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Research Article

Game Analysis of Supply Chain Enterprises' Choice of Carbon Emission Reduction Behavior under Environmental Regulation and Consumers' Low Carbon Preference

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Under the background of low-carbon economy, in order to explore the internal mechanism of enterprises implementing carbon emission reduction behavior, this paper uses evolutionary game theory and numerical simulation method to study the evolutionary stability strategy and its influencing factors of carbon emission reduction behavior of supply chain enterprises in a two-level supply chain composed of a single supplier and a single manufacturer from a dynamic perspective, considering environmental regulation and consumers' preference for low carbon emission. The results show that there are certain conditions that make supply chain enterprises converge to carbon emission reduction investment behavior under the effect of command-and-control environmental regulation and consumer low-carbon preference, and converge to cooperative carbon emission reduction behavior under the effect of market-based environmental regulation and consumer low-carbon preference. On this basis, the factors significantly influence the carbon emission reduction investment behavior of supply chain enterprises are the carbon emission reward and punishment coefficient and the low carbon preference coefficient of consumers. Increasing the carbon tax rate, carbon emission trading price and the proportion of cost subsidies, as well as encouraging consumers to consume low-carbon products will help promote the realization of cooperative carbon emission reduction.

1. Introduction

One of the characteristics of the 21st century is the excessive use of the atmosphere as a greenhouse gas disposal space [1]. In 2021, global carbon dioxide emissions from the global energy sector reached 36.3 billion tonnes, a 6% increase year-on-year, surpassing the level before the outbreak of the COVID-19 and setting an all-time record [2]. The 2021 Emission Gap Report issued by the United Nations Environment Programme pointed out that in order to control global warming below 1.5°C by the end of this century and achieve the ideal goal of the Paris Agreement, the world needs to halve its annual greenhouse gas emissions in the next 8 years. Enterprises are the main body of carbon emission, the total carbon dioxide emissions of the 100 listed companies mentioned in the "China Listed Company Carbon Emissions Ranking (2021)" totaled 4.424 billion tons, accounting for about 44.7% of the national total and 13.7% of the global total. However, due to the large cost of implementing carbon emission reduction investment, enterprises will face a lot of financial pressure, which makes enterprises lack enthusiasm and initiative in environmental protection investment. The behavior of enterprises is often a response to the government's environmental protection regulatory policies [3], governments of various countries have formulated carbon emission reduction targets and issued environmental regulatory policies (such as total emission control, emission standard control, and carbon emission trading, etc.) to regulate high-carbon emission industries.

While the government has stepped up efforts to promote emission reduction, consumers' low carbon awareness is also gradually increasing. Shuai et al. found that with the improvement of education level and income level, Chinese residents are more and more willing to pay more for low-carbon products [4]. According to Toluna's 2019 sustainability report, more than one-third (37%) of the 1000 U.S. consumers surveyed said they sought and were willing to pay 5% more for environmentally friendly products. It can be seen that in addition to the functional value of the commodity itself, consumers are gradually paying attention to the low-carbon attribute of the commodity, that is, consumers' low-carbon preference. Liu et al. and Wu et al. pointed out that the greater consumers' preference for low carbon, the more beneficial it is to supply chain enterprises [5, 6]. Therefore, the influence of consumers' low carbon preference should also be considered in the decision-making of enterprises' carbon emission reduction behavior.

The operation mode of enterprises is changing with the progress of science and technology, upstream and downstream enterprises gradually consider to form a community of interests from a link in the supply chain, which makes the decision of carbon emission reduction behavior closely related to the decision of upstream and downstream enterprises. Therefore, by analyzing the possible carbon emission reduction behavior response of enterprises in the supply chain (composed of a single supplier and a single manufacturer) under the dual effects of environmental regulation and consumers' low-carbon preference, this paper discusses what equilibrium state will be produced in the process of strategic interaction between enterprises? what conditions need to be met to achieve the ideal equilibrium state? And what factors affect these equilibrium states? Through the analysis of the above problems, it provides a theoretical basis for supply chain enterprises to implement carbon emission reduction behavior decision-making, and provides a reference for government environmental policy-making.

2. Literature Review

The profit-seeking nature of an enterprise determines that the choice of corporate behavior is based on cost and benefit. In the actual operation process, the cost and benefit of an enterprise are affected by many factors such as government policies and public preferences [7]. Environmental regulation is a necessary response to the problem of environmental impact [8], which is generated to solve the negative externality of environmental pollution, and it continues to expand with the development of ecological environment and people's demands for environmental improvement. According to the mechanisms, means and methods of functioning, environmental regulation policies can be divided into command-and-control policies, market-based policies, voluntary agreement policies and information tool policies [9].

The impact of environmental regulation policy on enterprise carbon emission reduction decision. Xu et al. investigated the impact of environmental penalties on enterprises' emission reduction decisions through the data of Chinese listed industrial companies, and found that China's environmental penalties did not have a substantial impact on enterprises' emission reduction decisions, but only reduced the absolute emission level of enterprises [10]. Han et al. studied the mechanism of environmental regulation driven emission reduction and found that the total amount of constrained pollutants has a significant emission reduction effect at the enterprise level, and it will drive enterprises to adopt cleaner production and end-of-line treatment to reduce pollutant emissions [11]. Huang et al. used the difference-in-difference method to find that environmental regulation has a positive impact on R&D spending [12]. However, since carbon tax will generate additional tax costs, it will also have a negative impact on corporate investment decisions [13]. Cheng and Sun divided environmental regulation into two categories: mandatory and incentive, and divided low-carbon manufacturing practice into five dimensions: supply chain enterprise cooperation, internal management support, production process management, low-carbon product design and environmental standard implementation, using structural equation model to explore the relationship between environmental regulation and low-carbon manufacturing practice. The results show that environmental regulation has a significant role in promoting low-carbon manufacturing practice, and the impact of mandatory and incentive environmental regulation on each dimension of low-carbon manufacturing practice is different. Mandatory environmental regulation has a significant positive impact on internal management support, low-carbon product design and implementation of environmental standards; incentive environmental regulation has a significant positive impact on supply chain enterprise cooperation and production process management [14]. However, there are also studie believe that environmental regulation cannot promote the practice of supply chain extension under carbon emission reduction targets [15]. Existing literature mainly studies the effects of single environmental regulation measures such as carbon tax and carbon emission right trading, and finds that different types of environmental regulation provide different constraints or incentive conditions for enterprises' carbon emission reduction behaviors, and enterprises may show different attitudes and behavior choices.

The environmental value function of low-carbon products can enhance the utility of consumers [16], making consumers more inclined to consume low-carbon products. Some scholars have studied the impact of consumers' low-carbon preference on enterprise decision-making. Du et al. studied the impact of carbon footprint and low carbon preference on the production decisions of emissions-dependent firms in the total amount control and trading system and found that low-carbon processing has no economic cost advantage for manufacturers who only consider total amount control and trading, when consumers have a strong low carbon preference, manufacturers will choose it [17]. Wen et al. used a duopoly game model to study the carbon emission reduction and pricing strategies of enterprises facing the dual pressures of emissions trading prices and consumers' carbon awareness in a competitive market. The results show that carbon price and consumer awareness have cumulative effects on the company's emission reduction efforts [18]. Sun et al. constructed a Stackelberg game model (dominated by manufacturers) to analyze the transfer and emission reduction of carbon emissions among enterprises in the supply chain. The results shows that the lag time of emission reduction technologies and consumers' low carbon preference has a positive effect on the carbon emission transfer level of manufacturers [19]. Liu et al. incorporated the change of consumer preference into the theoretical model and evaluated the impact of carbon emission reduction cost sharing on supply chain profits. The research shows that while achieving the carbon emission reduction target, consumers' preference for low-carbon products is beneficial to both supply chain enterprises [5]. To sum up, considering that consumers, as rational people, have a preference for low-carbon products, in addition to government environmental policies, enterprises' carbon emission reduction behavior strategies will also be affected by consumers' purchase intentions.

