

Original Research

Green Supply Chain Finance Credit Market under Government Regulation: An Evolutionary Game Theory Analysis

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Abstract

In light of growing global concerns for sustainable development and environmental protection, green supply chain finance has emerged as a promising approach to promoting environmentally responsible business practices. This paper examines the structure of the green supply chain finance credit market under government regulation and constructs a tripartite evolutionary game model involving green small and medium enterprises (SMEs), core enterprises, and financial institutions. Through analysis of game equilibrium points and numerical simulation, this study investigates the impact of initial conditions on evolutionary trajectories. Results indicate that the initial proportion of positive strategies adopted by game participants affects the system's evolutionary trajectories. A higher initial proportion of positive strategies facilitates achieving credit business in green supply chain finance. Increasing government regulation punishment values can help achieve credit business and stabilize the credit market. Cost factors are negatively correlated with the game system's evolution direction. Reducing admission costs for SMEs, evaluation costs for core enterprises, and evaluation and supervision costs for financial institutions can effectively promote convergence to a Pareto optimal state.

Keywords: green supply chain finance, credit market, government regulation, evolutionary game, numerical simulation

Introduction

Since the 21st century, the demand for fossil fuels such as coal and oil has continued to expand. The sharp increase in global energy consumption has led to a significant increase in greenhouse gas emissions. Global warming, rising sea levels, and frequent extreme weather events have posed serious threats to sustainable

development. In addition, due to the Ukrainian issue, European energy supplies tightened, and prices soared rapidly. Energy issues once again became a global focus and green low-carbon development is accelerating its occupation of key strategic points in international competition. To cope with the changing environment and practice green development concepts, developed countries and developing countries have made positive efforts. The European Union, as a leader in global green finance, has introduced a series of measures such as the "Green Deal Industrial Plan" to guide funds towards sustainable economic activities and achieve

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a circular economy. The United States has returned to the Paris Agreement to fully address climate challenges. Consistent with the goals of the Paris Agreement, Britain has legislated its commitment to achieving net-zero emissions by 2050. China has also made solemn commitments to peak carbon emissions by 2030 and strive for carbon neutrality by 2060. Building consensus on protecting greenery, accelerating industrial transformation towards green low-carbon development, and vigorously developing green finance have become very important and urgent tasks.

The concept of “sustainable development” can be traced back to the mid-1980s when the World Commission on Environment and Development published the report “Our Common Future”, which provided a detailed discussion of the concept and proposed that sustainable development is centered on achieving coordinated economic, social, and environmental development. As a financial development model under the concept of sustainable development, green supply chain finance is a supply chain financing pattern that supports trade transactions and places greater emphasis on environmental protection than traditional supply chain finance in terms of financing requirements, audit requirements, and operating models. Green supply chain finance embodies the concepts of green finance, green supply chain, and supply chain finance, aligns with the trend of green and low-carbon development in future industrial and supply chains, and is an important component of building a “community of life for all” with nature.

Credit is crucial for supply chain finance. Credit business is the primary financial activity among SMEs, core enterprises, and financial institutions in the supply chain finance ecosystem. From a micro perspective, the strategic choices of supply chain finance participants are the foundation for achieving credit business. From a macro perspective, the stable development of the supply chain credit market is the basis for the vigorous development of the supply chain finance market. The same applies to green supply chain finance. Currently, green supply chain finance, which is still in the exploration and development stage, often experiences “malfunction” in the credit market. At this point, government intervention and regulation will play an essential guiding role in the evolution and development of green supply chain finance. Special regulation is an important policy tool for the government to encourage and guarantee the development of green supply chain finance. However, there is a lack of research on the evolution of green supply chain finance credit markets considering government regulatory factors in existing literature. Studies analyzing credit market strategy behavior under government regulation from the perspective of the three-party entities are even rarer, providing insufficient theoretical support for regulatory policy decision-making. The development of the green supply chain finance credit market is a long-term and dynamic process. Exploring the green supply chain

finance credit market under government regulation through the evolution game method is more in line with the dynamic characteristics of real economic development and provides more precise reference for the government to effectively guide the development of green supply chain finance.

Literature Review

Supply Chain Finance

In the research field of supply chain finance, Timme and Williams-Timme [1] provided the first systematic overview of the concept of supply chain finance from macro and micro perspectives. They considered supply chain finance as a product of the interaction between members of the supply chain and banks, which is achieved through collaborative efforts to achieve mutual benefits. Caniato et al. [2] reviewed the history, current research, and future research directions of supply chain finance. They identified an important area of research related to the cost-benefit trade-offs of different participants and the design of profit allocation mechanisms. Literature in this area includes pure theoretical derivation and practical simulation with data. In theory, Liu et al. [3] used the theory of partial differential equations without grids and the theoretical and methodological approaches of game theory and information economics to establish a corresponding multi-party game model, exploring its application in the multi-party game of supply chain finance. Caldentey and Haugh [4] constructed a Stackelberg game model to study the equilibrium decision-making of producers and retailers in a supply chain system and its formal performance. Li et al. [5] analyzed the credit status of small and medium-sized enterprises under traditional financing structures and supply chain finance models using an evolutionary game model. The results showed that under the constraints of core enterprises, supply chain finance increased the possibility of small and medium-sized enterprises obtaining bank loans. Du et al. [6] used game theory tools to analyze the formation mechanism and probability of credit risk for small and medium-sized enterprises in the supply chain, and constructed profit functions for each participant under game equilibrium. The study found that the cost of bank supervision, enterprise compliance, and collusion were key factors affecting small and medium-sized enterprise loan defaults, providing a new path to reduce supply chain credit risk. Zhang [7] studied the choice of supply chain finance for Chinese small and medium-sized enterprises based on the theory of Go game models.

