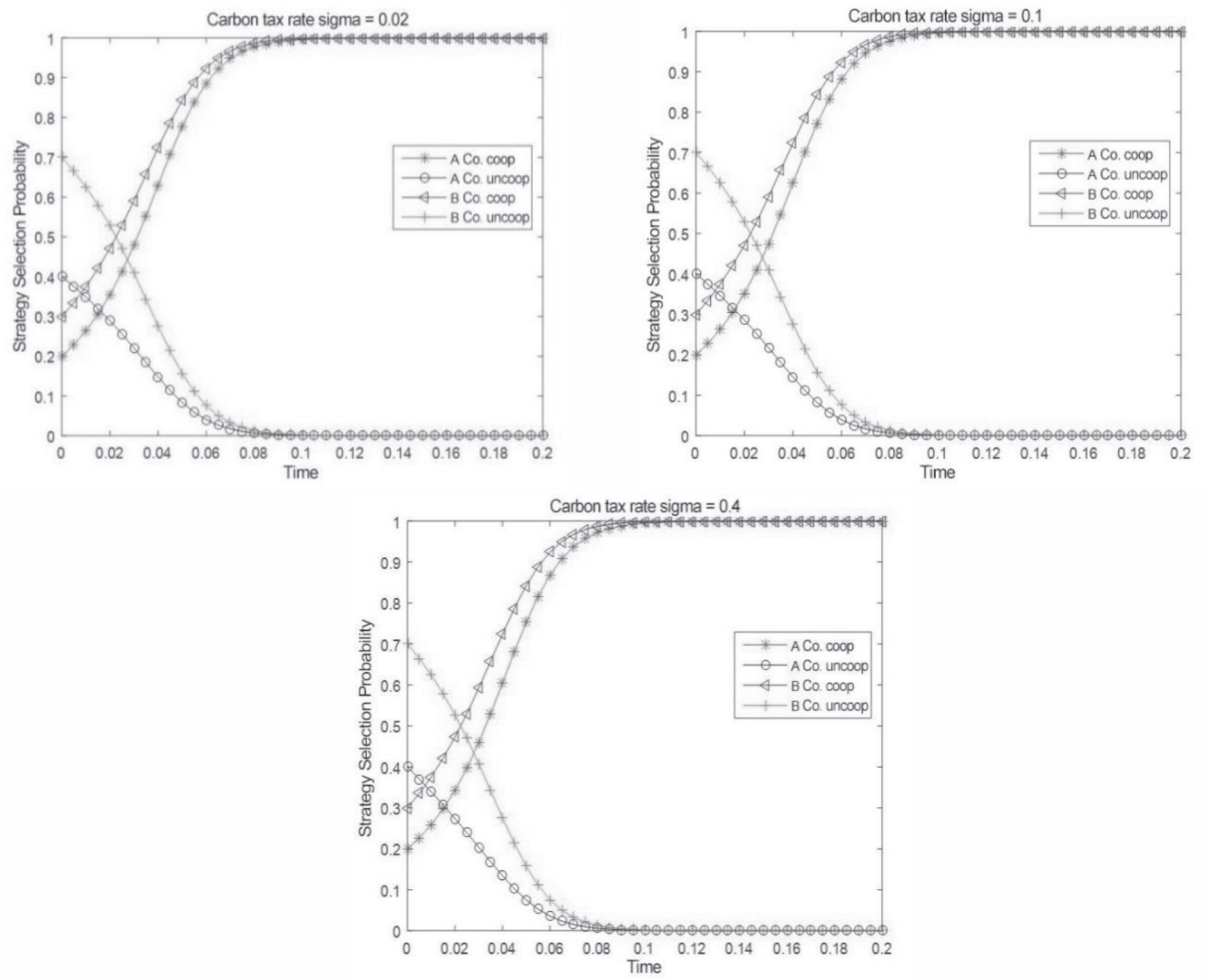


Fig. 2. Simulation results under different carbon tax rates.

low-carbon collaborative behavior.

