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Research article

Research on the evolution game of low-carbon operations in cold chain logistics considering environmental regulations and green credit

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ABSTRACT

To solve the problem of insufficient low-carbon operational motivation among cold chain logistics enterprises due to the high investment costs of low-carbon assets and considering the promotional effect of environmental regulatory policies and green credit, an evolutionary game model was constructed for the government, cold chain logistics enterprises, and financial institutions. The stability strategies of each participating entity and the stability of the system equilibrium point were analyzed, and the relevant conclusions were verified through numerical simulations. The research results indicated the following: (1) the initial willingness of the three parties to participate increased, the low-carbon operation of cold chain logistics enterprises and the speed of green credit services provided by financial institutions accelerated, and the rate of strict government regulation slowed down. (2) Moderate subsidies and taxes were conducive to the joint participation of the three parties. (3) Increasing the subsidy for green credit provided positive incentives for financial institutions to provide green credit services, while reducing credit interest rates accelerated the low-carbon operation rate of cold chain logistics enterprises.

1. Introduction

Cold chain logistics is an essential method for ensuring food safety and increasing consumption. However, because of its continuous operation and refrigeration, it has become one of the top generators of carbon emissions in the logistics industry [1]. China's 14th Five-Year Plan for the Development of Cold Chain Logistics states that the concept of green development should be incorporated across the cold chain logistics chain, along with other fields. In this context, enterprises should immediately integrate the concept of sustainable development into all aspects of low-carbon cold chain logistics operations [2], such as energy conservation and environmental protection in equipment manufacturing, efficiency improvements, emissions reductions in warehousing, and low-carbon transportation [3]. Digital technologies have been utilized in operations to reduce food spoilage. While decreasing losses, cold chain logistics firms assume related social duties and actively respond to national green and low-carbon policies, which provide certain benefits in terms of enterprises' image and soft power. Cold chain logistics is a heavy capital industry, and "carbon neutrality" as a new constraint raises the risk of stranding present high-carbon assets in addition to the investment cost of establishing new low-carbon assets for businesses [4].

Owing to external issues related to carbon dioxide emissions, enterprises are unable to automatically achieve the optimal allocation

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of emissions reduction resources. Therefore, the government must use corresponding environmental regulatory policies to regulate the pollution emission behavior of enterprises [5]. Environmental regulatory policies are mainly divided into two types: command and control and market incentives [6]. Market-driven environmental regulations can incentivize enterprises to engage in low-carbon operations [7]. Several studies have been conducted on the use of incentive-based environmental regulation tools for the low-carbon operational management of enterprises, mainly focusing on the impact of environmental taxes and emissions reduction subsidies on their carbon emissions reduction strategies [8,9]. The imposition of environmental taxes can motivate enterprises to improve their energy efficiency and production processes, thereby reducing pollution emissions; however, it also raises production costs and suppresses industry output and socioeconomic growth [10]. As the demand for low-carbon cold chain logistics grows, corresponding subsidy policies are required to guide cold chain logistics enterprises to conserve energy and reduce emissions. In terms of curbing carbon emissions, the combined use of environmental taxes and subsidies has a significant impact on corporate behavior [11,12].

To ease the financial pressure during the low-carbon transformation of cold chain logistics, in addition to government policy regulations, financial assistance to firms provided through financial channels is required. Green credit is one of the most important green financial strategies used by governments to encourage financial institutions to provide funds and direct capital flows toward clean production areas [13]. Green credit allows financial institutions to consider pollution management and environmental protection as significant requirements for credit acceptance [14]. Implementing green credit can help financial institutions improve their competitiveness, reduce their credit risk, and improve their long-term financial performance [15–17], but understanding environmental pollution information about enterprises or projects incurs additional review and supervision costs [18]. Green credit policies can dramatically boost the financing availability of green firms while also suppressing the investment and financing of heavily polluting enterprises. This heterogeneous effect can benefit low-carbon development [19] because low-carbon projects have higher financing costs than general projects, so banks that implement green credit policies increase their costs in the short run [20]. Consequently, the government has an interest in encouraging commercial banks to participate in green credit activities [21].