Cao et al. [8] studied the optimal payment scheme decisions in a decentralized supply chain composed of manufacturers and retailers under capital constraints, proposing the APS (advanced payment scheme), DPS (delayed payment scheme), and NPS (normal payment scheme). The Stackelberg game results

for manufacturers showed that commercial banks, retailers, and manufacturers tended to prefer DPS, and the conclusion still held when the loan rate for retailers was increased. However, when the loan rate for manufacturers was increased, manufacturers tended to prefer APS, and banks and retailers tended to use DPS more. In specific applications, Yu and Rehman Khan [9] used the method of evolutionary game theory to study the problem of green agricultural supply chain finance with agricultural suppliers and urban residents in the credit system against the background of Covid-19. Yan et al. [10] introduced core enterprises into the traditional accounts receivable financing model and further analyzed the strategic decision-making of banks, small and medium-sized enterprises, and core enterprises. Finally, through simulation analysis and evolutionary game theory, they demonstrated the feasibility of the accounts receivable pledge financing model based on supply chain finance, which can achieve a win-win situation for all three parties. Li [11] also demonstrated that supply chain financing can effectively increase the probability of bank lending while reducing moral hazard for SMEs in the sports industry. Supply chain financing not only alleviates the financing difficulties of SMEs but also improves the coordination of the supply chain, ensures the strategic expansion of core enterprises, and achieves the long-term development of the industry.

Modern game theory has extended from simple two-party interactions to three-party and even four-party games, with increasing complexity and realism considered in the modeling. Xian-jia [12] constructed an evolutionary game dynamic model for “financial institutions-core enterprises-SMEs” tripartite game subjects, using evolutionary game theory and Lyapunov stability analysis to analyze the equilibrium points and asymptotic stability of the dynamic model. The research results indicate that the higher the expected income and the greater the default cost for SMEs, the less likely they are to default. The financial supply chain will evolve to a stage where financial institutions provide loans to SMEs, core enterprises provide guarantees, and SMEs choose not to default, resulting in a healthy credit market. Similarly, Hu et al. [13] established an evolutionary game model for accounts receivable financing in the supply chain, analyzing the evolution path and rules of the model and conducting numerical simulations. The results show that the outcome of the evolutionary game depends on the initial values of the variables. When certain conditions are met, the system will evolve into (lending, complying). The likelihood of bank lending and SMEs complying increases with higher production, loan interest rates, and supply chain returns. Jia et al. [14] explored the cooperation mechanism of electronic warehouse receipt pledge financing in an alliance formed by loan companies, commercial banks, e-commerce platforms, and logistics companies, and obtained the game equilibrium strategy and analyzed its influencing factors by constructing a tripartite evolutionary game model. The study found that a stable strategy combination would emerge if the

loan company chooses to repay on time, the platform chooses to provide services, and the commercial bank chooses to continue cooperation. Mahmoudi and Rasti-Barzoki [15] modeled the comparison between government objectives and producer objectives using the two-population evolutionary game theory method under different scenarios, which is a new method in game theory.

Green Supply Chain Finance

Academic research on green supply chain management began relatively early. Bansal and Gangopadhyay [16] focused on environmental quality, pollution emissions, and social welfare, analyzing the different impacts of consistent policies and differentiated policies from the perspectives of subsidies and taxes. Hervani et al. [17] proposed that GSCM includes green procurement, green manufacturing, green marketing, and recycling, and constructed a management performance evaluation system for green supply chain management. Tsireme et al. [18] studied the impact of different policy tools on corporate GSCM decision-making. Perez [19] constructed the basic framework of green supply chain finance based on supply chain management theory, sustainable supply chain theory, and supply chain finance theory. They believed that the frequent financial crises have raised public doubts about whether financial institutions adhere to moral standards, leading to a trust crisis. Green supply chain finance reduces the reputational risks and costs of financial institutions while enhancing their responsible corporate strategic positioning. Li and Sha [20] analyzed the energy consumption levels in the retail industry and found that green supply chain management can reduce the energy consumption of the supply chain and improve energy efficiency. They used the analytic hierarchy process to verify that financial and policy support can effectively achieve high energy efficiency sustainability. Fatemi and Fooladi [21] argued that shareholder wealth maximization can no longer create sustainable wealth in the face of future social and environmental challenges. They proposed that green supply chain finance, which considers environmental and social responsibility performance, is the optimal strategy to meet the new paradigm shift towards sustainable values.

Game theory methods were frequently used in green supply chain management research. For example, Kang et al. [22] focused on studying the low-carbon supply chain enterprise behavior based on evolutionary theory and strategic issues related to government low-carbon policies and emerging low-carbon markets. They established a two-level supply chain consisting of retailers and manufacturers, using the Stackelberg game method to solve the low-carbon strategy combinations of four types of retailers and manufacturers, and then used the evolutionary game theory method to further analyze these strategies to determine the evolutionarily stable strategy. Panja and Mondal [23] constructed

a green supply chain game model containing retailers and manufacturers in three decision scenarios: integration mode, Stackelberg mode, and profit-sharing mode based on proportion. Some scholars focus on government intervention in GSCM. Madani and Rasti-Barzoki [24] found that as the government increases the subsidy rate, the demand, profit, and product greenness of green supply chain participants also increase. Furthermore, Sinayi and Rasti-Barzoki [25] studied sustainability from three dimensions (economic, social, and environmental), finding that government intervention in GSCM can increase consumer surplus. Ling et al. [26] constructed a Stackelberg game model for green supply chain containing government and two companies using different green technologies, finding that the introduction of government subsidies can increase the market share and profit of green products and promote environmental quality improvement. Liu et al. [27] analyzed the internal and external factors affecting the game behavior of both suppliers and retailers using an evolutionary game model, and conducted numerical simulation to study the system evolution and stability trend. They found that the government subsidy rate and income from collaborative emission reduction can directly affect the system's evolution path, and that this value is positively correlated with the likelihood of manufacturers and retailers choosing to collaborate on emission reduction.