(2) Impact of unit price of carbon emission trading on system evolution

With initial values set at (0.2, 0.4, 0.3, 0.7), the unit prices of carbon emission trading are 6, 30, and 120, corresponding to the left-to-right progression in Fig. 3. The results show that when the unit price of carbon emission trading η is set to 6, 30, and 120, the long-term stable equilibrium of the evolutionary system is robust. After iterative evolution through replicator dynamics, the evolutionary probability of the cooperative emission reduction strategies of enterprises A and B gradually converges to 1, and the probability of non-cooperative strategies converges to 0. Bilateral collaborative emission reduction among enterprises becomes the only stable evolutionary strategy.

Parameter heterogeneity analysis shows that the upward trend of carbon quota prices can significantly compress the convergence period of the system and accelerate the transition of group strategies to a cooperative steady state. From the perspective of external governance theory, carbon trading relies on market-oriented pricing mechanisms to internalize the external costs of carbon emissions. Specifically, the increase in carbon prices will increase the rigid expenditure of enterprises on purchasing carbon emission quotas in non-cooperative scenarios. The cooperative emission reduction model can increase the returns on cooperation by complementing emission reduction technologies among entities, optimizing production capacity, and reducing overall emission intensity. Therefore, the increase in the carbon price gradient widens the payoff matrix difference between the two strategies, accelerates the learning and imitation rates of boundedly rational enterprises, and thus strengthens the positive regulatory traction effect of the carbon emission trading system on enterprises' low-carbon collaborative decision-making.

(3) Impact of input subsidy coefficients on system evolution

With initial values set at (0.2, 0.4, 0.3, 0.7), the input subsidy coefficient values are 0.5, 2.5, and 10, corresponding to the left-to-right order in Fig. 4. The figure reveals that as the input subsidy coefficient increases, the rate at which enterprises evolve toward cooperative carbon emission reduction accelerates, progressing from slowest to fastest for input subsidy coefficients of 0.5, 2.5, and 10. Simultaneously, the rate at which non-cooperative carbon emission reduction declines also increases.