Therefore, in the context of low-carbon economic environment, how does the dual role of environmental regulation measures and consumers' low-carbon preference affect the choice of carbon emission reduction behavior and its long-term relationship of supply chain subjects? Evolutionary game theory originated from the application of game theory to the evolving population of life forms in biology. By introducing biological fitness function, variation mechanism and selection mechanism, the dynamic replicator equation is constructed, which can well reflect the process of observation, imitation and mutual learning experienced by enterprises in the decision-making process [20]. It has been proved to be an effective analytical tool to study the relationship between government behavior or carbon reduction strategy of supply chain enterprises. Zhao et al. constructed an evolutionary game model to analyze the possible responses of enterprises to incentive policies related to the implementation of carbon emission reduction labeling program, and found that relevant incentive policies have a positive impact on the implementation of carbon emission reduction labeling program [21]. Zhang et al. established an evolutionary game model between the government and manufacturers, and analyzed the influence of government policies (static carbon trading price and dynamic carbon trading price) on manufacturers' decisions and the dynamic trend of total cap trading market [22].

From the above literature review, it can be seen that previous studies mainly consider the relationship between single regulation policy and enterprise operation decision-making. The results show that enterprises show different attitudes and behaviors under the action of different types of environmental regulation. In addition to environmental regulation, corporate carbon emission reduction behavior strategy will also be affected by consumers' low-carbon preference. The innovation of this paper is that different environmental regulation policies have different soft and hard constraints on operation decisions, and enterprises can choose different carbon emission reduction behaviors. Considering the dual effects of comprehensive environmental regulation strategy constraints or incentive conditions and consumers' low-carbon preference, this paper explores the decision-making mechanism of enterprises' carbon emission reduction behavior. Therefore, this paper constructs a game model of a two-level supply chain composed of a single supplier and a single manufacturer, considering the impact of environmental regulation and consumers' low-carbon preference, market-oriented environmental regulation and consumers' low-carbon preference respectively, studying the strategic stability, the interactive relationship of strategic selection and the evolution path of dynamic decision-making of carbon emission reduction behavior of supply chain enterprises from a dynamic perspective. The influence of different parameters on the behavior decision of supply chain enterprises is analyzed by numerical simulation.

3. Analysis of Supply Chain Enterprises' Carbon Emission Reduction Investment Behavior under Command-and-Control Regulation and Consumers' Low-Carbon Preference

3.1. Problem Description and Model Assumptions. Command-and-control environmental regulation refers to the formulation of laws, regulations, policies and systems by the legislative and administrative departments in order to prevent individuals and enterprises from doing actions that are not conducive to environmental protection. Including setting emission standards, limiting pollution emissions, shutting down and transferring, etc. [23]. The main feature of this regulatory model is that polluters have almost no right to choose. In order to satisfy the law of the minimum environment requirements, companies will take the necessary adjustment measures, such as compliance costs, and increase the environmental investment, stimulate the enterprise to the environmentally friendly production technology innovation, to achieve reductions [24]. Or some enterprises, after comparing the cost of violation with the cost of compliance costs, choose to violate environmental laws and regulations and pay more pollution charges instead of reducing carbon emissions [25]. Therefore, it is assumed that in the face of such a policy environment, supply chain enterprises with supply-demand relationship can choose implementing carbon emission reduction investment or not.

In the stage of command-and-control environmental regulation, this paper focuses on the impact of emission standard policy on carbon emission reduction behavior strategy of supply chain enterprises. In order to more clearly analyze and describe this problem, this paper makes the following assumptions:

(1) Assume that the costs of carbon abatement investments by suppliers and manufacturers are C_S and C_M respectively. Referring to the research of Jones and Mendelson [26], the manufacturer's emission reduction investment cost is $C_M = 1/2\mu_M\lambda_M^2$, where $\lambda_M\,(0<\lambda_M<1)$ is the manufacturer's emission

reduction effort at the moment, and μ_M ($\mu_M > 0$) is the manufacturer's emission reduction cost coefficient. Similarly, the supplier's carbon emission reduction investment cost is $C_S = 1/2\mu_S\lambda_S^2$, make $\mu_M = \mu_S = \mu$.

(2) Referring to the research of Jiang et al. [27], the emission reduction of final products depends on the emission reduction efforts of manufacturers and suppliers. Assuming that β_S represents the impact coefficient of suppliers' emission reduction efforts on product emission reduction and the impact coefficient of β_M represents manufacturers' emission reduction efforts on product emission reduction. Then the change of product emission reduction is $\rho = \beta_i\lambda_i\,(i = M, S)$i $= M, S$ is the same in below. ρ_{0M} and ρ_{0S} are the carbon emissions (emission concentration) generated in the process of using raw materials to produce unit products before implementing carbon emission reduction behavior strategies for manufacturers and suppliers respectively. The amount of carbon emissions generated after the implementation of carbon emission reduction investment behavior is $\rho_{Li} = \rho_{0i} - \rho$. ρ_{LMS} or ρ_{LSM} represent the carbon emissions after both have made carbon reduction investments. $\rho_{LM}\,(\rho_{LS})$ represents the carbon emissions of the product after the manufacturer (supplier) has invested in carbon reduction.

(3) The market demand is $D(\rho) = \alpha$, which α is the potential market demand without carbon emission reduction investment. When the carbon content of products changes, the changes of market demand refer to the research of Jiang et al. [27], $D(\rho) = \alpha + \delta\rho$, $\delta > 0$ is the impact factor of carbon emission reduction of manufacturers and suppliers on the market demand, that is, the low-carbon preference coefficient of consumers. $\overline{\rho}_i\,(\rho_L < \overline{\rho} < \rho_0)$ is the upper limit of carbon emission concentration per unit product of manufacturers and suppliers set by the government. k $(k > 0)$ is reward and punishment coefficient for exceeding the standard of carbon emission per unit product formulated by the government.

(4) The marginal revenues of supply chain companies remain unchanged, and they are all the positive constants, which can be predicted from the actual financial data of the company, denoted by v_M and v_S respectively. v_S is the remaining part of the supplier's unit whole sale price minus the unit average cost excluding low-carbon investment expenses, v_M is the remaining part of the manufacturer's unit whole sale price minus the unit average cost excluding low-carbon investment expenses.

(5) Suppose the profits of manufacturers and suppliers are π_M and π_S respectively. The superscript N indicates that both manufacturers and suppliers do not take carbon emission reduction investment; the superscript U indicates that manufacturers take emission reduction investment but suppliers do not; the superscript D indicates that suppliers make emission reduction investment but manufacturers do not make emission reduction investment; the superscript B indicates that both manufacturers and suppliers take emission reduction investment.

(6) When an enterprise chooses to adopt the carbon emission reduction investment strategy, considering the external positive effect of carbon emission reduction investment in the supply chain, the other enterprise can adopt the behavior of "free-riding." In this case, the government will give certain punishment measures to the free-riding enterprise, the punishment intensity is F.