In terms of green supply chain finance, Yang et al. [28] considered the situation where retailers face capital constraints and studied different credit strategies such as internal and external financing in a green supply chain with one manufacturer and two retailers. Fang and Xu [29] considered bank factors and constructed a game model of green supply chain finance among banks, retailers, and manufacturers. They found that when manufacturers face weaker capital constraints or consumers have weaker environmental awareness, manufacturers tend to abandon mixed financing methods, which combine green credit and retailer prepayments. Wu and Kung [30] studied the impact of financial risk on the equilibrium output and price of green supply chains under complete and incomplete information scenarios from the perspective of financial risk. They believe that the government should encourage financial institutions to provide priority loans for green supply chains. Forcella and Hudon [31] studied the environmental performance of 58 small non-bank financial institutions in Europe. Empirical evidence shows that the loan size of microfinance institutions is closely related to their environmental performance. The persistent development of green supply chain finance should not ignore the impact of non-bank financial institutions.

Government Regulation and Green Supply Chain Finance

Scholars generally agree that government regulation is necessary for the development of green supply chain

finance. Raziye Reza-Gharehbagh et al. [32] studied the product portfolio optimization problem of capital-constrained supply chains and analyzed the decision-making behavior of supply chain participants and multi-party platforms under government regulation and no regulation through Stackelberg game analysis. They examined the equilibrium strategies of key participants under two types of government decisions: economic impact and social impact. The results show that appropriate government intervention policies can lead to better game results. Government regulation can incentivize supply chain participants to choose green product development, promote overall government benefits, and achieve sustainable development for multiple stakeholders. Wu and Shang [33] constructed a green supply chain system consisting of manufacturers, retailers, banks, and the government, and studied the equilibrium of green credit financing under horizontal competition and cooperation through Stackelberg game models and numerical analysis. They examined how government subsidies and supply uncertainty affect green credit financing decisions. The results show that government subsidies effectively alleviate the financing constraints of supply chain enterprises. Under horizontal competition, the optimal decisions of banks and supply chain participants are significantly higher than those under horizontal cooperation in terms of social welfare. Wang et al. [34] introduced a three-party evolutionary game model of commercial banks, core enterprises, and small and medium-sized enterprises under government intervention. They argue that government intervention affects the decisions of supply chain members. For small and medium-sized enterprises, government rewards and punishments increase their initiative for green production, promote the sustainable development of green supply chain finance, and increase the credit guarantee rate of core enterprises, which helps to balance the decision-making of three-party games by reducing the examination of bank green loans. An et al. [35] designed a green credit financing model for a supply chain system consisting of capital-constrained manufacturers and capital-sufficient suppliers. They found that strict carbon emission limits set by the government can help manufacturers define appropriate green investment scopes, achieving a win-win situation and sustainable development for supply chain members. Hafezalkotob [36] established a Stackelberg game model between the government and green supply chains to explore the best response strategies of supply chains under different government intervention policies. The study found that the social benefits generated by relaxed government regulation are the lowest, but non-profit intervention policies are beneficial to all parties in the supply chain system.

Summary

Through the literature review above, it can be found that green supply chain research has become a focus

of academic attention in recent years. Game theory research methods occupy the mainstream and scholars have found the role of government intervention in promoting the development of green supply chains. In terms of green supply chain finance, many literatures focus on topics such as development models, financial risk control, financing decisions, economic profits, and financing for small and medium-sized enterprises in supply chains. However, research on the role of government regulation in green supply chain finance is not deep enough. Secondly, scholars mostly study government intervention mechanisms from single dimensions such as green supply chains and supply chain finance. Based on this, this article intends to further subdivide enterprises into two types: core enterprises and green SMEs and construct a game model of green supply chain finance between core enterprises, green SMEs, and financial institutions from the perspective of government regulation.

Research Model

Analysis of the Strategies of the Participants in Green Supply Chain Credit Market

Similar to traditional supply chain finance credit markets, the green supply chain finance credit market involves participants such as SMEs, core enterprises, and financial institutions, with government intervention as an external factor. The academic community has conducted detailed research on the practical models of green supply chain finance [37–39]. In the industry, the International Finance Corporation's (IFC) Global Financial Markets department was the first to propose green supply chain financing services, aiming to address the sustainable financing issues of local financial institutions worldwide. For example, the IFC and PUMA, in cooperation with BNP Paribas, launched a green supply chain financing program, and enterprises that meet the IFC's Climate Trade

Finance Program list and green product requirements developed by Barclays and Sustainalytics can obtain preferential loans. In addition, OCBC, UOB, and BNP Paribas have established green and sustainable-linked loan frameworks, providing support for supply chain enterprises' circular economy activities by simplifying green loan assessments. Citibank also collaborated with Apple to develop a sustainable supply chain program aimed at promoting environmental responsibility for small and medium-sized enterprises in the supply chain. In China, Industrial Bank and Shanghai Pudong Development Bank were the first to integrate the concept of green supply chain finance into their business and offer comprehensive green supply chain finance support programs. This paper synthesizes existing literature to propose a credit behavior framework for the green supply chain finance credit market under government regulation, as shown in Fig. 1.