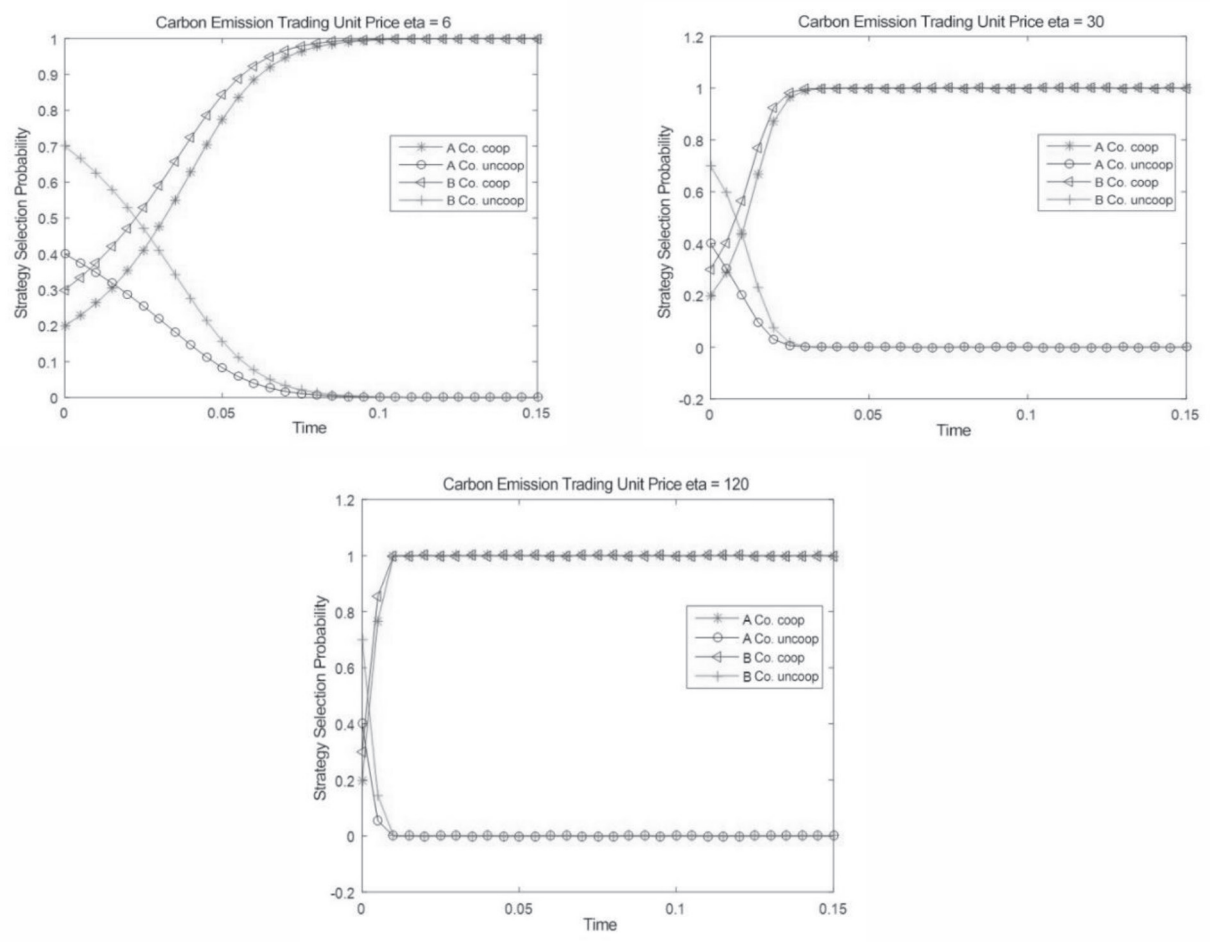


Fig. 3. Simulation results at different carbon emission trading unit prices.

As the subsidy coefficient increases, the convergence period of the system towards cooperative equilibrium is significantly shortened, and the iteration rate of enterprise decision-making is significantly accelerated. From the perspective of regulatory theory, investment subsidies can offset the sunk costs of technology research and development and equipment replacement in enterprises' low-carbon collaboration process, and improve the net profit level of cooperation strategies. The increase in subsidy intensity further reduces the marginal investment burden on the cooperative end and amplifies the payoff advantage compared to the non-cooperative path. Market entities with bounded rationality use strategy trial and group learning to identify the benefits of cooperation, thereby enhancing the policy intervention effectiveness of government subsidies to guide enterprises to carry out low-carbon cooperation.

The simulation results from Figs 2, 3, and 4 show that all three types of policies can correct the external market failures caused by carbon emissions, and regardless of the gradient of regulatory parameters, the system will eventually converge to an evolutionarily stable equilibrium of two-way cooperation between enterprises A and B in emission reduction. This proves that all three regulatory tools can promote enterprises to achieve a low-carbon collaborative pattern in the long run.

It is found that carbon tax, carbon emission trading, and emission reduction subsidies have heterogeneous effects on the evolution of inter-enterprise cooperative carbon reduction systems. Carbon emission trading relies on the dual mechanism of reward and punishment, which can simultaneously promote cooperation and restrain non-cooperation, achieving the best regulatory effect. Input subsidies form one-way positive incentives by compensating cooperative costs and also effectively drive the system to evolve toward cooperative equilibrium. In contrast, carbon tax imposes uniform cost constraints on all emission behaviors. Raising the tax rate cannot form a differentiated benefit structure; it not only fails to curb non-cooperative behaviors but also suppresses the profit level of cooperative carbon reduction. The essential differences in the operating logic of the three policies lead to different regulatory efficiencies. This conclusion provides a simulation basis for the coordinated implementation of diversified market-oriented carbon regulatory policies. In general, reasonable regulatory intensity and policy combinations play a decisive role in promoting inter-enterprise cooperative carbon reduction.