Assuming that both manufacturers and suppliers are bounded rational decision makers, x $(0 < x < 1)$ is the proportion of manufacturers adopting carbon emission reduction investment behavior strategy, then $1 - x$ is the proportion of non carbon emission reduction investment behavior strategy; y is the proportion of suppliers adopting carbon emission reduction investment behavior strategy, and $1 - y$ is the proportion of suppliers not adopting carbon emission reduction investment behavior strategy. The game payment matrix of carbon emission reduction behavior choice of supply chain enterprises under imperative environmental regulation and low-carbon preference of consumers is shown in Table 1.

3.2. Model Construction and Solution. Based on the above discussion, the evolutionary stability of emission reduction investment behavior strategy of upstream and downstream enterprises is analyzed by using the method of evolutionary game theory. Then the expected return of the manufacturer implementing the carbon emission reduction investment behavior strategy is u_M^{x1}, and the expected return of not implementing the carbon emission reduction investment behavior is $\mathrm{u}_\mathrm{M}^{x0}$:

$$u_M^{x1} = \pi_M^U + y\delta\beta_S\lambda_S v_M + y\beta_S\lambda_S k\{(\alpha + \delta\beta_M\lambda_M) + \delta[\overline{\rho}_M - (\rho_{0M} - \beta_M\lambda_M - \beta_S\lambda_S)]\}, \quad (1)$$

$$u_M^{x0} = \pi_M^N + y\delta\beta_S\lambda_S[v_M - k(\rho_{OM} - \overline{\rho}_M)] - yF. \quad (2)$$

Similarly, we can get the expected return $(\mathrm{u}_\mathrm{S}^{y1})$ of suppliers choosing to implement carbon emission reduction investment behavior and not implementing carbon emission reduction investment behavior strategy $(\mathrm{u}_\mathrm{S}^{y0})$.

In evolutionary game theory, replicator dynamics, as a method to study strategy selection, guides decision-makers to make dynamic decisions and promotes decision-makers' strategy selection to converge towards a stable state until it reaches a stable state.

The manufacturer's replicator dynamics equation obtained by formulas (1) and (2) is:

Table 1: Payment matrix of both parties in the game of carbon emission reduction investment behavior of supply chain enterprises.

Supplier	Manufacturer: Adopt carbon emission reduction investment x	Manufacturer: Non adopt carbon emission reduction investment $1-x$
Adopt carbon emission reduction investment y	$\pi_M^B = v_M D(\rho) + k(\overline{\rho}_M - \rho_{LMS})D(\rho) - C_M(\lambda)$ $\pi_S^B = v_S D(\rho) + k(\overline{\rho}_S - \rho_{LMS})D(\rho) - C_S(\lambda)$ $D(\rho) = \alpha + \delta(\beta_M\lambda_M + \beta_S\lambda_S)$	$\pi_M^D = v_M D(\rho) - k(\rho_{0M} - \overline{\rho}_M)D(\rho) - F$ $\pi_S^D = v_S D(\rho) + k(\overline{\rho}_S - \rho_{LS})D(\rho) - C_S(\lambda)$ $D(\rho) = \alpha + \delta\beta_S\lambda_S$
Non adopt carbon emission reduction investment $1-y$	$\pi_M^U = v_M D(\rho) + k(\overline{\rho}_M - \rho_{LM})D(\rho) - C_M(\lambda)$ $\pi_S^U = v_S D(\rho) - k(\rho_{0S} - \overline{\rho}_S)D(\rho) - F$ $D(\rho) = \alpha + \delta\beta_M\lambda_M$	$\pi_M^N = v_M D(\rho) - k(\rho_{0M} - \overline{\rho}_M)D(\rho)$ $\pi_S^N = v_S D(\rho) - k(\rho_{0S} - \overline{\rho}_S)D(\rho)$ $D(\rho) = \alpha$

$$f(x) = \frac{dx}{dt} = x(1-x)\left(u_M^{x1} - u_M^{x0}\right) = x(1-x)\left[\pi_M^U - \pi_M^N + y\beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + yF\right]. \tag{3}$$

In the same way, the supplier's repliction dynamic equation can be obtained as:

$$f(y) = \frac{dy}{dt} = y(1-y)\left(u_S^{y1} - u_S^{y0}\right) = y(1-y)\left[\pi_S^D - \pi_S^N + x\beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + xF\right]. \tag{4}$$

Make $f(x) = dx/dt = 0$ and $f(y) = dy/dt = 0$, The equilibrium point of the dynamic process of evolutionary game can be generated, including $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, $E_5(P^*, q^*)$. Where $E_5(P^*, q^*)$ is the equilibrium point of hybrid strategy.

The equilibrium point obtained from the replicated dynamic equation is not necessarily the evolutionary stability strategy (ESS) of the system. According to the method proposed by Friedman [28], the asymptotic stability of the equilibrium point is determined by Lyapunov discriminant method (indirect method). Take the first partial derivatives of $f(x)$ and $f(y)$ with respect to x and y respectively, then the Jacobian matrix of the system is as follows:

$$J = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} df(x)/dx & df(x)/dy \\ df(y)/dx & df(y)/dy \end{bmatrix} = \begin{pmatrix} (1-2x)\left[\pi_M^U - \pi_M^N + y\beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + yF\right] & x(1-x)\left[\beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + F\right] \\ y(1-y)\left[\beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + F\right] & (1-2y)\left[\pi_S^D - \pi_S^N + x\beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + xF\right] \end{pmatrix}. \tag{5}$$

Based on the local stability analysis of Jacobian matrix, the stability of the equilibrium point of the system is analyzed. For Jacobian matrix (J), the stable state satisfying the determinant of the matrix $\det(J) > 0$ and the trace time of the matrix $\mathrm{tr}(J) < 0$ is the evolutionary stability strategy.

In evolutionary game theory, evolutionary stable strategy (ESS), as a judgment method to judge whether the system reaches equilibrium, plays an important role in the process of game evolution. By solving the determinant of Jacobian matrix and the sign of trace of two-dimensional differential dynamic equations, the evolutionary stability strategy of the system can be determined. It can be calculated from Table 2 that at the equilibrium point $(x = p^*, y = q^*)$, $C_{11} = C_{12} = 0$ is not satisfied $C_{11} + C_{12} < 0$. So $(x = p^*, y = q^*)$ is not an ESS, it's just a non-asymptotically stable state. So we only need to talk about the stability of the other four equilibrium points.

(1) When $\pi_M^U - \pi_M^N < 0$, and $\pi_S^D - \pi_S^N < 0$, it can be concluded that $(0,0)$ is the evolutionary stable point of the system, i.e. (manufacturers do not take emission reduction investment measures and suppliers do not take emission reduction investment). In addition, $(1,0)$ and $(0,1)$ are unstable points, (P^*, q^*) is a saddle point, and $(1,1)$ is uncertain.

(2) When $\pi_M^U - \pi_M^N + \beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + F < 0$, and $\pi_S^D - \pi_S^N > 0$, it can be concluded that $(0,1)$ is the evolutionary stable point of the system, i.e. (manufacturers do not take emission reduction investment measures and suppliers take emission reduction investment). Similarly, when $\pi_M^U - \pi_M^N > 0$, $\pi_S^D - \pi_S^N + \beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + F < 0$, (1, 0) is the evolutionary stable point of the system, i.e. (manufacturers take emission reduction investment measures and suppliers do not take emission reduction investment). See Figures 1(a) and 1(b).

(3) When $\pi U/M - \pi N/M < 0$, $\pi D/S - \pi N/S < 0$, and $\pi_M^U - \pi_M^N + \beta_S \lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + F > 0$, $\pi_S^D - \pi_S^N + \beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + \mathrm{F} > 0$, $(0,0)$ and $(1,1)$ is the evolutionary stable point of the system, that is (manufacturer's do not take carbon emission reduction investment, suppliers's do not take carbon emission reduction investment) and (manufacturer's carbon emission reduction investment, suppliers's carbon emission reduction investment). At this point, the dynamic phase diagram under this condition can be obtained as shown in Figure 1(c).