In green supply chain finance, SMEs, core enterprises, and financial institutions are the main participants in the credit market. green SMEs apply for a “Pollutant Discharge Permit” from the environmental protection department. If they are accredited and obtain a green certificate issued by the environmental protection department, they can then apply for a pledge loan for polluting rights to financial institutions. Core enterprises refer to larger enterprises in green supply chain finance. They evaluate the qualifications of green SMEs and review their environmental certificates, and then decide whether to guarantee green SMEs for their loans from financial institutions. Financial institutions are responsible for providing loans in green supply chain finance. Government or relevant authorities intervene as external entities through regulatory punishment. The operation of the green supply chain finance market is built on the game of behavioral strategies among the participating entities.

The green supply chain finance credit market is characterized by information asymmetry, transaction frictions and incomplete rationality among participants. Engaging in gamesmanship, green SMEs, core

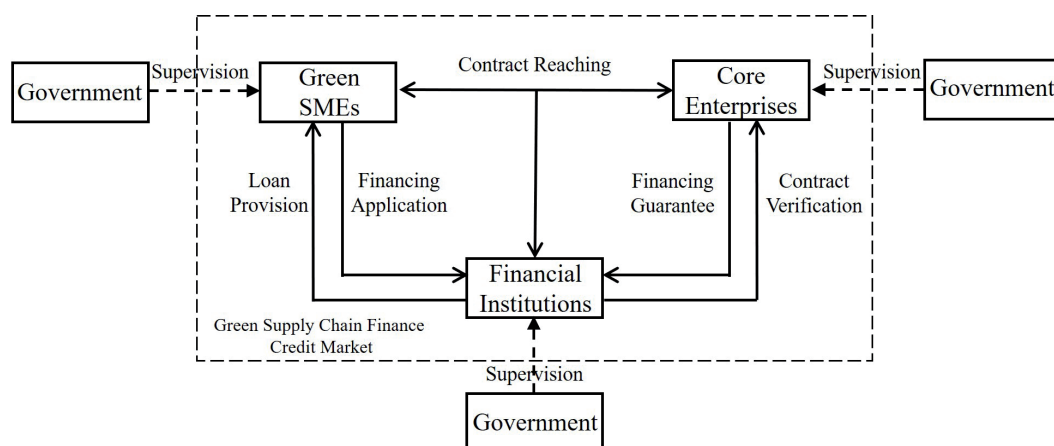


Fig. 1. The framework of green supply chain finance credit market under government regulation.

enterprises, and financial institutions have different interests. It is reasonable for green SMEs, whose funding chains are relatively unstable and require significant funds for energy conservation and emission reduction, to seek financing to alleviate financial pressure. If they choose the “financing” strategy, they must bear search and pledge costs and provide green certification as collateral, such as accounts receivable, orders, and warehouse receipts, to apply for financing, and repay the principal and interest upon loan maturity. Alternatively, they can choose the “no financing” strategy. Core enterprises can choose the “guaranteeing” strategy, but they must evaluate the green qualifications of green SMEs, pay evaluation costs, and bear a certain credit default risk, with income coming from interest. Alternatively, they can choose the “no guaranteeing” strategy. Financial institutions can choose the “serving” strategy by entrusting core enterprises to evaluate the feasibility of loans, paying evaluation and supervision costs in the process of developing and operating green supply chain finance, and earning income from interest. Alternatively, they can choose the “no serving” strategy. External regulatory agencies, such as governments, regulate the credit market. If green SMEs fail to repay or do not comply with contractual requirements within the specified time under government regulation, they will be punished in the form of fines or blacklisting.

Premises and Parameter Settings of the Evolutionary Game Model

It is assumed that the game participants in the green supply chain credit market are green SMEs A, core enterprises B, and financial institutions C. The model also assumes the following premises:

Premise 1: all participants are of bounded rationality. The strategy set for green SMEs includes “financing” and “no financing”. The strategy set for core enterprises includes “guaranteeing” and “no guaranteeing”. The strategy set for financial institutions includes “serving” and “no serving”. This paper categorizes “financing”, “guaranteeing”, and “serving” as positive strategies. On the other hand, “no financing”, “no guaranteeing”, and “no serving” are considered as negative strategies.

Premise 2: the proportions of choosing positive strategies among green SMEs, core enterprises and financial institutions are respectively x , y and z ($0 \leq x, y, z \leq 1$). Hence, the proportion of choosing negative strategies are respectively $1-x$, $1-y$ and $1-z$.

Premise 3: if green SMEs fail to repay according to the contract requirements within the specified time, the government and other relevant departments will punish green SMEs. The punishment methods include fines or blacklisting, etc. This paper assumes that the value of the punishment on green SMEs is P .

The definition of parameter is shown in Table 1. According to parameter settings the premises above, the payoff matrix of the game model is determined as shown in Table 2.

Table 1. Definition of parameter.