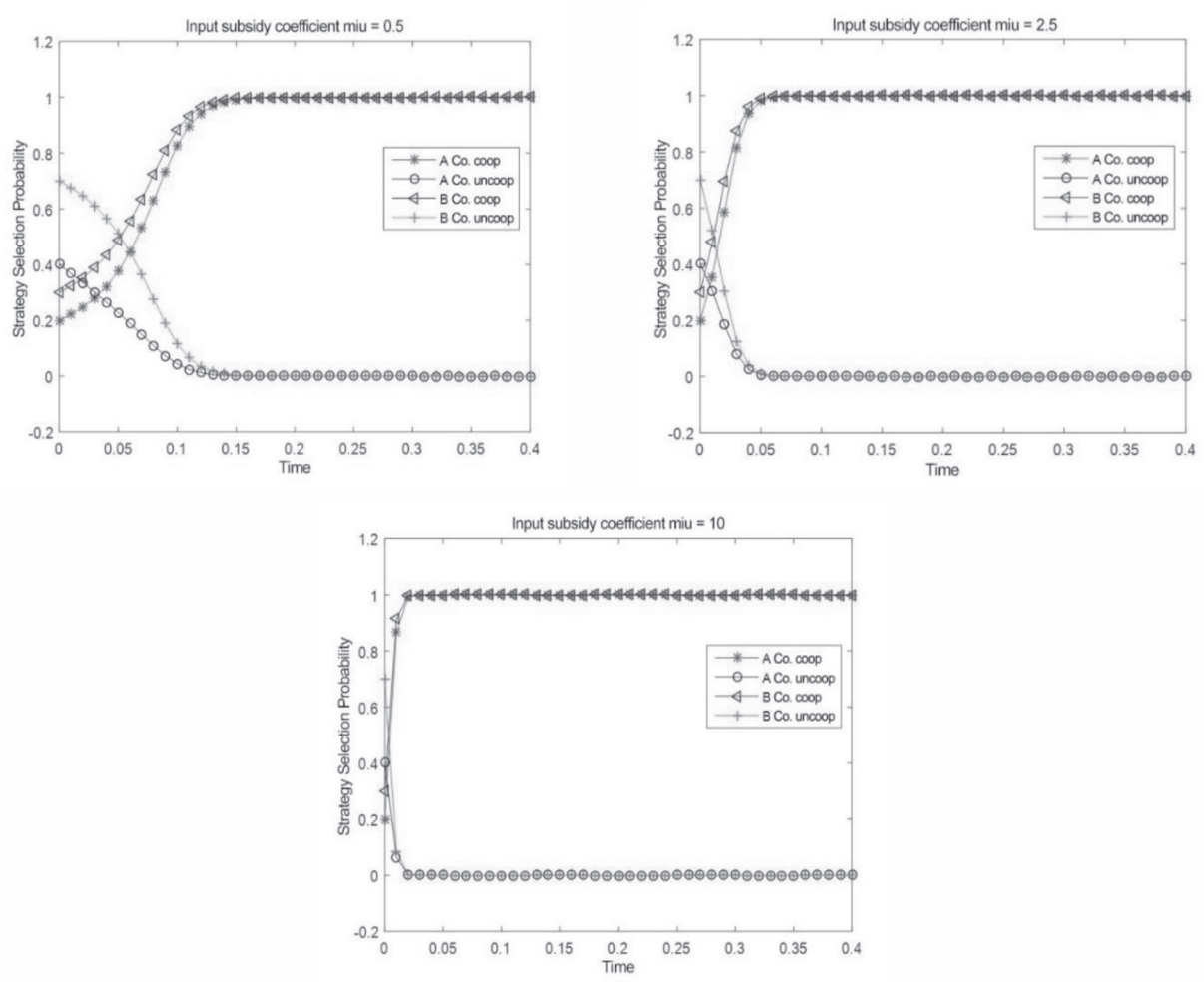


Fig. 4. Simulation Results under Different Input Subsidy Coefficients.