3.3. Simulation Analysis of Evolutionary Stability. Based on the above theoretical analysis, with the help of constraints and replication dynamic equations, this paper uses Matlab tool to simulate the evolution process of carbon emission reduction behavior of supply chain enterprises. Suppose that the parameter values in the game payment matrix are as follows: $\nu_M = 50$, $a = 40$, $\delta = 0.2$, $\beta_M = 0.3$, $\beta_S = 0.2$, $\lambda_M = 20$, $\mathrm{K} = 2$, $\overline{\rho}_M = 15$, $\rho_{0M} = 20$, $\lambda_s = 20$, $\mu = 0.1$, $F = 10$, $\nu_S = 50$, $\overline{\rho}_s = 13$, $\rho_{0s} = 16$.

Figures 2(a)–2(d) respectively show the influence of consumers' low carbon preference coefficient, enterprises' upper limit of carbon emission concentration, incentive and punishment coefficients for exceeding carbon emission per unit product, and free-rider penalty intensity on the change of supply chain enterprises' behavioral strategy choice after the expansion of the same multiple. The results show that with the learning and imitation behavior of both parties, the carbon emission reduction behavior strategies of supply chain enterprises ultimately evolve in the direction of (carbon emission reduction investment, carbon emission reduction investment). Among all kinds of influencing factors, the carbon emission incentive and punishment coefficient has the most obvious influence, the consumer's low-carbon product preference coefficient has the middle influence, the enterprise emission concentration ceiling and the government's punishment intensity have no significant effect.

The introduction of command-and-control environmental regulations will put some pressure on the development of enterprises. For example, the EU stipulates that the average emission of new cars sold by 2021 should not exceed 95 grams of CO_2 equivalent. The implementation of such policies will make enterprises weigh the punishment of violation with the investment of emission reduction, so as to make the carbon emission reduction behavior choice strategy. The larger the reward and punishment coefficient of carbon emission per unit product exceeds the standard, the greater the loss the enterprise will bear when it does not take emission reduction measures. Therefore, the enterprise will be more willing to take carbon emission reduction investment behavior, and finally stabilize the carbon emission reduction investment behavior.

At the same time, corporate environmental responsibility will increase the attractiveness of a company's products or services to customers in the industrial market [29], which will then be transformed into consumers' intention to purchase corporate products [30]. In order to maintain certain market competitiveness, enterprises will also be influenced by consumers' low-carbon preference when making carbon emission reduction behavior decisions, as shown in Figure 2(a).

4. Analysis of Carbon Emission Reduction Cooperation Behavior of Supply Chain Enterprises under Market-Based Environmental Regulation and Consumers' Low-Carbon Preference

4.1. Problem Description and Model Assumptions. Under command-based environmental regulations, enterprises pay attention to whether their carbon emissions in each link of production meet the requirements of laws and regulations from their own perspective [14]. Different from the compulsion in the implementation of command-and-control environmental regulations, market-based environmental regulations are formulated by the government according to the operation mechanism of the market [31], which uses the signal mechanism of the market to guide enterprises to conduct pollution control. The main feature is that it provides enterprises with options, and polluters can choose the most effective way to maximize their own interests. Studies have found that incentive environmental regulation has an impact on cooperation and production process management of supply chain enterprises [14], and the model of supply chain enterprise cooperation will lead to the simultaneous increase of product greenness, supply chain profit and consumer surplus [32]. At the same time, with the promotion of the "dual carbon" strategic goal, low-carbon life such as shared travel and recyclable online shopping packaging has gradually become a new trend in society, and consumers' low-carbon demand preference plays an important role in the carbon reduction decision of supply chain enterprises. Therefore, how to realize supply chain coordination under the influence of environmental regulations and consumers' low-carbon preference has become a key direction. This paper assumes that in this environment, the behavioral strategy space of supply chain enterprises is (cooperative carbon emission reduction, noncooperative carbon emission reduction).

Under the premise of carbon emission reduction investment cooperation consensus, there are two cooperation modes of revenue sharing and cost sharing among enterprises. Liu et al. proposed that cost-sharing contracts for carbon emission reduction can promote and coordinate the development of supply chains in the context of consumers' preference for low-carbon products [5]. In this paper, cost-sharing contract is considered to study the cooperative carbon emission reduction behavior of supply chain enterprises. At the same time, based on Kem's [33] classification of the current macro environmental policies to

TABLE 2: The value of $C_{11}C_{12}C_{21}C_{22}$ at local equilibrium.

Equilibrium	C_{11}	C_{12}	C_{21}	C_{22}
$x = 0, y = 0$	$\pi_M^U - \pi_M^N$	0	0	$\pi_S^D - \pi_S^N$
$x = 0, y = 1$	$\pi_M^U - \pi_M^N + \beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + F$	0	0	$-(\pi_S^D - \pi_S^N)$
$x = 1, y = 0$	$-(\pi_M^U - \pi_M^N)$	0	0	$\pi_S^D - \pi_S^N + \beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + F$
$x = 1, y = 1$	$-[\pi_M^U - \pi_M^N + \beta_S\lambda_S k(\alpha + 2\delta\beta_M\lambda_M + \delta\beta_S\lambda_S) + F]$	0	0	$-[\pi_S^D - \pi_S^N + \beta_M\lambda_M k(\alpha + 2\delta\beta_S\lambda_S + \delta\beta_M\lambda_M) + F]$
$(x = p^*, y = q^*)$	0	*	*	0

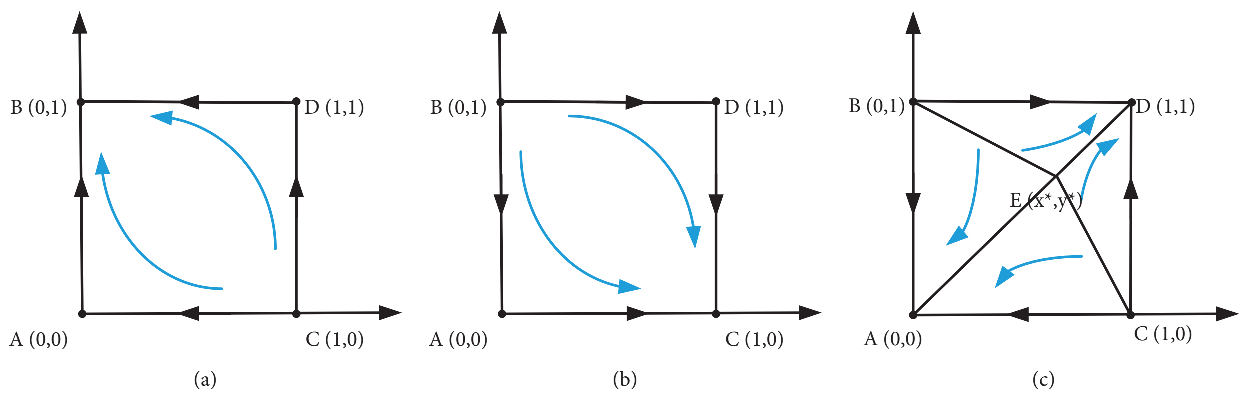

FIGURE 1: Dynamic phase diagram.

