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The Evolutionary Game Theoretic Analysis for Emission Reduction and Promotion in Low-Carbon Supply Chains

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Abstract: Aiming at exploring the interplay principles of operations strategies among members of dvertising and emission reduction cost sharing contracts and coordination in low-carbon sulow-carbon supply chain, as well as their impact on system performance, we develop an evolutionary game model to capture emission reduction and low-carbon promotion actions, which are typically conducted by one manufacturer and one retailer in every two-echelon supply chain, respectively. We exploit the evolutionary game model to analyze players' behavioral patterns of their interacting strategies, whereby we attain the evolutionary stable strategies and their associated existing preconditions under various scenarios. We acquire a number of managerial insights, and particularly find that the evolutionary stable strategies of the channel carbon reduction and promotion are remarkably influenced by incremental profits resulted from causes, such as every player's unilateral participation in emission reduction. In addition, we investigate a player's free-rider opportunistic practice in cooperative carbon reduction and joint participation in emission reduction. However, the magnitude of profit increment will heavily influence the result of Evolutionary Stable Strategy (ESS). Finally, the extensive computational studies enable us to verify the effectiveness of preceding models.

Keywords: low-carbon supply chain; carbon reduction; low-carbon promotion; evolutionary game; green operations

1. Introduction

The dramatically rapid development of the global economy has incurred a large amount of carbon emission over the world, which consequently causes some challenging environmental and climate issues. Generally, energy-saving and emission reduction are effective ways to confront these issues, which is therefore promoted by many countries using mandatory regulations, such as mandatory cap, cap and trade, carbon tax, and carbon offset, in view of the differences over industries. These administrative regulations transfer the carbon emission permit as one kind of production factor for manufacturing industry. Additionally, an increasing number of countries have implemented the project of low-carbon products certification (such as Germany's Product carbon footprint (PCF) Pilot Project, UK's Carbon Reduction Label Scheme, China's Administration Measures of Energy-saving, and Low-carbon Product Certification). These activities granting low-carbon label to products urge the whole society to pay attention to and participate in coping with global warming. For instance, manufacturing firms may turn to carbon efficient procurement and energy-saving consumption pattern referring to consumers' low-carbon preference. Moreover, substantial enterprises might adopt low-carbon technology and switch to low-carbon production mode. Behind these endeavors is the pulsion and ambition of governments, e.g., Chinese government promised to reduce carbon emission in a certain period.

The literature and practice both show that consumers' low-carbon awareness is increasing under the appealing and guide of governmental policies and low-carbon economy atmosphere. This further provides manufacturing industry the motivation to adopt low-carbon technology and improve emission intensity. Laroche et al. [1] showed that a growing number of consumers are willing to pay higher price for environment friendly products. According to Brécarda et al. [2], 75% European planned to purchase costly green products in the year of 2008 more than just 31% of this kind in 2005. Furthermore, Bai and Liu [3] verified that emission reduction policies of government also have an impact on consumers' low-carbon awareness and behavior by empirical research. The phenomenon presented that environmental factors of products is not a neglectable factor for products' demand. For instance, in response to government appeal and consumers' low-carbon preference, Haier Electronics developed disruptive technology of water heater-three-dimensional (3D) Fast Heat, which can remarkably reduce energy consumption and bring convenience for consumers.

From the viewpoint of supply chain, its members may play different roles in energy-saving and carbon emission reduction. Taking a simple dyadic supply chain as an example, reducing emission intensity might go throughout the entire process from purchasing through manufacturing, distribution, transportation, storage, and operation to retailing activities. The retailer can promote carbon-efficient products and enhance consumers' low-carbon awareness to increase demand and marginal profit. For instance, Walmart once held consumption week with the topic of "Green life, Consumption with Wisdom aiming at drawing consumers" attention to green food sources and energy-saving appliances. Apparently, the manufacturer naturally takes the main role of reducing carbon emission, the cost of which, however, can be pooled by the retailer. The cooperation on emission reduction as well as promoting low-carbon demand can be helpful in carbon control and profitability for the whole supply chain. Therefore, one of our main research questions is whether these two parties can have stable strategy of energy-saving and emission reduction in the long-term cooperation.

Before giving response to this question, we can observe in reality some typical cases in which manufacturers and retailers cooperate in handling carbon reduction and low-carbon supply chain operations. For instance, Haier, one of Chinese main household appliances manufacturers, allies manufacturer GE, giant retailers, like Gome and Suning, Chinese Association of Environmental Protection Industry and some other organizations to form the first "Zero-Carbon-Conversion Alliance" in China. However, the free-rider problem, a well-known economics phenomenon, can still take place naturally in the aforementioned alliance with carbon-reduction cooperation. For example, when manufacturers strive to decrease emission intensity to achieve lower carbon in products attracting increased demand from consumers with low-carbon preference, from which the retailer can benefit even if she has done nothing. However, the free-riding phenomenon harms fairness, ruins the supply chain performance, and hampers the construction of long-run advantage for the entire supply chain.

Motivated by this, one of our main objectives is to explore whether free riding behavior has impacts on the cooperation strategy of emission reduction among vertical supply chain cooperation in the long term. We therefore attempt to conduct evolutionary game theoretic analysis for the supply chain while considering the behaviors of emission reduction, low-carbon promotion, and free riding in the long-term cooperation. Moreover, we will investigate the impact of free riding behavior on the cooperative strategy of emission reduction in long-run vertical channel interaction. Although evolutionary game is widely used in the field of biology and economics, few researches considered the free riding problem within the vertical cooperation of carbon emission reduction. Hence, taking aim at this gap, we strive to focus on three research questions, as follows: (1) What is the evolutionary trend of carbon emission reduction under long-term cooperation in supply chains? (2) What affects evolutionary stable strategy of carbon emission reduction in a long-term cooperative supply chains? (3) What is the impact of the free-riding behavior on vertical cooperative strategy of emission reduction for supply chain enterprises in the long term? In response to these main questions, we construct evolutionary game models to depict chain members' behavioral patterns upon their interacting strategies. Then, we attain evolutionary stable strategies and their associated existing preconditions under various scenarios, which provides a lot of managerial insights, and particularly shows that the evolutionary stable strategy (ESS) of the channel carbon reduction and promotion is apparently affected by incremental profits attributed to factors, including each player's unilateral participation in emission reduction. Moreover, we explore a player's free-rider opportunistic practice in cooperative carbon reduction and joint participation in emission reduction. However, the profit increment degree will heavily affect the result of ESS.

The remainder of this paper is organized as follows. In Section 2, we give a detailed review on related literature. In Section 3, we then address evolutionary game models for vertical cooperation of carbon emission reduction. In Section 4, we provide typical computational experiments and analysis. Concluding remarks and future research directions come in Section 5.

2. Literature Review

In this section, we give a review on three streams of literature that are closely related to our research, i.e., vertical channel cooperation, low-carbon operations and the applications of evolutionary game theory in supply chain.

In the field of supply chain management, many scholars report that vertical cooperation in supply chain can improve the chain performance [4–6]. A lot of literature in this kind mainly includes vertical cooperative advertising and research and development (R&D) and so on.

The literature on vertical cooperative advertising mainly states that upstream manufacturers through sharing downstream advertising cost to stimulate retailers to enhance promotion ability, which thus generates more market demand, like [7], as the first study on this topic. Decades hereafter, the development of vertical cooperative advertising can be divided into short-term static cooperation and long-term dynamic cooperation, where the former kind mainly uses Stackelberg game to develop contract design of cooperative advertising in supply chain [8,9], while our research belongs to the latter one. Some other researchers considered risk preference and vertical cooperation both for supply chain firms, like [10], and differential games for long-run cooperation (e.g., [11–13]). In this study, we simultaneously consider the behavior of retailers' low-carbon promotion and that of manufacturers' emission-reduction investment, while we primarily analyze the ESS of vertical cooperative behaviors on emission reduction upon the evolutionary game model. This is distinct from Jørgensen et al. [12] using differential game to get optimal feedback strategy.

There are also a number of literature referring to vertical cooperative R&D, such as [14–18]. Remarkably, some literature studies the contract design for solving free-riding problem emerging from R&D technology spillover in the supply chain, like [19,20]. However, different from previous literature, we focus on cooperative carbon emission reduction coupled with the low-carbon promotion, particularly from the viewpoint of evolutionary game theoretic analysis.