Parameter	Definition
R_1	Basic benefits of green SMEs
R_2	Basic benefits of core enterprises
R_3	Basic benefits of financial institution
r	Additional benefits of green SMEs after loan approval
m	Amount of loan application of green SMEs
P	Punishment on green SMEs after their credit default
i_1	The interest paid to core enterprises by green SMEs
i_2	The interest paid to financial institution by core enterprises
θ	The probability of green SMEs repaying on time
k	Core enterprises' benefit of pledge disposal after green SMEs' credit default
T	Search cost of green SMEs applying for loan
C_1	Evaluation cost of core enterprises as guarantor
C_2	Evaluation cost and supervision cost of financial institutions

Establishment of the Payoff Matrix and Equilibrium Analysis

This paper uses the replicator dynamics method for game analysis. According to the payoff matrix in Table 2, the replicator dynamics equations for the tripartite game of green supply chain finance under government regulation are listed as follows:

$$\begin{cases} F(x) = \frac{dx}{dt} = x(1-x)[yzr - yz\theta(m+i_1) - yz(1-\theta)P - T] \\ G(y) = \frac{dy}{dt} = y(1-y)[xz(i_1+k-i_2) - xz(1-\theta)(m+i_1) - C_1] \\ H(z) = \frac{dz}{dt} = z(1-z)(xyi_2 - C_2) \end{cases} \tag{1}$$

With $\frac{dx}{dt} = 0$, $\frac{dy}{dt} = 0$, and $\frac{dz}{dt} = 0$ in equation

group (1), the local equilibrium points of the game system are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(0,1,1)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1,1)$ and $E_9(x^*,y^*,z^*)$, where (x^*,y^*,z^*) is the solution of equation group (2).

$$\begin{cases} yz[r - \theta(m+i_1) - (1-\theta)P] - T = 0 \\ xz[i_1+k-i_2 - (1-\theta)(m+i_1)] - C_1 = 0 \\ xyi_2 - C_2 = 0 \end{cases} \tag{2}$$

Table 2. Payoff matrix of the tripartite game model.

Game participant		Financial institutions		
		Core enterprises	Serving	No serving
Green SMEs	Financing	Guaranteeing	$R_1+r-\theta(m+i_1)-(1-\theta)P-T$, $R_2+i_1-C_1-(1-\theta)(m+i_1)+k-i_2$, $R_3+i_2-C_2$	R_1-T , R_2-C_1 , R_3
		No guaranteeing	R_1-T , R_2 , R_3-C_2	R_1-T , R_2 , R_3
	No financing	Guaranteeing	R_1 , R_2-C_1 , R_3-C_2	R_1 , R_2-C_1 , R_3
		No guaranteeing	R_1 , R_2 , R_3-C_2	R_1 , R_2 , R_3

Since the stable solution in a multi-population evolutionary game must be a strict Nash equilibrium solution, this paper focus on the equilibrium points. According to the method proposed by Friedman [40], the local stability of the equilibrium point can be determined by the characteristics of the system Jacobian matrix. The Jacobian matrix of the game system is in the form of:

$$J = \begin{bmatrix} \partial F / \partial x & \partial F / \partial y & \partial F / \partial z \\ \partial G / \partial x & \partial G / \partial y & \partial G / \partial z \\ \partial H / \partial x & \partial H / \partial y & \partial H / \partial z \end{bmatrix} \quad (3)$$

Where the core part for mathematical judgement is

$$F_{11} = \frac{\partial F(x)}{\partial x} = (1-2x)[yzr - yz\theta(m+i_1) - yz(1-\theta)P - T] \quad (4)$$

$$F_{22} = \frac{\partial G(y)}{\partial y} = (1-2y)[xz(i_1+k-i_2) - xz(1-\theta)(m+i_1) - C_1] \quad (5)$$

$$F_{33} = \frac{\partial H(z)}{\partial z} = (1-2z)(xyi_2 - C_2) \quad (6)$$

If there is a possibility of increasing the welfare of some people in the process of resource allocation without lowering the welfare of others, then this state is called Pareto dominance or Pareto improvement, otherwise, it is called Pareto optimality [41]. The Pareto optimal state corresponds to a frictionless and ideal economic environment, and the market converges to this state under the premise of free exchange and distribution among all individuals. There is no room for Pareto improvement in this state [42]. On the contrary, the Pareto worst state is completely opposite to the Pareto optimal state, and refers to the worst state of resource allocation.

The local stability of equilibrium points in the multi-party game system can be determined using Lyapunov's criterion. By applying this method, the local stability of $E_1 \sim E_8$ can be analyzed, resulting in Propositions 1 to 3.

Proposition 1. The $E_1(0,0,0)$ is the ESS (Evolutionarily Stable Strategy) of the game system, which is a stable state and a Pareto worst state. This state is highly unfavorable for the development of green supply chain finance.

Proof of Proposition 1. Substituting $(0,0,0)$ into equation group (3), the Jacobian matrix of E_1 is obtained as:

$$J = \begin{bmatrix} -T & 0 & 0 \\ 0 & -C_1 & 0 \\ 0 & 0 & -C_2 \end{bmatrix} \quad (7)$$

Given that $-T < 0$, $-C_1 < 0$, and $-C_2 < 0$, the Jacobian matrix of E_1 has all negative eigenvalues, indicating that $E_1(0,0,0)$ is the ESS of the system, as determined by Lyapunov criterion. However, this stable state is highly unfavorable for the development of green supply chain finance, as it leads to green SMEs choosing "no financing," core enterprises choosing "no guaranteeing," and financial institutions choosing "no serving".