Conclusions

It is of great practical significance to use incentive-based environmental regulations to promote enterprise cooperation in carbon reduction. In practice, enterprises often exhibit non-cooperative behavior that deviates from the direction of cooperation due to factors such as selfishness and bounded rationality, which has a certain impact on the achievement of cooperation contracts and the maximization of benefits, and also poses certain obstacles to the achievement of carbon emission reduction goals. This paper utilizes the relevant knowledge of game theory to construct an evolutionary game model for cooperative carbon emission reduction among enterprises. Based on this model, the strategic choices and path evolution of the game subjects are analyzed, and the effects of carbon tax rates, carbon emission trading unit prices, and input subsidy coefficients on cooperative carbon emission reduction behavior among enterprises are examined. The research findings indicate: (1) The process of selecting strategies for cooperative carbon emission reduction among enterprises is a constantly changing process. The choice of cooperative carbon emission reduction or non-cooperative carbon emission reduction by enterprises depends on the behavioral strategy of the other enterprise. At the same time, enterprises' choice of a cooperative carbon emission reduction strategy depends on the parameter value relationship, which in turn depends on the carbon tax rate, carbon emission trading unit price, and input subsidy coefficient; (2) When Scenario 3: When $U_1 > G_2$ and $Z_1 + U_1 > U_2 + \theta \times k(W_i)^2$, the optimal choice for both enterprises is to adopt cooperative carbon reduction behavior; (3) Incentive-based environmental regulation, as a normative additional cost, hinders the formation of cooperative reduction behavior when the carbon tax rate increases. Conversely, higher carbon emission trading prices and input subsidy coefficients ignificantly promote inter-enterprise cooperative carbon reduction.

Based on the above conclusions, the following policy implications are proposed. In order to ensure the smooth implementation of environmental protection taxes, most provinces and municipalities have shifted their environmental protection taxes from the original pollutant discharge fee collection standards. The appropriate pollutant tax amount for different

regions should be determined based on their economic development status. At the same time, the preferential policies for environmental protection taxes, such as linking tax optimization policies with the ways in which enterprises reduce pollutant emissions, and leveraging the dual mechanisms of “constraints” and “incentives”, should be refined. Policies such as environmental protection tax reduction and exemption, tax incentives for high-tech enterprises, etc., should be integrated to form a policy synergy, thereby promoting internal control and green research and development among various taxpayers to reduce tax costs.

In addition, a collaborative mechanism among multiple departments such as ecological environment, development and reform, finance, taxation, and banking should be established to coordinate policies such as carbon tax, carbon trading, and subsidies and form a policy synergy. For example, the finance department is responsible for the overall arrangement of subsidy funds, the tax department implements carbon tax reduction policies, the financial department provides financing support such as green loans and green bonds, and the ecological environment department is responsible for verifying and supervising the emission reduction effect to ensure that various policies are interconnected and coordinated.

The findings of this study provide valuable guidance for optimizing cooperative carbon reduction behavior among enterprises. However, the analysis is limited to a two-party game scenario. Future research could explore multi-agent, multi-strategy evolutionary game problems. Additionally, this study did not account for other factors influencing inter-enterprise cooperation, such as spillover effects from environmental regulations. In addition, it is possible to further explore the linkage effects of various incentive-based regulatory tools on the stable carbon emission reduction strategies, green innovation behaviors, and long-term sustainable performance in inter-enterprise cooperation by combining incentive-based environmental regulation scenarios.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, Huo H.H., upon reasonable request.

Author Contributions

All authors contributed equivalently to this research. H.H. developed the original idea. All authors designed this study and collected and analyzed the data. H.H. and W.Z. established the model and wrote the initial draft. W.Z. read and modified the initial draft and provided suggestions for improvement. All authors have read and agreed to the published version of the manuscript.

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AI Usage Disclosure Statement

In the process of writing the manuscript, the authors mainly used the artificial intelligence tool Dou Bao to check the spelling and grammar in the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

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