Recently, the low-carbon supply chain management has been extensively studied, such as [21–25]. Our paper is related to literature involving consumers' sensitivity on low-carbon products. [26] consider consumers' low-carbon awareness based on traditional supply chain management. Assuming demand dependent on emission reduction level, [27] discussed the effects of several contracts on supply chain performances as well as the carbon reduction effectiveness over different contracts. The literature [28] studied cooperative emission reduction in retailer-dominant and power-balanced supply chains and further discussed coordinating the emission reduction activities based on cost sharing contract and wholesale price premium contract, respectively. Other more recent researches on low-carbon supply chain management include [29–31]. Generally, the existing literature usually discusses single-cycle joint emission reduction problem, whereas the current paper explores vertical cooperation of long-term emission reduction and low-carbon promotion in supply chain from the evolutionary process angle.

Our study is also related to the applications of evolutionary game theory in supply chain management. Evolutionary game theory is a combination of game theory and dynamic evolution process analysis, which emphasizes the analysis of dynamic equilibrium strategy and stable results. Evolutionary game model is not a monocyclic optimization model but it is concerned with how the players choose strategies when the time is approaching infinity, and furthermore discuss the stability of this strategy selection behavior. A stable strategy combination showing definitely robust to small perturbations can be called an evolutionary stable strategy (ESS), that is, an evolutionary stable strategy determined by replicating dynamic equations requires that the strategy combination itself must be an equilibrium state with the property that the dynamic replication system can still revert to the evolutionary stability strategy if some players deviate from equilibrium due to accidental selection. Originating from biological evolution theory, evolutionary game theory is initially studied and with basic concept Evolutionary Stable Strategy (ESS) that was proposed by [32,33], which makes evolutionary game theory develop and apply greatly in many fields. The literature [34] summarizes the evolutionary game theory systematically, including some well-developed theoretical researches, while [35] thinks that evolutionary game has a great application prospect in the economic field and further discusses some dynamic systems of specific scenes. Evolutionary game not only can analyze the evolutionary dynamic process between dual populations, but also can explain the problems of long-term replicator games between two individuals. Xiao and Yu [36] describe the proportion in dual population as the ratio of individuals selected for a certain strategy in the population, and adopt probability in replicator game to represent the randomness of a certain strategy to be chosen. Recently, there have been many scholars studying evolutionary problems of long-term cooperation among supply chain enterprises. There are researches most relevant to ours, such as general evolutionary game applications [37,38] and evolutionary game in environmental supply chain management [31,39–41]. Although these mentioned literature refers to evolutionary game applications in supply chain operations, few of them explores the cooperative problem of long-term emission reduction and low-carbon promotion while considering free-riding behavior.

In summary, the existing literature on vertical advertising or R&D cooperation mainly incorporates only the same kind of activity (either advertising or R&D) cooperatively carried out simultaneously in the upstream and the downstream, whereas our study paper considers the separate carbon emission reduction in the upstream and low-carbon promotion in the downstream, respectively, which heretofore has not been studied yet. For the existing literature on supply chain decarburization, most researches focus on the impact of manufacturer's emission reduction on chain performances without considering retailers' cooperative behavior, even though a few occasionally indicating this kind of problems only involves a single cycle of time horizon. However, this paper considers the long-term cooperation between the manufacturer's emission reduction and retailer's low-carbon promotion. Evolutionary game is one of important methods analyzing the long-term dynamic evolution of a system. Using the method of dual-population evolutionary game, this paper analyzes the evolution process of long-term cooperation between manufacturer's emission reduction and retailer's low-carbon promotion in supply chain to obtain the evolutionary stable equilibrium strategy and its managerial implications, which accordingly enriches the economic knowledge body of evolutionary game theory and it provides theoretic guidance for emission reduction and low-carbon promotion in practice.

3. Evolutionary Game Model for Carbon Emission Reduction

3.1. Preliminaries and Notations

We consider a group of manufacturers and also a group of retailers in two-echelon supply chains, both of whom are homogeneous and profit-maximizing in their own group. Suppose that each manufacturer sells products through multiple retailers, and each retailer will purchase products from multiple manufacturers. Every manufacturer needs to pay a certain cost due to the governmental constraints for energy consumption per unit product, even if he quits the cooperation of reducing emissions. Assuming that consumers have the willingness to pay for environment-friendly products. Therefore, manufacturers have strategies of high-level emission reduction and low-level emission reduction while considering the cost input and consumers preference. For retailers, the promotion of low-carbon products can elevate consumers' low-carbon awareness resulting in the increase of market demand. Accordingly, retailers also hold strategies of high-level promotion and low-level promotion due to the similar reason to manufacturers. Supposing manufacturers and retailers have bounded rationality, hence it is hard for one party to accurately know the other's profit function and strategic choice. In other words, it is difficult to keep the optimal strategies the same over time. All of the players will adjust their choices by learning continually. In long-term cooperation on emission-reduction in supply chains, the population of manufacturers and retailers play multiple games randomly by continuous adjustment and strategic improvement, which eventually leads to the evolutionary equilibrium. Based on the above description, the evolutionary game model is used to analyze evolutionary stable strategies for two groups.

The notations used in this paper are described, as follows.

Notation/Description	
M_H:	Manufacturers' strategy of high-level input on emission
M_L:	Manufacturers' strategy of low-level input on emission
R_H:	Retailers' strategy of high-level promotion on low carbon
R_L:	Retailers' strategy of low-level promotion on low carbon
u_M:	Constant marginal profit for each manufacturer, $u_M > 0$
u_R:	Constant marginal profit for each retailer, $u_R > 0$
c_M:	Difference of emission-reduction cost between high-level and low-level strategies for manufacturers
c_R:	Difference of emission-reduction cost between high-level and low-level strategies for retailers
r_M:	Net income of manufacturers when manufacturers and retailers both adopt low-level emission reduction and promotion strategies, $r_M > 0$
r_R:	Net income of retailers when manufacturers and retailers both adopt low-level emission reduction and promotion strategies, $r_R > 0$
q_1:	Sales increment when manufacturers and retailers adopt high-level emission reduction strategy
q_2:	Sales increment when manufacturers adopt the strategy of high-level emission reduction, while retailers use low-level low carbon promotion strategy (retailers' free riding behavior), $q_1 > q_2 > 0$
q_3:	Sales increment when manufacturers use the strategy of low-level emission reduction, while retailers adopt high-level low carbon promotion strategy (manufacturers' free riding), $q_1 > q_3 > 0$
$u_M q_3$:	The profit of manufacturers from free riding
$u_R q_2$:	The profit of retailers from free riding

3.2. Mathematical Models

Step 1: Establishing a pay-off matrix

Denote x $(0 \leq x \leq 1)$ as the proportion of manufacturers choosing high-level emission reduction strategy and otherwise $1 - x$ as those choosing low-level strategy. Similarly, denote y $(0 \leq y \leq 1)$ the proportion of retailers choosing high-level strategy on promoting low-carbon products, and $1 - y$ the proportion of retailers choosing low-level strategy.

Under above assumptions, the payment matrix of both parties is as shown in Table 1.

Table 1. A pay-off matrix of two players.

Manufacturers	**Retailers**	
	High-Level Promotion on Low Carbon (*H*)	**Low-Level Promotion on Low Carbon (*L*)**
High-level emission reduction investment (*H*)	$r_M + u_M q_1 - c_M, r_R + u_R q_1 - c_R$	$r_M + u_M q_2 - c_M, r_R + u_R q_2$
Low-level emission reduction investment (*L*)	$r_M + u_M q_3, r_R + u_R q_3 - c_R$	r_M, r_R

According to Table 1, we express the expected profits for manufacturers' strategies of high-level emission reduction and low-level emission reduction and their average profits, and U_{MH}, U_{ML} and $\overline{U_M}$ as follows, respectively.

$$U_{MH} = (r_M + u_M q_1 - c_M)y + (r_M + u_M q_2 - c_M)(1-y) \tag{1}$$

$$U_{ML} = (r_M + u_M q_3)y + r_M(1-y) \tag{2}$$

$$\overline{U}_M = xU_{MH} + (1-x)U_{ML} \tag{3}$$

For manufacturers, when they choose high-level emission reduction strategy, the dynamic change rate for the proportion of manufacturers choosing high-level emission reduction strategy can be expressed as the following dynamic differential equation:

$$\frac{dx}{dt} = x(U_{MH} - \overline{U_M}) \tag{4}$$

Substituting Equations (1)–(3) into (4), we have:

$$\frac{dx}{dt} = x(1-x)[u_M(q_1 - q_2 - q_3)y + u_M q_2 - c_M] \tag{5}$$

The differential Equation (5) is called the replicator dynamic equation. The speed of rate change for the proportion of manufacturers choosing high level emissions reduction strategy is positively related to both the proportion and the difference between the expected profit choosing this strategy and the average profit. Similarly, retailers' expected profits incurred respectively by high-level and low-level promotion on low carbon, the average profit are expressed as U_{RH}, U_{RL}, and $\overline{U_R}$, respectively.