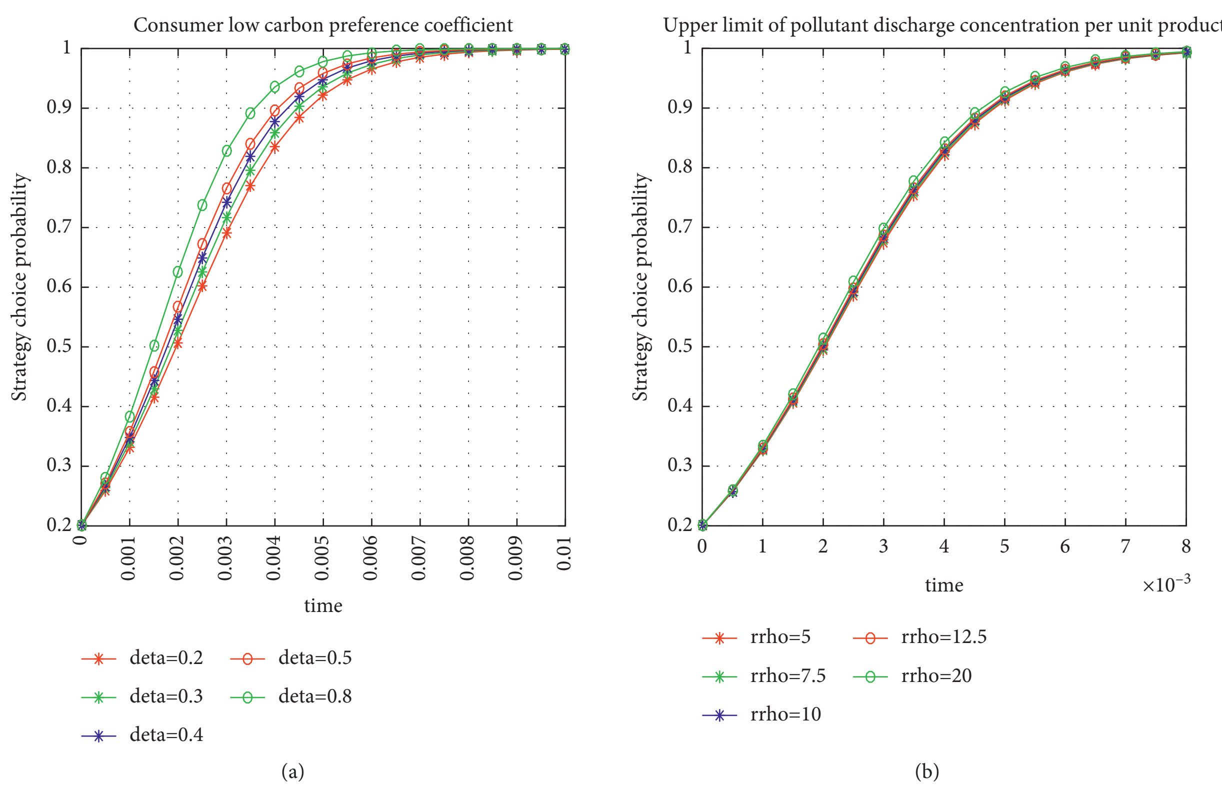

FIGURE 2: Continued.

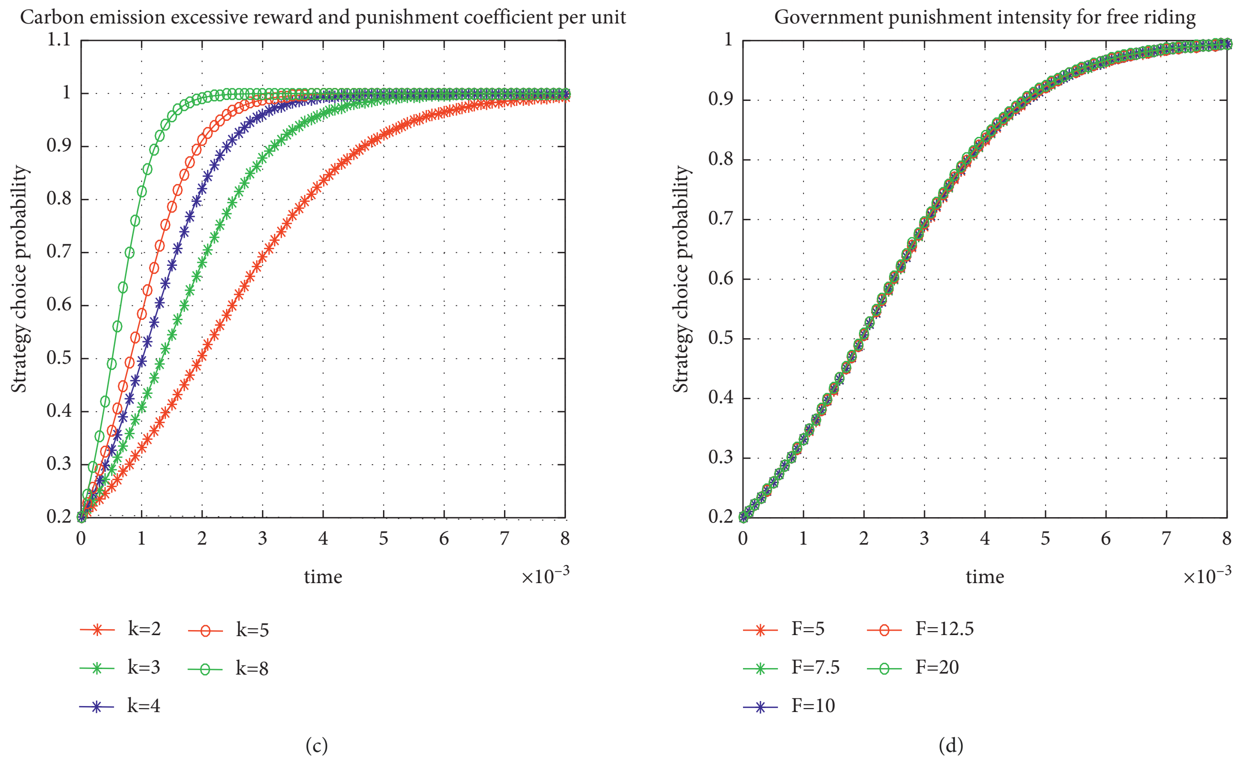

FIGURE 2: Impact of different parameter changes on carbon emission reduction investment behavior of supply chain enterprises.

encourage enterprises to reduce carbon emissions, and referring to Wang et al.'s research [34], this paper focuses on the impact of three different market-oriented environmental regulation policies, namely, carbon tax, emission trading and cost subsidy, on the cooperative carbon emission reduction behavior of supply chain enterprises. In order to analyze and describe this problem more clearly, this paper makes the following assumptions:

(1) When supply chain enterprises all choose cooperative carbon emission reduction behavior strategy, we can define it as joint emission reduction [35]. In order to promote cooperation behavior between enterprises, it is assumed that one party will bear part of the cost θ_i $(i = M, S)$ of the other party. For example, the proportion of cooperative carbon emission reduction cost borne by the manufacturer is θ_M, and the proportion of cooperative carbon emission reduction investment cost borne by the supplier is θ_S. Carbon emission reduction behaviors of both parties through cooperation will have an impact on market demand.