Proposition 2. Regardless of parameter values, E_2 , E_3 , E_4 , E_5 , E_6 , and E_7 are either unstable or saddle points. **Proof of Proposition 2.** The Jacobian matrix of E_2 is:

$$J = \begin{bmatrix} T & 0 & 0 \\ 0 & -C_1 & 0 \\ 0 & 0 & -C_2 \end{bmatrix} \quad (8)$$

According to Lyapunov criterion, an equilibrium point is an ESS only if all values on the diagonal of its Jacobian matrix are negative. Given that $T > 0$, E_2 is unstable or saddle point. Similarly, E_3 , E_4 , E_5 , E_6 , and E_7 are all either unstable or saddle points.

Proposition 3. When $r > \theta(m+i_1) + (1-\theta)P+T$, $i_1+k > C_1 + (1-\theta)(m+i_1)+i_2$, and $i_2 > C_2$ are met

simultaneously, $E_8(1,1,1)$ becomes the ESS for the game system, leading to the optimal development of green supply chain finance.

Proof of Proposition 3. The Jacobian matrix of E_8 is:

$$J = \begin{bmatrix} \theta(m+i_1) + (1-\theta)P+T-r & 0 & 0 \\ 0 & C_1 + (1-\theta)(m+i_1) + i_2 - i_1 - k & 0 \\ 0 & 0 & C_2 - i_2 \end{bmatrix} \tag{9}$$

When

$r > \theta(m+i_1) + (1-\theta)P+T$, $i_1+k > C_1 + (1-\theta)(m+i_1)+i_2$, and $i_2 > C_2$ are met simultaneously, all eigenvalues of the Jacobian matrix are less than 0, thus E_8 becomes the ESS of the game system. In this stable state, green SMEs tend to opt for “financing” strategy, core enterprises for a “guaranteeing” strategy, and financial institutions for “serving” strategy.

Table 3 summarizes the local stability of equilibrium points in the game system, as inferred from the propositions above. $E_1(0,0,0)$ is always the ESS, leading the game system towards the Pareto worst state with all entities opting for negative strategies. Only when condition $r > \theta(m+i_1) + (1-\theta)P+T$, $i_1+k > C_1 + (1-\theta)(m+i_1)+i_2$, and $i_2 > C_2$ are met simultaneously, $E_8(1,1,1)$ becomes the ESS, leading the game system towards the Pareto optimal state with all entities opting for positive strategies. While $E_8(1,1,1)$ is either a saddle point or an unstable point in all other cases. E_2, E_3, E_4, E_5, E_6 , and E_7 can only be unstable or saddle points, regardless of the parameter values.

Results and Discussion

This section utilizes MATLAB to conduct numerical simulations of a three-party green supply

chain finance credit game system involving green SMEs, core enterprises, and financial institutions, based on theoretical analysis. The initial values of the parameters are defined using the benchmark interest rate for commercial loans released by the People’s Bank of China on June 20, 2022. Specifically, assuming a loan of 200 thousand yuan for 8 years, the interest rate of about 40 thousand yuan is used as a benchmark. The values of each parameter in the system are proportionally reduced for analysis purposes, with $\alpha = 1, \beta = 1, \gamma = 1, m = 5, r = 10, \delta = 0.8, \varepsilon = 50\%, k = 4, T = 2, \eta = 0.3$, and $\theta = 0.3$. Furthermore, assuming that the government punishes green SMEs for not repaying the loan with $P = 1$, the initial conditions satisfy the conditions of Propositions 1 and 3. Except for studying the effect of the initial proportion of positive strategy on the evolutionary path, the initial proportion of positive strategy of the game participants is set to 0.5.

The Influence of Initial Positive Strategies Proportion on Evolutionary Trajectories

Fig. 2 illustrates the evolutionary path of the credit three-party game system, with the X, Y, and Z axes representing the proportion of green SMEs choosing “financing,” the proportion of core enterprises choosing “guaranteeing,” and the proportion of financial institutions choosing “serving” respectively. The evolutionary direction and path of the 5-point method and the multi-point method are consistent, and they evolve towards the Pareto worst state (0,0,0) when the initial proportion of positive strategy is low and towards the Pareto optimal state (1,1,1) when the initial proportion of positive strategy is high. Under the above initial values, the credit game system has two evolutionary stable strategies (0,0,0) and (1,1,1), which confirms the analysis of Propositions 1 and 3 and validates the accuracy of the model derivation. The evolutionary path of the game system is related to the initial proportion of positive strategy of the participants. The higher the proportion of positive strategies chosen

Table 3. Equilibrium point analysis of the game system.

Equilibrium Point	(F_{11}, F_{22}, F_{33})	Det J	Tr J	Stability Judgement
$E_1(0,0,0)$	$(-, -, -)$	-	-	ESS
$E_2(1,0,0)$	$(+, -, -)$	+	TBD	Unstable or saddle point
$E_3(0,1,0)$	$(-, +, -)$	+	TBD	Unstable or saddle point
$E_4(0,0,1)$	$(-, -, +)$	+	TBD	Unstable or saddle point
$E_5(0,1,1)$	$(-, +, +)$ or $(+, +, +)$	- or +	TBD or +	Unstable or saddle point
$E_6(1,0,1)$	$(+, -, +)$ or $(+, +, +)$	- or +	TBD or +	Unstable or saddle point
$E_7(1,1,0)$	$(+, +, -)$ or $(+, +, +)$	- or +	TBD or +	Unstable or saddle point
$E_8(1,1,1)$	$(TBD, TBD, TBD)^1$	TBD	TBD	ESS, unstable or saddle point

¹ “TBD” stands for “to be determined”.