$$U_{RH} = (r_R + u_R q_1 - c_R)x + (r_R + u_R q_3 - c_R)(1-x) \tag{6}$$

$$U_{RL} = (r_R + u_R q_2)x + r_R(1-x) \tag{7}$$

$$\overline{U_R} = yU_{RH} + (1-y)U_{RL} \tag{8}$$

The replicator dynamic equation for retailers is:

$$\frac{dy}{dt} = y(U_{RH} - \overline{U_R}) \tag{9}$$

Substituting Equations (6)–(8) into Equation (9) and combining Equation (5) yield the following dynamic replicator system of long-term emission reduction game:

$$\begin{cases} dx/dt = x(1-x)[u_M(q_1 - q_2 - q_3)y + u_M q_2 - c_M] \\ dy/dt = y(1-y)[u_R(q_1 - q_2 - q_3)x + u_R q_3 - c_R] \end{cases} \tag{10}$$

Proposition 1 *The above dynamic replicator system has four unconditional equilibrium points,* i.e., $E_1(0,0)$, $E_2(1,0)$, $E_3(0,1)$ and $E_4(1,1)$. *Furthermore,* $E_5(x_0, y_0)$ *can be also an equilibrium point if (i)* $c_M < u_M q_2 < u_M q_1 < c_M + u_M q_3$, $c_R < u_R q_3 < u_R q_1 < c_R + u_R q_2$, *or (ii)* $u_M q_2 < c_M < c_M + u_M q_3 < u_M q_1$, $u_R q_3 < c_R < c_R + u_R q_2 < u_R q_1$, $0 < x_0 < 1$, $0 < y_0 < 1$ *where* $x_0 = (c_R - u_R q_3)/[u_R(q_1 - q_2 - q_3)]$, $y_0 = (c_M - u_M q_2)/[u_M(q_1 - q_2 - q_3)]$. *However, the equilibrium* $E_5(x_0, y_0)$ *does not exist if* $q_1 = q_2 + q_3$.

The proof is shown in the Appendix A.

Proposition 1 implies that there exist five equilibrium points during the long-term evolving process of supply chain dynamic replication system, including four equilibrium points unconstrained by parameters and one point existing upon parameters. For example, equilibrium $E_1(0,0)$ reflects during their long-term cooperative emission reduction all manufacturers will choose low-level of carbon emission reduction (x = 0), while all retailers will choose a low-level of low-carbon product promotion (y = 0), which is invariant over time (i.e., dx/dt = 0 and dy/dt = 0). However, whether the strategies of manufacturers and retailers can converge to this point $E_1(0,0)$ under some external disturbance will be discussed in the succeeding subsection.

3.3. Stability Analysis on System Equilibrium Point

The equilibrium points that were obtained from the dynamic replicator system are not necessarily the ESS in the system. According to Lyapunov stability, which ensures the stability of an equilibrium point by observing that solutions starting out near this equilibrium point stay near the equilibrium point forever [42,43], we judge their evolutionary stability strategy by analyzing the Jacobian matrix. Only the status in which the Jacobian determinant of a matrix $\det(J)$ in the system is positive and trace $tr(J)$ is negative means the equilibrium points the ESS. The $\det(J)$ and $tr(J)$ are shown as follows.

$$J = \begin{bmatrix} \partial\dot{x}/\partial x,\ \partial\dot{x}/\partial y \\ \partial\dot{y}/\partial x, \partial\dot{y}/\partial y \end{bmatrix} = \begin{bmatrix} (1-2x)[u_M(q_1-q_2-q_3)y+u_Mq_2-c_M]x(1-x)u_M(q_1-q_2-q_3) \\ y(1-y)u_R(q_1-q_2-q_3)(1-2y)[u_R(q_1-q_2-q_3)x+u_Rq_3-c_R] \end{bmatrix} \tag{11}$$

$$\begin{aligned} \det(J) = \ & (1-2x)(1-2y)[u_M(q_1-q_2-q_3)y+u_Mq_2-c_M][u_R(q_1-q_2-q_3)x+u_Rq_3-c_R] \\ & -x(1-x)y(1-y)u_Mu_R(q_1-q_2-q_3)^2 \end{aligned} \tag{12}$$

$$tr(J) = (1-2x)[u_M(q_1-q_2-q_3)y+u_Mq_2-c_M]+(1-2y)[u_R(q_1-q_2-q_3)x+u_Rq_3-c_R] \tag{13}$$

Proposition 2 *For these points of evolution stability strategy, there exist the following results as well as preconditions.*

(1) $E_1(0,0)$ is the evolution stability strategy (ESS) of dynamic replicator system, if (i) $u_Mq_2 < c_M$, $u_Mq_1 < u_Mq_3 + c_M$ and $u_Rq_3 < c_R$, $u_Rq_1 < u_Rq_2 + c_R$, or (ii) $u_Mq_2 < c_M < u_Mq_3 + c_M < u_Mq_1$ and $u_Rq_3 < c_R$, $u_Rq_1 < u_Rq_2 + c_R$ or (iii) $u_Mq_2 < c_M$, $u_Mq_1 < u_Mq_3 + c_M$ and $u_Rq_3 < c_R < u_Rq_2 + c_R < u_Rq_1$;

(2) $E_2(1,0)$ is the ESS of dynamic replicator system, if (i) $c_M < u_Mq_2$, $u_Mq_1 > u_Mq_3 + c_M$ and $u_Rq_3 < c_R$, $u_Rq_1 < u_Rq_2 + c_R$, or (ii) $c_M < u_Mq_2$, $u_Mq_1 > u_Mq_3 + c_M$ and $c_R < u_Rq_3 < u_Rq_1 < u_Rq_2 + c_R$ or (iii) $c_M < u_Mq_2 < u_Mq_1 < u_Mq_3 + c_M$ and $u_Rq_3 < c_R$, $u_Rq_1 < u_Rq_2 + c_R$;

(3) $E_3(0,1)$ is the ESS of dynamic replicator system, if (i) $u_Mq_2 < c_M$, $u_Mq_1 < u_Mq_3 + c_M$ and $u_Rq_3 > c_R$, $u_Rq_1 > u_Rq_2 + c_R$, or (ii) $c_M < u_Mq_2 < u_Mq_1 < u_Mq_3 + c_M$ and $u_Rq_3 > c_R$, $u_Rq_1 > u_Rq_2 + c_R$, or (iii) $u_Mq_2 < c_M$, $u_Mq_1 < u_Mq_3 + c_M$ and $c_R < u_Rq_3 < u_Rq_1 < u_Rq_2 + c_R$;

(4) $E_4(1,1)$ is the ESS of dynamic replicator system, if (i) $u_Mq_2 < c_M < u_Mq_3 + c_M < u_Mq_1$ and $u_Rq_3 > c_R$, $u_Rq_1 > u_Rq_2 + c_R$, or (ii) $u_Mq_2 > c_M$, $u_Mq_1 > u_Mq_3 + c_M$ and $u_Rq_3 < c_R < u_Rq_2 + c_R < u_Rq_1$, or (iii) $u_Mq_2 > c_M$, $u_Mq_1 > u_Mq_3 + c_M$ and $u_Rq_3 > c_R$, $u_Rq_1 > u_Rq_2 + c_R$;

(5) $E_1(0,0)$ and $E_4(1,1)$ are the ESS of the dynamic replicator system, if $u_Mq_2 < c_M < u_Mq_3 + c_M < u_Mq_1$ and $u_Rq_3 < c_R < u_Rq_2 + c_R < u_Rq_1$;

(6) $E_2(1,0)$ and $E_3(0,1)$ are the ESS of the dynamic replicator system, if $c_M < u_Mq_2 < u_Mq_1 < u_Mq_3 + c_M$ and $c_R < u_Rq_3 < u_Rq_1 < u_Rq_2 + c_R$.

The proof is shown in the Appendix A.

Proposition 2 points out the prerequisites under which the stability of five equilibrium points holds and these points become the evolutionary stable strategies. The aforementioned example of equilibrium point $E_1(0,0)$ still holds in case of those conditions given, which is elaborated in subsequent analysis.

3.4. Managerial Insights

In this subsection, analyzing the evolutionary stable strategies in proposition 2 summarizes the managerial implications as below.

Observation 1 For manufacturers and retailers, the system actions will converge to $E_1(0,0)$ with evolutionary stable equilibrium strategy (M_L, R_L), that is, manufacturers and retailers both choose low-level emission reduction and promotion strategies, respectively, when parameters satisfy conditions (i) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$, or (ii) $u_M q_2 < c_M < u_M q_3 + c_M < u_M q_1$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$, or (iii) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R < u_R q_2 + c_R < u_R q_1$.