(2) As can be seen from the previous section, the market demand for carbon emission reduction investment by both parties is $\mathrm{D}(\rho) = \alpha + \delta\rho$. Enterprise cooperation in carbon emission reduction is a manifestation of enterprises actively fulfilling their social responsibilities. Existing research results show that corporate social responsibility has a positive impact on the brand evaluation of entrepreneurs and consumers [36]. This paper assumes that when enterprises choose cooperative carbon emission reduction behavior, the market demand is $D(\rho) = \alpha + \delta\rho + \varphi \mathrm{CCo}$, CCo is the change in brand image of products under cooperative carbon emission reduction behavior, and φ is the influence factor of brand image between manufacturers and suppliers on market demand. $\mathrm{CCo} = \eta_S \mathrm{Co}_S + \eta_M \mathrm{Co}_M$, η_S and η_M respectively represent the influence coefficient of the supplier's and manufacturer's cooperative carbon emission reduction efforts on the product's brand image; Co_S and Co_M respectively collaborative carbon reduction efforts of suppliers and manufacturers. Based on the hypothesis of the investment cost of carbon emission reduction in 3.1 (1), this part assumes the co-emission reduction cost coefficient is equal to 1, then the value of cooperation emission reduction cost of supply chain enterprises is $1/2\mathrm{Co}_i^2$.

(3) In order to reduce carbon emissions and stimulate enterprises to produce and promote low-carbon products, the government will formulate environmental regulations policies based on the carbon emissions of products. In this model, it is assumed that manufacturers and suppliers obtain a specific initial carbon quota from the government, and that

the maximum carbon emission standards of manufacturer and supplier in the supply chain by the government are $\overline{W_M}$ and $\overline{W_S}$. When the company adopts the carbon emission reduction investment behavior model alone, the carbon emissions generated by the manufacturer and the supplier are $W_M = \rho_{LM} D(\lambda)$ and $W_S = \rho_{LS} D(\lambda)$, $(W_M > \overline{W}_M, W_S > \overline{W}_S)$ respectively. When both companies adopt cooperative carbon emission reduction actions, the carbon emissions generated by the manufacturer and supplier are W_{MC} and $W_{SC}\,(W_{MC} < \overline{W}_M, W_{SC} < \overline{W}_S)$ respectively. When the actual carbon emissions are greater than the initial carbon quato, the enterprise needs to buy the difference in the carbon emission trading market. On the contrary, the enterprise can sell the difference in the carbon emission trading market. The unit price of carbon emission trading is ε.

(4) The government will also give a certain degree of subsidy to enterprises actively participating in cooperative carbon cooperative emission reduction according to the size of cooperative emission reduction, and the subsidy coefficient is μ. According to the "China Carbon Tax System Design," the government imposes a specific carbon tax on the carbon dioxide emitted by manufacturing companies, and the carbon tax rate is $t = (10\text{–}40)$ RMB/t.

(5) Punishment mechanisms have been shown to motivate firms to engage in long-term cooperation [37]. In order to promote the realization of joint emission reduction mode among enterprises, it is assumed that the government will punish enterprises that do not actively participate in cooperative carbon emission reduction to a certain extent, and the intensity of punishment is set as $F\prime\,(F\prime \rangle 0)$. For other parameters, see 3.1 Model.

(6) Suppose the profits of manufacturers and suppliers are π_M' and π_S' respectively. The superscript $N\prime$ indicates that neither manufacturers nor supplier are working together to reduce carbon emissions; the superscript $U\prime$ indicates that manufacturers cooperate in emission reduction while suppliers do not; the superscript $D\prime$ indicates that suppliers cooperate in emission reduction while manufacturers do not; the superscript $B\prime$ indicates that both manufacturers and suppliers adopt cooperative carbon emission reduction behavior.

Assuming that both manufacturers and suppliers are bounded rational decision makers, x $(0\langle x \langle 1)$ is the proportion of manufacturers adopting carbon emission reduction cooperative behavior strategy; y is the proportion of suppliers adopting carbon emission reduction cooperative behavior strategy. The game payment matrix of carbon emission reduction behavior choice of supply chain enterprises under imperative environmental regulation and low-carbon preference of consumers is shown in Table 3.

4.2. Model Construction and Solution. Suppose that the expected return of manufacturers choosing cooperative carbon emission reduction strategy is u_M^{X1}, and the expected return of non cooperative carbon emission reduction is u_M^{X0}:

$$u_M^{x1} = \pi_M^{U'} + y\left[v_M\,\varphi\,\eta_S \mathrm{Co}_S + (1-\mu)\theta_S \frac{1}{2}\mathrm{Co}_M^2\right], \tag{6}$$

$$u_M^{x0} = \pi_M^{N'} + y\left[v_M\,\varphi\,\eta_S \mathrm{Co}_S + (1-\mu)\theta_s \frac{1}{2}\mathrm{Co}_M^2 - F'\right]. \tag{7}$$

Similarly, the expected benefits of supplier cooperative carbon emission reduction and non cooperative carbon emission reduction behavior strategies can be obtained.

The manufacturer's replicated dynamic equation obtained from equations (6) and (7) is:

$$f(x) = \frac{dx}{dt} = x(1-x)\left(u_M^{x1} - u_M^{x0}\right) = x(1-x)\left(\pi_M^{U'} - \pi_M^{N'} + yF'\right). \tag{8}$$

Similarly, the supplier's replication dynamic equation can be obtained as follows:

$$\begin{aligned} f(y) &= \frac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)\left(u_S^{y1} - u_S^{y0}\right) \\ &= y(1-y)\left(\pi_S^{D'} - \pi_S^{N'} + xF'\right). \end{aligned} \tag{9}$$

Make $f(x) = \mathrm{d}x/\mathrm{d}t = 0$, $f(y) = \mathrm{d}y/\mathrm{d}t = 0$, it can produce the equilibrium point of the dynamic process of evolutionary game, include $E_1'(0,0), E_2'(0,1), E_3'(1,0), E_4'(1,1), E_5'(p^* q^*)$. Where $E_5'(p^* q^*)$ is the equilibrium points of the hybrid strategy. The Jacobi matrix is:

$$J = \begin{bmatrix} df(x)/dx & df(x)/dy \\ df(y)/dx & df(y)/dy \end{bmatrix} = \begin{pmatrix} (1-2x)*\left(\pi_M^{U'} - \pi_M^{N'} + yF'\right) & x*(1-x)F' \\ y*(1-y)*F' & (1-2y)\left(\pi_S^{D'} - \pi_S^{N'} + xF'\right) \end{pmatrix}. \tag{10}$$

Based on the local stability analysis of Jacobian matrix, the equilibrium point of the system is analyzed. The results are shown in Table 4:

The evolutionary stability strategy of the system can be determined by the determinant and the sign of trace of Jacobian matrix. As mentioned in 3.2, the equilibrium point $(x = p^*, y = q^*)$ is not an ESS, it is only a non-asymptotically stable state.

It can be calculated from Table 4 that when $\pi_M^{U'} - \pi_M^{N'} < 0$, $\pi_S^{D'} - \pi_S^{N'} < 0$, $(0,0)$ is the evolutionary

Table 3: Payment matrix of both parties in the game of carbon emission reduction cooperation of supply chain enterprises.