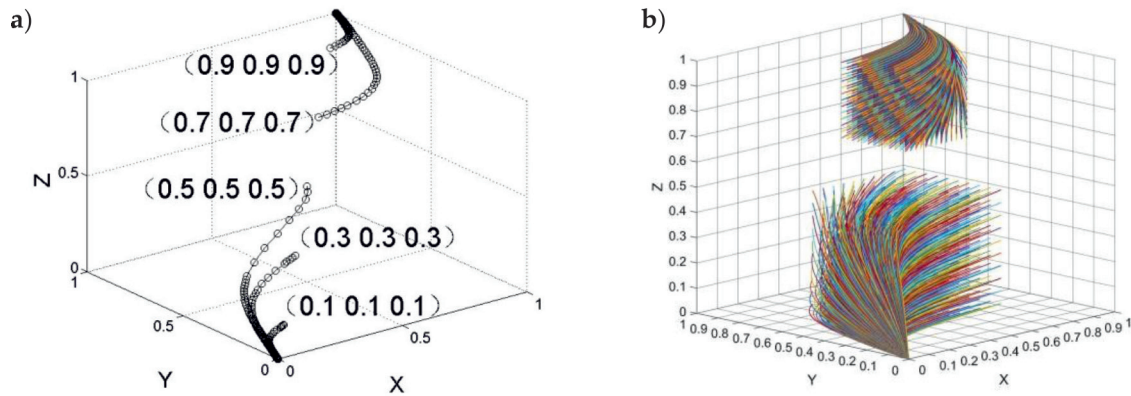


Fig.2. The evolutionary trajectories with variation of initial proportion of positive strategy: a) by 5-point method; b) by multi-point method.

by each participant at the beginning, the higher the probability that the game system will converge to the equilibrium stable point (1,1,1). Conversely, the probability that the game system will converge to the equilibrium stable point (0,0,0) is higher. This indicates that the initial proportion of positive strategies chosen by each participant affects the evolutionary path of the game system in the green supply chain finance credit game.

The Influence of Punishment Value on Evolutionary Trajectories

In the operational process of green supply chain finance, the government implements regulatory measures, such as fines or blacklisting, to ensure smooth credit progress. This study examines the impact of punishment factors on the evolution of the game system, as shown in Fig. 3. Results indicate that when the initial proportion of positive strategy is (0.5, 0.5, 0.5), the game system converges to (no financing, no guaranteeing, no serving) when the value of regulatory punishment P is 0 or 10. This suggests that mild subsidy incentives may be more appropriate than strict regulatory punishment measures in the initial stage of

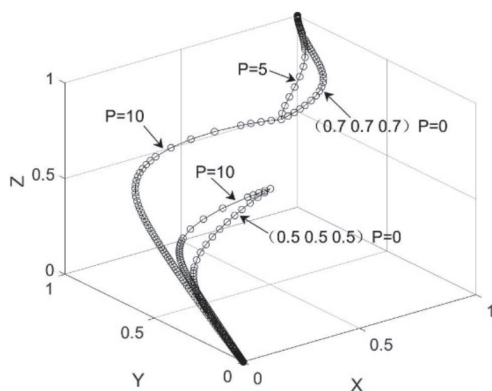


Fig. 3. The evolutionary trajectories with variation of punishment value.

green supply chain finance credit development. When initial proportion of positive strategy is (0.7, 0.7, 0.7), the game system converges to (financing, guaranteeing, serving) when the regulatory punishment value is 0 or 5, and converges to the worst point when P is 10. This implies that there exists a threshold value P' , such that when $P > P'$, the game system will converge to (no financing, no guaranteeing, no serving). Therefore, the study concludes that regulatory punishments in the development stage of green supply chain finance can safeguard the interests of core enterprises and financial institutions to some extent, and a reasonable increase in regulatory punishment values can facilitate the achievement of credit business.

The Influence of Cost Factors on Evolutionary Trajectories

The impact of admission cost on system evolution is shown in Fig. 4a). As depicted in the figure, when the admission cost T is 1, the game system converges to (financing, guaranteeing, serving); while for admission cost T of 3 or 5, the game system converges to (no financing, no guaranteeing, no serving). The influence of admission cost T on the behavioral evolution of green SMEs is demonstrated in Fig. 5. When the admission cost T is 0 or 1, green SMEs tend to choose the “financing” strategy, and the speed of convergence to the optimal strategy decreases with an increase in admission cost T. However, when the admission cost T is 1.5, 2, or 4, green SMEs tend to choose the “no financing” strategy. In conclusion, a decrease in admission cost for green SMEs has a positive effect on credit business achievement and the development of green SMEs.