That is, for either the manufacturer or the retailer, the firm's profit from unilaterally participating in emission reduction is less than that under no participation in emission reduction, if one of the three conditions below holds: (1) For the manufacturer and retailer, their total profit under emission-reduction cooperation between two parties is less than that in the setting where there exists the free- riding behavior ((i) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$); (2) Comparing with the cooperative emission reduction, manufacturer's free-riding behavior will decrease his own individual profit, while retailer's free-riding behavior will increase her own profit ((ii) $u_M q_2 < c_M < u_M q_3 + c_M < u_M q_1$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$); and (3) Still referring to the cooperative emission reduction, manufacturer's free-riding behavior will increase his own profit, while retailer's free-riding behavior will decrease her own profit ((iii) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R < u_R q_2 + c_R < u_R q_1$), the evolutionary stable equilibrium strategies for manufacturers and retailers is (M_L, R_L).

This Observation has some implications to practice. Retailers' high-level low-carbon promotion has limited effect on the demand (i.e., q_3 is small or c_R is large) and in the case that consumers have a full understanding of low carbon products; Meanwhile, manufacturers may confront bottleneck in reducing emission when high-level input on emission reduction contributes little to revenue increase(i.e., q_2 is small or c_M large). Thus, profit maximizing will be the dominant principle for decision making resulting in those two parties both adopting low-level emission reduction strategy become the ESS, which usually takes place at the late period of the life cycle of low-carbon products.

Observation 2 For manufacturers and retailers, the system actions will converge to $E_2(1,0)$ with evolutionary stable equilibrium strategy (M_H, R_L), i.e., manufacturers choose high-level emissions reduction strategy and retailers choose low-level promotion strategy, respectively; when parameters satisfy (i) $c_M < u_M q_2$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$, or (ii) $c_M < u_M q_2$, $u_M q_1 > u_M q_3 + c_M$ and $c_R < u_R q_3 < u_R q_1 < u_R q_2 + c_R$, or (iii) $c_M < u_M q_2 < u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$.

Namely, this ESS exists if one of the following three conditions remains: (1) For manufacturer, his/her profit under his/her unilateral emission-reduction is greater than that in the setting without emission reduction, while conversely the retailer's profit under his/her unilateral emission reduction is less; moreover, for the manufacturer, his/her total profit under emission-reduction cooperation between two parties is more than that in the setting where there exists the free-riding behavior, while conversely the retailer's profit under emission reduction cooperation is less ((i) $c_M < u_M q_2$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$); (2) for either manufacturer or retailer, the profit under unilateral emission reduction is greater than that without emission reduction; moreover, for the manufacturer, her total profit under emission-reduction cooperation between two parties is more than that in the setting where there exists the free-riding behavior, while conversely the retailer's profit under emission reduction cooperation is less ((ii) $c_M < u_M q_2$, $u_M q_1 > u_M q_3 + c_M$ and $c_R < u_R q_3 < u_R q_1 < u_R q_2 + c_R$); (3) Comparing with no emission reduction cooperation, the manufacturer's unilateral involvement definitely increases his/her profit, whereas the retailer's unilateral involvement definitely decreases his/her profit; moreover, for either manufacturer or retailer, the unilateral free-riding behavior will increase the firm's profit, comparing with emission-reduction cooperation between two parties ((iii) $c_M < u_M q_2 < u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 < c_R$, $u_R q_1 < u_R q_2 + c_R$).

The above Observation implies that manufacturers can gain bonus from emission reduction, that is, the higher the investment efficiency of emission reduction is, the more profit the emission reduction strategy can bring. We can attribute this phenomenon to two reasons: First, manufacturers' investment for low-carbon emission reduction in the earlier stage can substantially decrease the carbon footprint of products (since emission-reducing efficiency follows the principle of diminishing marginal utility). Second, there is steadily increasing demand that is ascribed to the growing of consumers' low-carbon awareness. However, it will be ineffective but cost inefficient to conduct low-carbon promotion when consumers' low-carbon awareness is high. Taking home appliance sales market as an example, manufacturers will strengthen technological innovation to launch products since consumers realize that products with low-energy consumption are more environment-friendly.

Observation 3 For manufacturers and retailers, the system evolutionary actions will converge to $E_3(0,1)$ with evolutionary stable equilibrium (M_L, R_H) in case that one of three conditions holds, (i) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$, or (ii) $c_M < u_M q_2 < u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$, or (iii) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $c_R < u_R q_3 < u_R q_1 < u_R q_2 + c_R$.

That is, these elaborated conditions: (1) Comparing with no cooperative emission reduction, retailer's unilateral participation in emission reduction may increase her profit, whereas manufacturer's unilateral involvement will decrease his profit; moreover, when comparing with the profits under cooperative emission reduction, retailer's free riding action decreases her own profit but manufacturer's free riding action increase manufacturer's profit ((i) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$); (2) Unilateral emission reduction for manufacturers and retailers is anyhow better than no emission reduction; furthermore, retailer's profit under bilateral cooperative emission reduction is more than that with his/her free-riding behaviors, however, manufacturer's profit under bilateral cooperative emission reduction less than that with his/her free-riding actions ((ii) $c_M < u_M q_2 < u_M q_1 < u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$); (3) For the retailer, unilateral involvement can generate more profit than no participation in emission reduction, whereas for manufacturer his unilateral emission reducing incurs less profit than no emission; moreover, free-riding again cause more profit than bilateral emission reduction ((iii) $u_M q_2 < c_M$, $u_M q_1 < u_M q_3 + c_M$ and $c_R < u_R q_3 < u_R q_1 < u_R q_2 + c_R$).

The above explanation shows that for manufacturers increasing input on emission reduction might have a weak effect on profit and emission due to possible emission-reducing technology bottleneck. However, for retailers grasping the increase of consumers awareness to low carbon can substantially impact the system performance.

Observation 4 Manufacturers' and retailers' actions will converge to $E_4(1,1)$ with evolutionary stable equilibrium strategy (M_H, R_H), i.e., they both choose high-level emissions-reduction/promotion strategy when one of three conditions as follows holds, namely, (i) $u_M q_2 < c_M < u_M q_3 + c_M < u_M q_1$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$ or (ii) $u_M q_2 > c_M$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 < c_R < u_R q_2 + c_R < u_R q_1$, or (iii) $u_M q_2 > c_M$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$, that is, elaborately, (1) Comparing with no emission reduction, unilateral participation in emission reduction is beneficial to the retailer, yet adverse to manufacturer; moreover, for manufacturers and retailers bilateral cooperation on emission reduction can generate more profit than that with free riding behavior ((i) $u_M q_2 < c_M < u_M q_3 + c_M < u_M q_1$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$); or (2) Comparing with no emission reduction, unilateral participation in emission reduction is beneficial to manufacturers, yet adverse to retailers; furthermore, for manufacturers and retailers bilateral cooperation on emission reduction will generate more profit than that with free riding behavior ((ii) $u_M q_2 > c_M$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 < c_R < u_R q_2 + c_R < u_R q_1$); or (3) Comparing with no emission reduction, unilateral participation in emission reduction is both beneficial to retailers and manufacturers; what is more, bilateral cooperation on emission reduction will bring about more profit than that with free riding actions ((iii) $u_M q_2 > c_M$, $u_M q_1 > u_M q_3 + c_M$ and $u_R q_3 > c_R$, $u_R q_1 > u_R q_2 + c_R$).

The above Observation implies some insights as follows. For either the manufacturer or the retailer, the profit increment by bilateral cooperative emission reduction is greater than that with his or her free-riding behavior, respectively. Therefore, both sides have the incentive to participate in emission reduction. Note that two special cases in Proposition 2 are stated in Observation 5 and 6 as follows.

Observation 5 When parameters satisfy $u_M q_2 < c_M < u_M q_3 + c_M < u_M q_1$ and $u_R q_3 < c_R < u_R q_2 + c_R < u_R q_1$, in other words, for manufacturers and retailers, unilateral participation in emission reduction will incur less profit than that by no emission reduction, while bilateral cooperative emission reduction may bring about more profit than free riding behavior; in addition, the demand increment by cooperative emission reduction is more than separate emission reduction ($q_1 > q_2 + q_3$), the system might converge to $E_1(0,0)$ or $E_4(1,1)$. Finally, the system converges to which stable point determined by the initial probability of two parties' choice for emission reduction strategy (x, y). We show the phase diagram under the condition in Figure 1 with two unstable point,$E_2(1,0)$ and $E_3(0,1)$, a saddle point $E_5(x_0, y_0)$ which converges to the boundary of two stable points $E_1(0,0)$ and $E_4(1,1)$. If initial probability is at below the polyline A of area, the system finally evolves to the steady point $E_1(0,0)$, where both sides don't participate in emission reduction. On the contrary, in case that the initial probability is over the polyline of B region, the system eventually evolves to a stable point $E_4(1,1)$, where both parties participate in emission reduction.