Supplier	Manufacturer: Adopt cooperative measures to reduce carbon emission x	Manufacturer: Adopt non cooperative carbon emission reduction measures $1-x$
Adopt cooperative measures to reduce carbon emission y	$\pi_M^B = v_M D(Co) - tW_{MC} - (1-\mu)\begin{bmatrix}(1-\theta_S)1/2Co_M^2 \\ +\theta_M 1/2Co_S^2\end{bmatrix} + \varepsilon(\overline{W}_M - W_{MC})$ $\pi_S^B = v_S D(Co) - tW_{SC} - (1-\mu)\begin{bmatrix}(1-\theta_M)1/2Co_S^2 \\ +\theta_S 1/2Co_M^2\end{bmatrix} + \varepsilon(\overline{W}_S - W_{SC})$ $D(Co) = \alpha + \delta\rho + \varphi(\eta_M Co_M + \eta_s Co_s)$	$\pi_M^D = v_M D(Co) - tW_M - (1-\mu)[(1-\theta_S) * 1/2Co_M^2] - \varepsilon(W_M - \overline{W}_M) - F\prime$ $\pi_S^D = v_S D(Co) - tW_{SC} - (1-\mu)(1/2Co_S^2 + \theta_S * 1/2Co_M^2) + \varepsilon(\overline{W}_S - W_{SC})$ $D(Co) = \alpha + \delta\rho + \varphi\eta_s Co_s$
Adopt non cooperative carbon emission reduction measures 1-y	$\pi_M^U = v_M D(Co) - tW_{MC} - (1-\mu)(1/2Co_M^2 + 1/2\theta_M Co_S^2) + \varepsilon(\overline{W}_M - W_{MC})$ $\pi_S^U = v_S D(Co) - tW_S - (1-\mu)[(1-\theta_M) * 1/2Co_S^2] - \varepsilon(W_S - \overline{W}_S) - F\prime$ $D(Co) = \alpha + \delta\rho + \varphi\eta_M Co_M$	$\pi_M^N = v_M D(Co) - tW_M - (1-\mu)1/2Co_M^2 - \varepsilon(W_M - \overline{W}_M)$ $\pi_S^N = v_S D(Co) - tW_S - (1-\mu)1/2Co_S^2 - \varepsilon(W_S - \overline{W}_S)$ $D(Co) = \alpha + \delta\rho$

Table 4: The value at the $C_{11}C_{12}C_{21}C_{22}$ local equilibrium.

Equilibrium	C_{11}	C_{12}	C_{21}	C_{22}
$(x = 0, y = 0)$	$\pi_M^{U'} - \pi_M^{N'}$	0	0	$\pi_S^{D'} - \pi_S^{N'}$
$(x = 0, y = 1)$	$\pi_M^{U'} - \pi_M^{N'} + F'$	0	0	$-(\pi_S^{D'} - \pi_S^{N'})$
$(x = 1, y = 0)$	$-(\pi_M^{U'} - \pi_M^{N'})$	0	0	$\pi_S^{D'} - \pi_S^{N'} + F'$
$(x = 1, y = 1)$	$-(\pi_M^{U'} - \pi_M^{N'} + F')$	0	0	$-(\pi_S^{D'} - \pi_S^{N'} + F')$
$(x = p^*, y = q^*)$	0	*	*	0

stability point of the system, that is (manufacturers do not cooperate in emission reduction measures, suppliers do not cooperate in carbon emission reduction). $(1, 0)$ and $(0, 1)$ are unstable points, and $(1, 1)$ is uncertain.

When $-F' < \pi_M^{U'} - \pi_M^{N'} < 0$, $-F' < \pi_S^{D'} - \pi_S^{N'} < 0$, $(0, 0)$ and $(1, 1)$ is the evolutionary stability point of the system, that are (manufacturers do not take cooperative emission reduction measures and suppliers do not take cooperative emission reduction measures) and (manufacturers take cooperative emission reduction measures and suppliers take cooperative emission reduction measures). In addition, $(1, 0)$ and $(0, 1)$ are the unstable points, as shown in Figure 3.

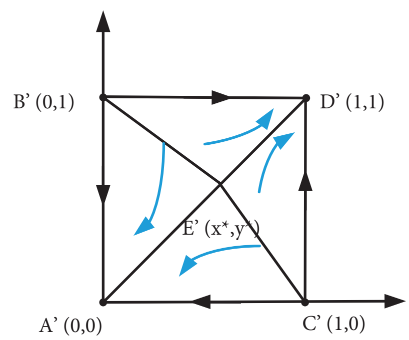

Figure 3: Dynamic phase diagram.

4.3. Simulation Analysis of Evolutionary Stability. Based on the above theoretical analysis, with the help of constraints and replication dynamic equations, Matlab is used to simulate the evolution process of cooperative carbon emission reduction behavior among supply chain enterprises.

Suppose that in the game payment matrix, the parameter values are as follows: $v_M = 50$, $a = 40$, $\delta = 0.2$, $\varphi = 0.2$, $\eta_M = 0.3$, $Co_M = 30$, $t0 = 10$, $W_M = 30$, $\mu = 0.2$, $\theta_M = 0.5$, $Co_s = 30$, $\varepsilon = 8$, $\overline{W}_M = 20$, $\eta_S = 0.2$, $W_{MC} = 15$, $F' = 10$, $v_S = 40$, $W_S = 25$, $\theta_S = 0.2$, $\overline{W}_S = 18$, $W_{SC} = 12$, $\beta_M = 0.3$, $\lambda_s = 20$, $\lambda_M = 20$, $\beta_S = 0.2$, $W_{MS} = 10$.

Figures 4(a)–4(d)show the impact of input subsidy coefficient, unit carbon emission transaction price, carbon tax rate and low-carbon preference of consumers on corporate carbon reduction cooperative behavior strategy. The results show that the system eventually evolves in the direction of (cooperative emission reduction investment, cooperative emission reduction investment). The convergence rate of cooperative carbon emission reduction behavior strategy of supply chain enterprises is relatively fast under the influence of carbon tax rate, the convergence rate is in the middle under the influence of carbon emission trading price.

Under fiscal policies, governments of various countries often levy taxes or provide subsidies according to the energy consumption of different products, so as to drive enterprises in the supply chain to realize product substitution and low-carbonization while maximizing profits [38]. In the cooperative emission reduction investment mode, this paper considers the influence of subsidies when investing in carbon emission reduction. However, the input subsidy coefficient is reflected in the two-way cost mutual sharing, and the cost sharing accounts for a small proportion in the total cost. Therefore, the expansion of the input subsidy coefficient by the same factor in Figure 4(a) has a smaller impact on the cooperative carbon emission reduction behavior than other variables. In terms of environmental regulation policies, carbon tax will increase the tax burden of enterprises, while subsidies will reduce the production cost of enterprises. Therefore, we can consider to combining the two to achieve the regulation of enterprises' carbon emission reduction behavior.

Figure 4(b) shows the impact of unit carbon trading price on emission reduction behavior strategy under different scenarios. It is found that the larger the unit carbon trading price is, the faster the convergence rate of cooperative carbon emission reduction behavior strategy is. It shows that carbon trading price can effectively promote the cooperative carbon emission reduction behavior of supply chain enterprises. This is mainly because under the carbon regulatory policy, if the carbon emission level is lower than the initial carbon quota, suppliers and manufacturers can sell the remaining quota in the carbon trading market to obtain additional profits, and the increase of the carbon trading price leads to the increase of additional profits. The carbon trading price is determined by the carbon emission trading market [34]. Therefore, the carbon emission trading market can stimulate the supply chain to reduce carbon emissions by regulating the carbon trading price.

Carbon tax policy is implemented by the government, which is an effective means of carbon emission control by directly taxing enterprises that emit carbon dioxide [39]. Figure 4(c) shows the results of corporate behavior strategy selection under different carbon tax rates. It can be seen that the change of carbon tax rate has a significant impact on the convergence rate of corporate cooperative carbon emission reduction behavior strategy. The implementation of carbon tax policy in supply chain enterprises has a certain incentive effect on carbon emission reduction in manufacturing industry, and encourages manufacturers to increase investment in carbon emission reduction, so as to obtain environmental and economic benefits.