The impact of evaluation cost on game system evolution is shown in Fig. 4b). As illustrated in the figure, when the initial proportion of positive strategy is (0.5, 0.5, 0.5), the presence of evaluation cost leads the game system to converge to (no financing, no guaranteeing, no serving). When the initial proportion

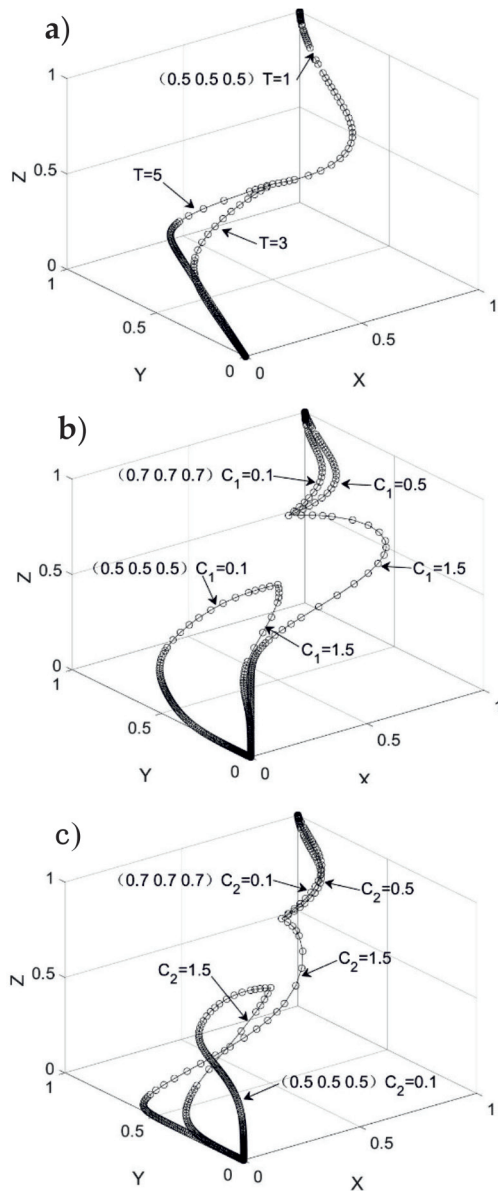


Fig. 4. The evolutionary trajectories with variation of costs: a) admission cost of SMEs; b) evaluation cost of core enterprises; c) evaluation and supervision cost of financial institutions.

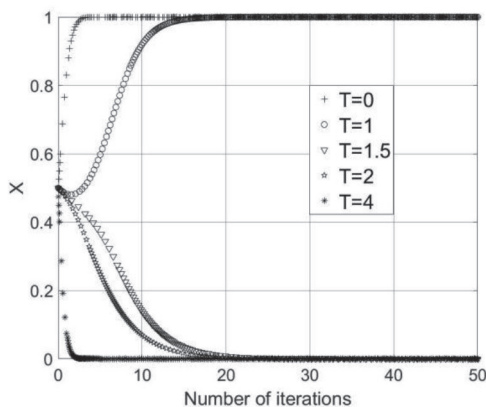


Fig. 5. The influence of admission cost on proportion of SMEs adopting positive strategy.

of positive strategy is (0.7, 0.7, 0.7), the game system converges to (financing, guaranteeing, serving) for evaluation cost of 0.1 or 0.5, while it converges to (no financing, no guaranteeing, no serving) for evaluation cost of 1.5. Therefore, under government regulatory environment, reducing evaluation cost can lead the system to converge to Pareto optimal state.

The impact of financial institution evaluation and supervision cost on evolution is shown in Fig. 4c). When the initial proportion of positive strategy is (0.5, 0.5, 0.5), the presence of evaluation and supervision cost leads the game system to converge to (no financing, no guaranteeing, no serving). When the initial proportion of positive strategy is (0.7, 0.7, 0.7), the game system converges to (financing, guaranteeing, serving) for evaluation and supervision cost of 0.1 or 0.5, while it converges to (0, 0, 0) for evaluation and supervision cost of 1.5. Therefore, under government regulatory environment, the presence of evaluation and supervision cost has a negative impact on credit business achievement, and reducing the evaluation and supervision cost can lead the game system to converge to Pareto optimal state, especially when the initial proportion of positive strategy is high.

Conclusions

Based on green supply chain finance theory and evolutionary game theory, this study establishes a tripartite evolutionary game model of green supply chain finance credit among green SMEs, core enterprises and financial institutions under government regulation. A tripartite game replicator dynamic system is constructed to solve for eight evolutionary equilibrium points. The stability of these points is analyzed using the Jacobian matrix and Lyapunov criterion. Numerical simulations are performed using MATLAB to derive the following conclusions.

For the game system to evolve to the Pareto optimal state of (financing, guaranteeing, serving), the following conditions must be met: (1) the additional income generated by green small and medium-sized enterprises after financing must exceed the sum of loan principal and interest, entry costs, and penalties imposed by relevant government departments for failure to repay; (2) the interest and collateral disposal income obtained by core enterprises after guaranteeing must exceed the sum of evaluation costs, interest paid to financial institutions, and risk losses from green small and medium-sized enterprises' default; (3) the interest earned by financial institutions from cooperation must exceed the sum of evaluation and supervision costs.

The initial proportion of positive strategies chosen by participants affects the outcome of the game system's evolution. A higher initial proportion results in faster convergence to the Pareto optimal state.

During the early development phase of green supply chain finance, punitive factors negatively

impact green SMEs' financing decisions. However, regulatory punitive factors protect the benefits of core enterprises and financial institutions. Increasing regulatory punitive values benefits credit business matchmaking and market stability. Therefore, punitive systems and policies in the practice should be formulated in accordance with reality through continuous regulation and standardization to determine optimal punitive values.

Cost factors negatively impact all evolutionary paths within the game system. Lowering costs and reducing information asymmetry promotes stable credit market development. Specifically lowering access costs for green SMEs effectively promotes convergence to a Pareto optimal state; lowering evaluation costs enables convergence to a Pareto optimal state; lowering evaluation and supervision costs for financial institutions promotes credit business matchmaking.

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Conflict of Interest

The authors declare no conflicts of interest.

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