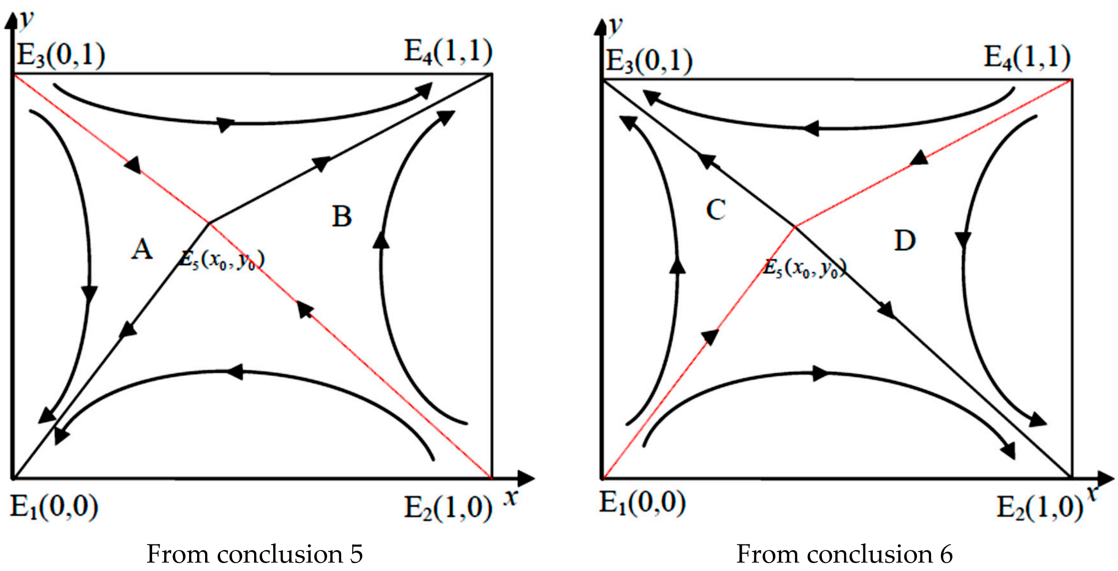


Figure 1. The dynamic phase diagram of system evolution under conclusion 5 and conclusion 6.

Observation 6 When parameters satisfy $c_M < u_M q_2 < u_M q_1 < u_M q_3 + c_M$ and $c_R < u_R q_3 < u_R q_1 < u_R q_2 + c_R$, namely, for manufacturers and retailers unilateral participation in emission reduction can entail more profit than that under no emission reduction, yet bilateral cooperative emission reduction unexpectedly incur less profit than that with free-riding behaviors; in addition, bilateral cooperative emission reduction will incur less total demand increment than unilateral emission reduction ($q_1 < q_2 + q_3$), the system maybe converge to $E_2(1,0)$ or $E_3(0,1)$. Similarly, the system converges to which stable point, which is determined by the initial probability of two parties' choice for emission reduction strategy (x, y). The phase diagram under the condition can be shown as Observation (6) in Figure 1, where there are two unstable point, $E_1(0,0)$ and $E_4(1,1)$, a saddle point $E_5(x_0, y_0)$ which converges to the boundary of two stable points, $E_2(1,0)$ and $E_3(0,1)$. If initial probability is over the polyline of C area, the system finally evolves to the steady point $E_3(0,1)$, where manufacturers adopt low level emission reduction strategy, however retailers choose high level emission reduction. On the contrary, if the initial probability is at below the polyline of D region, the system eventually evolves to a stable point $E_2(1,0)$, where manufacturers adopt high level emission reduction strategy, however retailers choose low level emission reduction.

In this study, we focus on the selection of long-term emission reduction cooperation strategies between manufacturers and retailers (manufacturer's high/low level emission reduction strategy and retailer's high/low level low-carbon promotion strategy), and whether the combination of these strategies is stable, and further discuss which parameters affect these stability strategies. Proposition 1 gives the equilibrium point of the choice of the two strategies. Proposition 2 discusses the stability of these equilibrium strategies in what parameter range. Conclusion 1–6 explains the management meaning of the parameter range of these evolutionary stability strategies, respectively, and gives the managerial insights and suggestions of long-term emission-reduction cooperation between manufacturers and retailers.

4. Computational Study and Analysis

Taking supermarkets and her suppliers (manufacturers) as an example, the section conducts computational experiments for emission reduction cooperation between manufacturers and retailers, and further provides managerial implications for their emission reduction strategy in the long term.

4.1. Parameter Setting

In this paper, we consider the supply chain system consisting of many homogeneous manufacturers and homogeneous retailers, who transacts mutually for optimizing their own profits. This structure of supply chains is common in the super market and home electric appliance retail store. Therefore, in this numerical experiment, suppose that several (no less than three) homogeneous retail supermarkets sell eight kinds of goods (A_1–A_8) contemporaneously and each commodity has many (no less than three) homogeneous manufacturers. Accordingly, the parameters values assigning is shown in Table 2.

Table 2. Parameters of Simulation Experiment.

Production	u_M	u_R	c_M	c_R	q_1	q_2	q_3
A_1	0.1	0.08	0.5	0.45	8	1	4
A_2	0.2	0.16	0.2	0.8	7	5	3
A_3	0.2	0.16	0.2	0.35	8	6	4
A_4	0.11	0.21	0.9	0.45	8	1	4
A_5	0.4	0.21	0.5	0.15	8	2	7
A_6	0.2	0.21	0.5	0.65	8	4	2
A_7	0.2	0.21	0.5	0.65	8	2	2
A_8	0.2	0.21	0.5	0.65	8	5	6

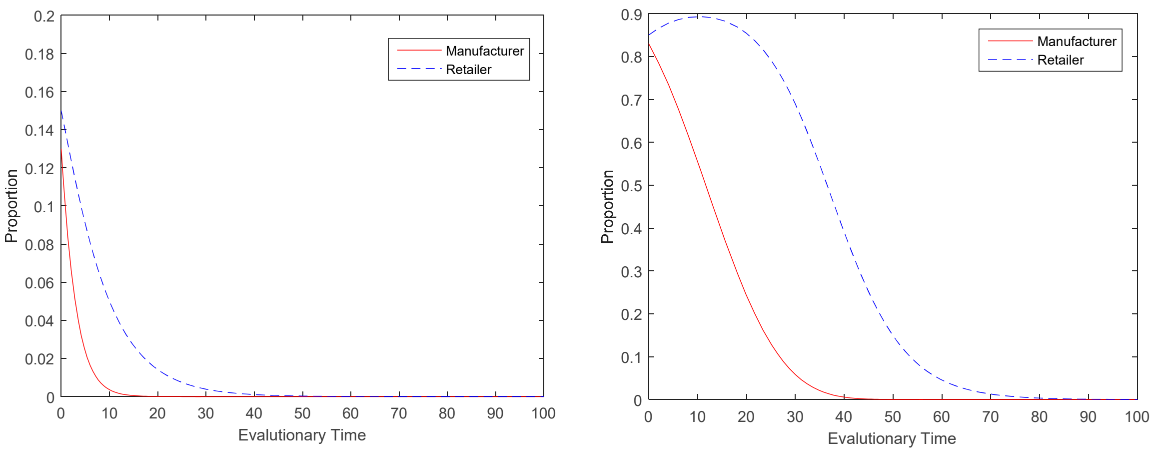
After setting the initial value of x and y, the evolution results of carbon emission reduction in the long-term cooperation between manufacturers and retailers for each commodity are generated by the replicator dynamic Equation (10) and simulation experiment runs in MATLAB 7.12 (R2011a).

4.2. Evolution Results and Analysis

Suppose a number of retail supermarkets sell eight kinds of products, each of which is supplied by a single manufacturer. Eight different simulation experiments will be carried out. The evolution process and results are shown from Figures 2–7, simulating six types formations of evolution results. Among the six pictures, the real-line curve represents the evolution trend of the manufacturer's emission reduction strategy, and the virtual-line indicates the evolution trend of the retailer's low-carbon promotion strategy. The results of the simulation experiment verify those managerial insights that are mentioned in Section 3.