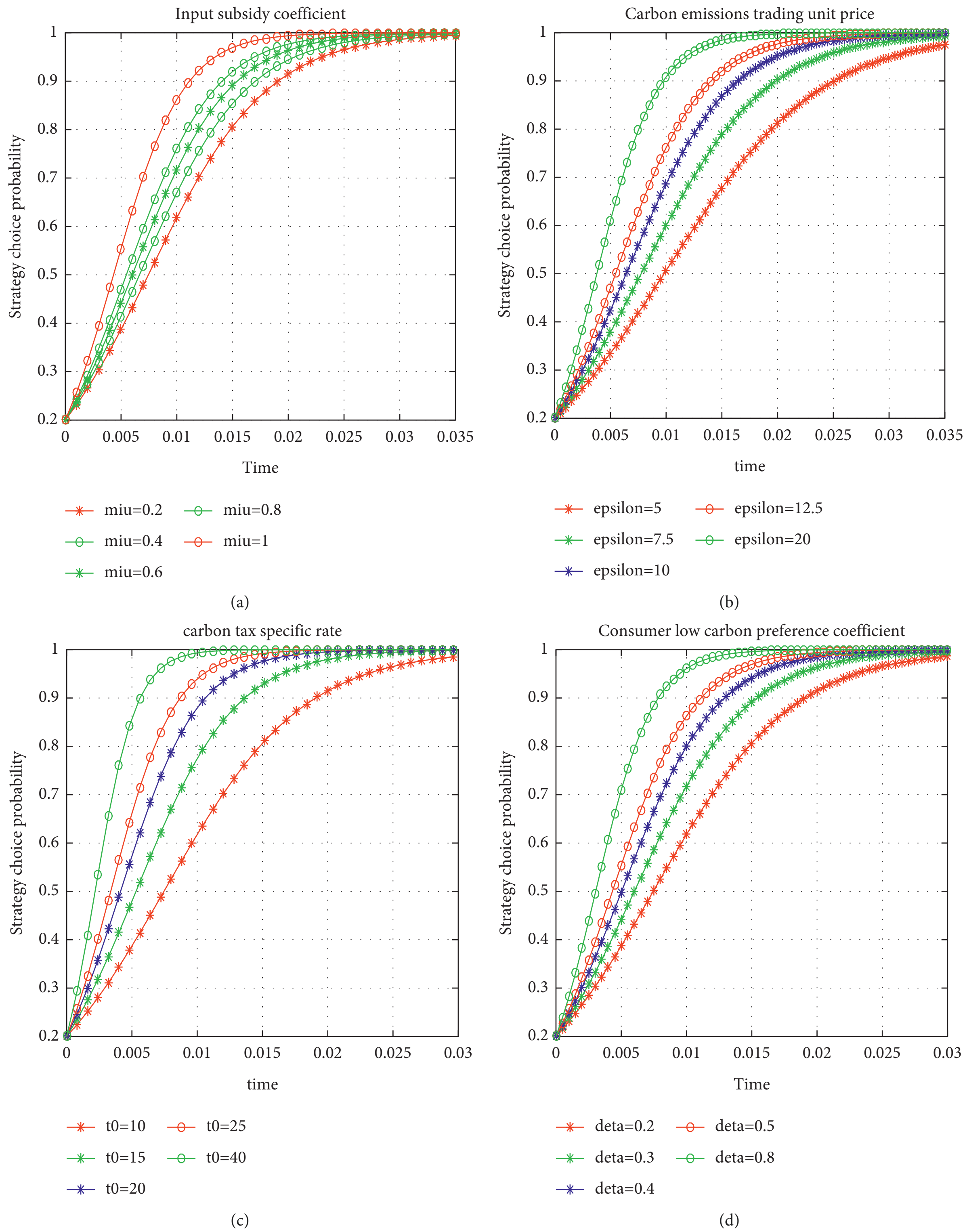

Figure 4: Enterprise behavior strategy under different parameter changes.

Figure 4(d) shows the results of corporate behavior strategy selection under the effect of low-carbon consumption preference. It can be seen that the higner the consumer's low-carbon preference coefficient is, the faster the convergence rate of corporate cooperative carbon emission reduction behavior selection probability will be. Some studies has also confirmed that consumers are more willing to choose environmentally friendly products and services [29]. Therefore, with the further improvement of consumers' awareness of environmental protection, it has become a key factor influencing enterprises' choice of carbon emission reduction behavior.

5. Conclusions and Prospects

This paper first obtains the respective profits of supply chain enterprises under different strategy combinations, and then obtains the evolutionary stability strategy of carbon emission reduction investment behavior and cooperative carbon emission reduction behavior by using evolutionary game theory. Finally, numerical simulation is used to analyze the low-carbon decision-making behavior of supply chain enterprises under different circumstances. It can be found that: (1) In the strategy of choosing whether to implement carbon emission reduction investment behavior, when the profit difference between the two sides of the enterprise does not participate in carbon emission reduction investment behavior and only one side chooses to participate in carbon emission reduction behavior is less than a certain threshold value, and the difference between the two is greater than 0, enterprises will evolve towards the trend of (carbon emission reduction investment, carbon emission reduction investment) in a long time. Through numerical simulation, it is found that the preference coefficient of consumers' low-carbon products and the incentive and punishment coefficient of carbon emissions significantly promote enterprises' carbon emission reduction investment behavior, the upper limit of enterprises' emission concentration and the government's punishment intensity have no significant effect; (2) Under the influence of market-based environmental regulation and consumers' low-carbon preference, when the profit difference between the only one party choosing cooperative carbon emission reduction and two parties' not participating in cooperative carbon emission reduction investment is more than a certain threshold value, the two parties' enterprises will evolve towards the trend of (cooperative carbon emission reduction investment, cooperative carbon emission reduction investment) in a long time. Carbon tax rate, input subsidy cost, unit carbon emission trading price and consumers' preference for low-carbon demand are important factors influencing the cooperative carbon emission reduction behavior among supply chain enterprises.

This paper puts forward the following suggestions: first of all, as the key force in supply chain emission reduction, manufacture can adopt improved emission reduction technology to reduce the carbon content of products, and the suppliers' investment in carbon emission reduction can help promote consumers' consumption of low-carbon products. Considering the long-term development, both parties can consider actively seeking cooperation opportunities through two-way cost sharing, so as to achieve coordinated development in the supply chain and achieve the emission reduction goal; Secondly, the government's environmental regulation policy has a great impact on the carbon reduction decision of supply chain enterprises. Therefore, the government can promote supply chain enterprises to reduce carbon emissions by regulating the upper limit of emission concentration, carbon emission reward and punishment coefficient of carbon emissions, input subsidy coefficient, etc. For example, by drawing on the experience of Sweden, France and other countries and combining China's national conditions and industry characteristics, the carbon tax rate is formulated to achieve the purpose of stimulating emission reduction through carbon tax; Finally, supply chain members and governments can promote consumers' awareness of low-carbon consumption through advertising and other strategies. At the same time, they should also timely collect and feedback consumers' information about low-carbon products to help manufacturers improve their products, so as to increase product sales.

This paper deduces and reveals the dynamic mechanism of carbon emission reduction investment behavior and cooperative carbon emission reduction behavior among supply chain enterprises, which provides a certain reference basis for the choice of carbon emission reduction behavior strategy of supply chain enterprises and the formulation of government environmental regulation measures. However, the current research only stays at the level of theoretical deduction, and further research can be carried out based on the collection of actual data in the later stage. In addition, the supply chain composed of one manufacturer and one supplier is considered in our study, and the case of multiple suppliers and multiple manufacturers can be considered in future research.

Data Availability

All data used in this study can be accessed by request.

Conflicts of Interest

The authors declare no conflict of interest.

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