(1) The system evolutionary stability strategy $E_1(0,0)$

In the process of evolution concerning the first category (as shown in Figure 2), we conduct 100 times simulation (procurement procedures) for manufacturers and retailers, which involved A_1, and dynamic replicator system converges to point $E_1(0,0)$. However, we set different initial conditions ($x = 0.13$ and $y = 0.15$ in Figure 2a and $x = 0.83$ and $y = 0.85$ in Figure 2b). The system varies in the convergent process. For example, most of manufacturers tend to choose emission reduction in Figure 2b in the first 10 times simulation (x tended to 1), and then fell rapidly, then converged to $E_1(0,0)$. Even if the system set high initial value ($x = 0.83$ and $y = 0.85$) in the beginning, two sides still fail to cooperate eventually. The main reason is that, when two parties reduced emission individually, the profit of them reducing emission is less than that they quit reducing emission; in addition, when two sides cooperate on emission reduction, the retailers' profit emission is more than that they choose free riding. However, the manufacturers' profit is less than that under free riding when they cooperate to reduce emission. Therefore, among several games, retailers choose to cooperate but manufacturers adopt free riding, which induces retailers change their strategies to quit cooperating. Finally, ESS is adopted by two parties is non-cooperative emission.

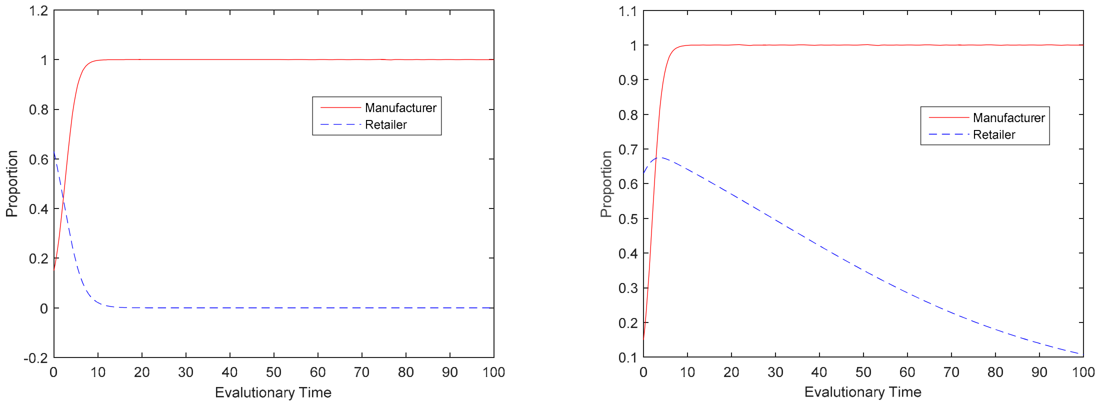


(a) $x = 0.13$, $y = 0.15$ **(b)** $x = 0.83$, $y = 0.85$

Figure 2. The evolution process of evolutionary stable strategy of $E_1(0,0)$.

(2) The system evolutionary stable strategy $E_2(1,0)$

In the process of evolution concerning the second category (as shown in Figure 3), we conduct 100 times simulation (procurement procedures) for manufacturers and retailers, which involved A_2 and A_3, respectively, and the dynamic replicator system converges to $E_2(1,0)$. We set the same initial conditions ($x = 0.15$ and $y = 0.63$) in Figure 3a,b, which means the proportion of manufacturers choosing high-level carbon emission reduction strategy is lower, but the proportion of retailers choosing high-level low carbon promotion strategy is higher at the beginning. Finally, they all converge to $E_2(1,0)$. Furthermore, the system varies in the convergence process. In Figure 3b, retailers tended to choose cooperative emission reduction in the first 5 times simulation, and then gradually shifted till converged to $E_2(1,0)$. The main reason is that, the low-carbon promotion cost of retailers in A_3 is not too higher, so retailers were inclined to choose cooperative emission reduction at first; however when consumers' low-carbon awareness had formed, low-carbon products would have larger demand even if retailers chose low-level promotion. What's more, retailers' profit when free riding is more than that when they cooperate to reduce emission. Finally, manufacturers choosing high-level emission reduction but retailers adopting low-level promotion is their ESS The stimulation is consistent with the conclusion 2 in Section 3.4.



(**a**) $u_R = 0.16$, $c_R = 0.8$, $q_3 = 3$ (**b**) $u_R = 0.16$, $c_R = 0.35$, $q_3 = 4$

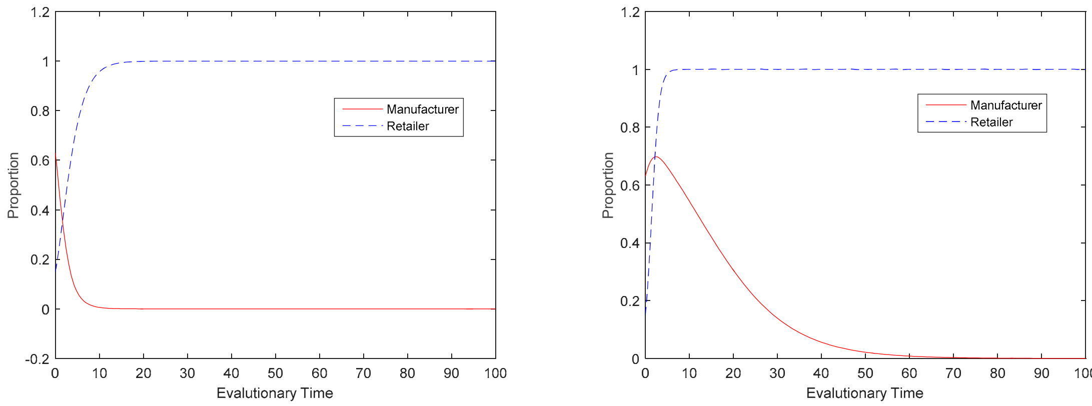
Figure 3. The evolution process of evolutionary stable strategy of $E_2(1,0)$.

(3) The system evolutionary stable strategy $E_3(0,1)$

In the process of evolution concerning the third evolution result (as shown in Figure 4), we conduct 100 times simulation (procurement procedures) for manufacturers and retailers, which involved A_4 and A_5, respectively, and dynamic replicator system converges to $E_3(0,1)$. We set same initial condition ($x = 0.63$ and $y = 0.15$) in Figure 4a,b. In the moment, the proportion of manufacturers choosing high-level carbon emission reduction strategy is higher, but the proportion of retailers choosing high-level low carbon promotion strategy is lower in the beginning. Finally, two systems converge to $E_3(0,1)$, but vary in the convergence process. In Figure 4b, in the first five times simulation, manufacturers tended to choose cooperative emission reduction, then fell down rapidly, and converged to $E_3(0,1)$. The main reason is that, when they conduct reduce emission of high level in A_5 product, the emission reduction cost of manufacturers is not higher. Therefore, they will choose cooperative emission reduction strategy in the early game. However, after forming consumers' low-carbon awareness, retailers have a lower emission reduction cost for promotion, and low-carbon promotion can increase demand largely. In this time, the profit of manufacturers when free riding is more than that cooperation. At the last, manufacturers choose low-level emission reduction, but retailers adopt high-level low-carbon promotion is their ESS. The result accords with the conclusion 3 in Section 3.4.

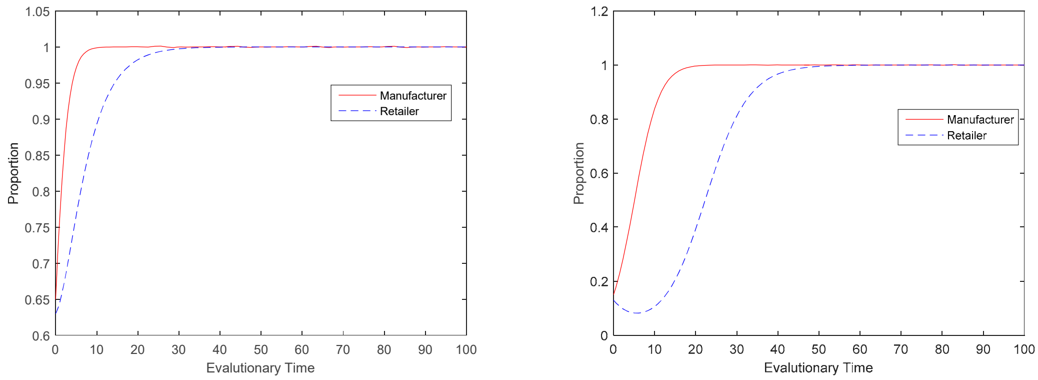
(4) The system evolutionary stable strategy $E_4(1,1)$

In the process of evolution concerning the fourth evolution result (as shown in Figure 5), we conduct 100 times simulation (procurement procedures) for manufacturers and retailers, which involved A_6 product, and dynamic replicator system converges to $E_4(1,1)$. For the product of A_6, we set different initial conditions ($x = 0.65$, $y = 0.63$ in Figure 5a; $x = 0.15$, $y = 0.13$ in Figure 5b). The system varies in the convergence process. In Figure 5b, in the first 10 times simulation, retailers tended to choose low-level low carbon promotion, then changed their strategies and converged to $E_4(1,1)$. Because the proportion of retailers choosing low-level low-carbon promotion strategy is higher in the initial setting, and the low-carbon promotion cost of retailers is higher. Therefore, in the beginning, most retailers quit to reduce emission; however, when they cooperate with manufacturers on emission reduction, consumers' low-carbon demand increase largely emission, and finally two parties converge to $E_4(1,1)$.



(a) $c_M = 0.9$, $q_2 = 1$, $c_R = 0.45$, $q_3 = 4$ **(b)** $c_M = 0.5$, $q_2 = 1$, $c_R = 0.15$, $q_3 = 7$

Figure 4. The Evolution Process of Evolutionary Stable Strategy of $E_3(0, 1)$.

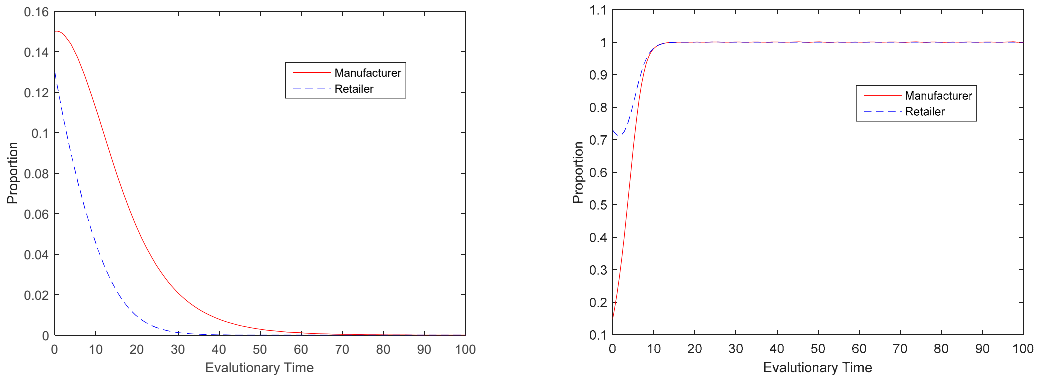


(a) $x = 0.65$, $y = 0.63$ **(b)** $x = 0.15$, $y = 0.13$

Figure 5. The Evolution Process of Evolutionary Stable Strategy of $E_4(1, 1)$.

(5) The system evolutionary stable strategy $E_1(0, 0)$ or $E_4(1, 1)$

In the process of evolution concerning the fifth evolution result (as shown in Figure 6), we conduct 100 times simulation (procurement procedures) for two parties, which involved A_7, and dynamic replicator system converges to $E_1(0, 0)$ or $E_4(1, 1)$. We set different initial conditions ($x = 0.15, y = 0.13$ in Figure 6a; $x = 0.15, y = 0.73$ in Figure 6b), and the system has different convergence results, converging to $E_1(0, 0)$ or $E_4(1, 1)$, respectively. For the product of A_7, when manufacturers and retailers conduct emission reduction unilaterally, the cost of low-carbon strategy emission is higher; in addition, the increasement of demand from two sides unilaterally conducting high-level emission reduction strategy is lower. Therefore, two parties would not like to choose high-level emission reduction unilaterally. However, when they cooperate to reduce emission, the increasement of products' demand is larger. In other words, when the proportion of two population choosing high level emission reduction is lower, two parties are unwilling to choose high-level strategy on emission reduction. Therefore, the final evolutionary result is shown in Figure 6a, where they all choose emission reduction strategy of low level, the result converges to $E_1(0, 0)$. Otherwise, in the beginning of the system, the proportion of retailers' population choosing high level low-carbon promotion strategy is higher, meanwhile, manufacturers realized the fact that, when they cooperate, the profit of himself is more than that when free riding, then increasing the proportion of manufacturers in the population choosing high-level emission reduction. In the early games, when manufacturers choose low-level emission reduction, there is free riding behavior, so retailers' willingness to choose high-level low-carbon promotion will decrease. However, because two parties gradually realize that cooperative emission reduction will increase the market demand of products largely. Finally, two sides will choose emission reduction of high level. As shown in Figure 6b, the result converges to $E_4(1, 1)$.

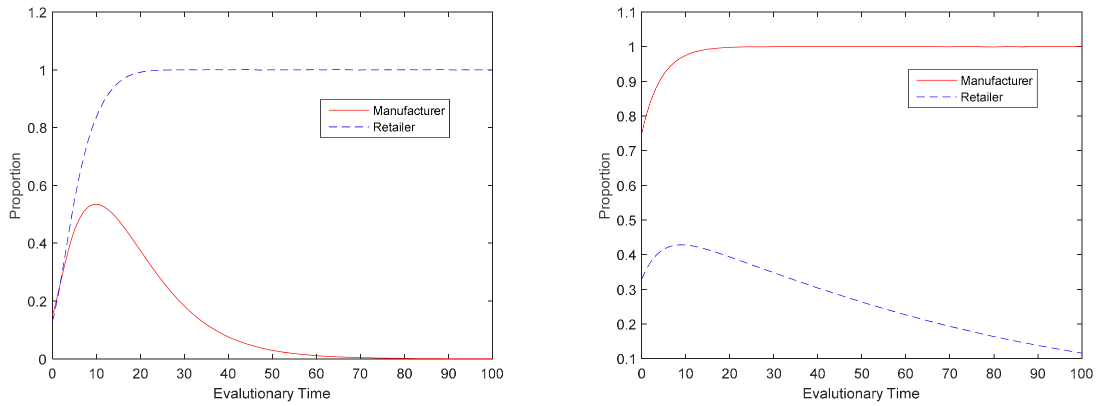


(**a**) $x = 0.15$, $y = 0.13$ (**b**) $x = 0.15$, $y = 0.73$

Figure 6. The Evolution Process of Evolutionary Stable Strategy of $E_1(0,0)$ or $E_4(1,1)$.

(6) The system evolutionary stable strategy $E_2(1,0)$ or $E_3(0,1)$

In the process of evolution concerning the sixth evolution result (as shown in Figure 7), we conduct 100 times simulation (procurement procedures) for manufacturers and retailers, which involves A_8. We set different initial condition ($x = 0.15$ and $y = 0.13$ in Figure 7a; $x = 0.75$ and $y = 0.33$ in Figure 7b), and the system have different convergence results, converging to $E_2(1,0)$ or $E_3(0,1)$, respectively. For the product of A_8, when manufacturers and retailers conduct high-level emission reduction unilaterally, the cost of low-carbon strategy is higher, but the increasement of demand from two sides conducting high-level emission reduction strategy unilaterally is higher. In other words, there is large profit of free riding. However, when they choose to cooperate with each other, the increasement of the products' market demand is not high. Therefore, when the proportion of two parties choosing high level emission reduction is lower in their respective population, they all have the motivation to choose high level strategy unilaterally. From Figure 7a, in the first 10 times, the proportion of two sides choosing high-level emission reduction will increase; in addition, manufacturers also find that, two parties cooperating to reduce emission cannot increase products' demand a lot. Therefore, with time going by, more manufacturers will choose free riding. Finally, the evolutionary stable results are that retailers choose high level strategy of low-carbon promotion and manufacturers adopt low level emission reduction strategy, the result converges to $E_3(0,1)$. On the contrary, if in the beginning of the system, the proportion of manufacturers adopting high level low-carbon investment is higher, but the proportion of retailers choosing low level low-carbon promotion is lower, finally retailers will choose free riding after several games. As shown in Figure 7b, the strategy of two sides will converge to $E_2(1,0)$.



(**a**) $x = 0.15$, $y = 0.13$ (**b**) $x = 0.75$, $y = 0.33$

Figure 7. The Evolution Process of Evolutionary Stable Strategy of $E_2(1,0)$ or $E_3(0,1)$.

5. Conclusions

The paper focused on the decisions of emission-reduction relevant production and low-carbon promotion in low-carbon supply chain while using evolutionary game. The main contributions of our work can be summarized in the following three aspects. First, we investigate the long-term evolutionary stability strategies with vertical cooperative emission reduction in supply chain under different parameter combinations, which contains manufacturers' low-carbon production and retailers' low-carbon promotion, and discuss how parameters affect the results of evolutionary stability. Second, we consider free-riding behavior in carbon emission-reduction and demonstrate its impact on supply chain performances (profit and emission reduction). Finally, for giving some managerial insights, this study provided theoretical analysis for supply chain firms in the evolving process of long-term cooperative emission reduction to confront and even diminish free riding behaviors by altering strategies and adjusting parameter.

There are still some limitations in this work. The following directions therefore can be extended in the future. First, the vertical cooperative emission reduction not only contains manufacturers and retailers, but it also involves other parties, like upstream suppliers and third-party logistics providers, which can be considered in a more complicated situation, but closer to reality. Second, the impact of carbon emission regulations on the system evolutionary stable strategies may highly depend on concrete policies, while this paper only considered emission reduction behavior under general government regulation. Nevertheless, our research can provide some reference for future researches on evolutionary game analysis of supply chains under diverse policies of carbon emission reduction.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The Proof of Proposition 1

The proof process of proposition 1 is as follows:

For dynamic replicator systems (10), if $dx/dt = 0$ and $dy/dt = 0$, the equilibrium points of the system are $E_1(0,0)$, $E_2(1,0)$, $E_3(0,1)$ and $E_4(1,1)$. If $x_0 = (c_R - u_R q_3)/[u_R(q_1 - q_2 - q_3)]$, $y_0 = (c_M - u_M q_2)/[u_M(q_1 - q_2 - q_3)]$, when parameters satisfy $c_M < u_M q_2 < u_M q_1 < c_M + u_M q_3$ and $c_R < u_R q_3 < u_R q_1 < c_R + u_R q_2$, we have $q_1 < q_2 + q_3$; when parameters satisfy $u_M q_2 < c_M < c_M + u_M q_3 < u_M q_1$ and $u_R q_3 < c_R < c_R + u_R q_2 < u_R q_1$, we have $q_1 > q_2 + q_3$. Here, $0 < x_0 < 1$, $0 < y_0 < 1$, from $dx/dt = 0$ and $dy/dt = 0$, we can know that $E_5(x_0, y_0)$ also is an equilibrium point of the system. If $q_1 = q_2 + q_3$ and $E_5(x_0, y_0)$ does not exist.

The Proof of Proposition 2

The proof process of proposition 2 is as follows:

Substituting the five equilibrium points from dynamic replicator system (10) in proposition 1 into Equations (12) and (13), respectively. We have the determinant and trace values of the Jacobian matrix J in the system at each equilibrium point, which is as shown in Table A1:

Table A1. The determinant and trace of Jacobian matrix of J the dynamic replicator system at each equilibrium point.

Equilibrium Point	det($\boldsymbol{J}$)	$\boldsymbol{tr}(\boldsymbol{J})$
$E_1(0,0)$	$(u_Mq_2 - c_M)(u_Rq_3 - c_R)$	$(u_Mq_2 - c_M) + (u_Rq_3 - c_R)$
$E_2(1,0)$	$-(u_Mq_2 - c_M)(u_Rq_1 - c_R - u_Rq_2)$	$-(u_Mq_2 - c_M) + (u_Rq_1 - c_R - u_Rq_2)$
$E_3(0,1)$	$-(u_Mq_1 - c_M - u_Mq_3)(u_Rq_3 - c_R)$	$(u_Mq_1 - c_M - u_Mq_3) - (u_Rq_3 - c_R)$
$E_4(1,1)$	$(u_Mq_1 - c_M - u_Mq_3)(u_Rq_1 - c_R - u_Rq_2)$	$-(u_Mq_1 - c_M - u_Mq_3) - (u_Rq_1 - c_R - u_Rq_2)$
$E_5(x_0, y_0)$	$-x_0y_0(1-x_0)(1-y_0)u_Mu_R(q_1 - q_2 - q_3)^2$	0

Based on the principle of evolutionary stable strategy of Jacobian determinant and decision system of trace values, The equilibrium stable is unstable if $\det(J) > 0$ and $tr(J) > 0$; The equilibrium point is the ESS if $\det(J) > 0$ and $tr(J) < 0$; The equilibrium point is the saddle point if $\det(J) < 0$ and $tr(J)$ is arbitrary value. Therefore, evolutionary stable results of equilibrium points in dynamic replicator system are shown in Table A2.

Table A2. Analysis of evolutionary stability of equilibrium points.

	Condition	Determinant	Equilibrium Point				
			$\boldsymbol{E_1}$(0,0)	$\boldsymbol{E_2}$(1,0)	$\boldsymbol{E_3}$(0,1)	$\boldsymbol{E_4}$(1,1)	$\boldsymbol{E_5}$($\boldsymbol{x_0}$,$\boldsymbol{y_0}$)
1	$u_Mq_2 - c_M < 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	> 0 < 0 ESS	< 0 ? saddle point	< 0 ? saddle point	> 0 > 0 instability point	Non-existent
2	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	> 0 < 0 ESS	< 0 ? saddle point	> 0 > 0 instability point	Non-existent
3	$u_Mq_2 - c_M < 0$ $u_Mq_1 - c_M > u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	> 0 < 0 ESS	< 0 ? saddle point	> 0 > 0 instability point	< 0 ? saddle point	Non-existent
4	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M > u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	> 0 < 0 ESS	> 0 > 0 instability point	< 0 ? saddle point	Non-existent
5	$u_Mq_2 - c_M < 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R > 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	< 0 ? saddle point	> 0 < 0 ESS	> 0 > 0 instability point	Non-existent
6	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R > 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	> 0 > 0 instability point	> 0 < 0 ESS	> 0 < 0 ESS	> 0 > 0 instability point	< 0 ? saddle point
7	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M > u_Mq_3$ $u_Rq_3 - c_R > 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	> 0 > 0 instability point	> 0 < 0 ESS	< 0 ? saddle point	< 0 ? saddle point	Non-existent
8	$u_Mq_2 - c_M < 0$ $u_Mq_1 - c_M > u_Mq_3$ $u_Rq_3 - c_R > 0$ $u_Rq_1 - c_R < u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	< 0 ? saddle point	< 0 ? saddle point	< 0 ? saddle point	Non-existent
9	$u_Mq_2 - c_M < 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R > u_Rq_2$	det(J) $tr(J)$ result	> 0 < 0 ESS	> 0 > 0 instability point	< 0 ? saddle point	< 0 ? saddle point	Non-existent
10	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M < u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R > u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	< 0 ? saddle point	< 0 ? saddle point	< 0 ? saddle point	Non-existent
11	$u_Mq_2 - c_M > 0$ $u_Mq_1 - c_M > u_Mq_3$ $u_Rq_3 - c_R < 0$ $u_Rq_1 - c_R > u_Rq_2$	det(J) $tr(J)$ result	< 0 ? saddle point	< 0 ? saddle point	> 0 > 0 instability point	> 0 < 0 ESS	Non-existent

Table A2. *Cont.*

	Condition	Determinant	Equilibrium Point				
			$E_1(0,0)$	$E_2(1,0)$	$E_3(0,1)$	$E_4(1,1)$	$E_5(x_0,y_0)$
12	$u_M q_2 - c_M < 0$ $u_M q_1 - c_M > u_M q_3$ $u_R q_3 - c_R < 0$ $u_R q_1 - c_R > u_R q_2$	det(J) $tr(J)$ result	> 0 < 0 ESS	> 0 > 0 instability point	> 0 > 0 instability point	> 0 < 0 ESS	< 0 ? saddle point
13	$u_M q_2 - c_M < 0$ $u_M q_1 - c_M < u_M q_3$ $u_R q_3 - c_R > 0$ $u_R q_1 - c_R > u_R q_2$	det(J) $tr(J)$ result	< 0 ? saddle point	> 0 > 0 instability point	> 0 < 0 ESS	< 0 ? saddle point	Non-existent
14	$u_M q_2 - c_M < 0$ $u_M q_1 - c_M > u_M q_3$ $u_R q_3 - c_R > 0$ $u_R q_1 - c_R > u_R q_2$	det(J) $tr(J)$ result	< 0 ? saddle point	> 0 > 0 instability point	< 0 ? saddle point	> 0 < 0 ESS	Non-existent
15	$u_M q_2 - c_M > 0$ $u_M q_1 - c_M < u_M q_3$ $u_R q_3 - c_R > 0$ $u_R q_1 - c_R > u_R q_2$	det(J) $tr(J)$ result	> 0 > 0 instability point	< 0 ? saddle point	> 0 < 0 ESS	< 0 ? saddle point	Non-existent
16	$u_M q_2 - c_M > 0$ $u_M q_1 - c_M > u_M q_3$ $u_R q_3 - c_R > 0$ $u_R q_1 - c_R > u_R q_2$	det(J) $tr(J)$ result	> 0 > 0 instability point	< 0 ? saddle point	< 0 ? saddle point	> 0 < 0 ESS	Non-existent

Note: '?' expresses the case is indeterminate in the table.

Sorting out the evolutionary stability results and corresponding conditions of the equilibrium points in Table A2, we obtain the proposition 2.

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