In summary, the existing literature primarily examines low-carbon enterprise operational issues through the lens of environmental regulatory policies and the application effects of green credit, thus providing an important foundation for low-carbon operational decisions in cold chain logistics. However, most recent research has concentrated on the influence of single policies on low-carbon firm development, with few dynamic game studies that combine environmental rules and green credit policies to change the strategies of cold chain logistics enterprises. Considering the different positions of the three parties mentioned above, this study puts forward the following viewpoint: enterprises need to make a trade-off between emissions reduction and profitability, and if the government imposes loose regulations on cold chain logistics enterprises and lacks green credit support, thus relying entirely on enterprises to consciously fulfill their social responsibilities, the probability of them choosing low-carbon operations is extremely low. In this case, if neither the government nor financial institutions take low-carbon action, it will be difficult to fulfill the country's carbon emissions reduction targets. Therefore, it is of great practical significance to study the strategic game processes among cold chain logistics enterprises, governments, and financial institutions.

Therefore, this study focuses on the issue of insufficient power caused by cold chain logistics enterprises' high low-carbon investment costs; places cold chain logistics enterprises, governments, and financial institutions in the same evolutionary model; and examines the impact of environmental regulatory policies and green credit on game systems. The study attempts to answer the following questions:

(1) How can the government utilize environmental regulations to incentivize low-carbon operations by cold chain logistics firms, and how can financial institutions use green credit mechanisms to expedite this?
(2) How can the behavioral tactics of cold chain logistics companies, governments, and financial institutions adapt to reach equilibrium in the face of various interests?
(3) Can certain parameters be altered to allow cold chain logistics companies to transition from non-low-carbon to low-carbon operating strategies and achieve a more stable and ideal position faster?

Making low-carbon operational decisions in the cold chain logistics business is a dynamic game. Given the impact of insufficient information, businesses must constantly learn and change their tactics to increase revenues [22]. The evolutionary game model can describe the dynamic decision-making process and demonstrate that game subjects are rationally bounded [23]. Therefore, this study introduces a dynamic game model based on the current situation of the low-carbon operating capital constraints of cold chain logistics enterprises, considering the effects of environmental regulation policies and green credit on the low-carbon operating behavior strategies of such enterprises, and analyzes the behavioral decisions of participants based on numerical simulation to help enterprises better meet their capital needs.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature. Section 3 introduces the game subjects' behavior, the assumptions, and the design of the tripartite evolutionary game model. Section 4 analyzes three-party principal strategy stability and system stability. Section 5 presents the simulation results.

2. Literature review

2.1. Low-carbon cold chain logistics

On the one hand, research into low-carbon cold chain logistics focuses on the issue of green vehicle paths for cold chain logistics and distribution. Chen et al. [24] studied the cold chain green multi-depot vehicle routing problem with time windows and mixed fleets using both electric and gasoline vehicles in urban logistics distribution. Zhang et al. [25] constructed a cold chain logistics distribution model that included different types of delivery vehicles and different route optimization criteria, and studied the effects of low carbon emissions and multi-objective optimization on hybrid vehicle allocation and routes. Alkaabneh et al. [26] investigated the inventory path problem for perishable products seeking near-optimal replenishment scheduling and vehicle paths with the objectives of maximizing supplier profit and minimizing greenhouse gas emission costs.

On the other hand, some scholars have explored how to achieve carbon emissions reduction through the operations of cold chain logistics companies and have considered the impact of government policies. Based on field surveys of cold chain firms, Ma et al. [27] concluded that carbon emissions policies have an impact on the operation of enterprises offering perishable product preservation services. Zhang et al. [28] developed a decision model for cold chain logistics systems using a bi-level programming method, arguing that combining carbon reduction subsidies and carbon emission limits would more effectively encourage energy saving and emissions reduction by firms. To explore the impact of carbon emissions from cold chain storage and transportation under carbon tax regulations, Babagolzadeh et al. [29] proposed a mathematical algorithm based on an iterative local search algorithm and mixed-integer programming to achieve the goal of minimizing operating costs.

2.2. Environmental regulations and corporate carbon reduction

There are two schools of thought regarding whether environmental restrictions help or hinder reductions in carbon emissions. Some researchers believe that environmental regulations reduce carbon emissions [30], while others feel that they increase them, resulting in a “green paradox” effect [31].

Different environmental regulation policies have varying effects on the carbon emissions of companies. Ren et al. [32] used tax income from 21 OECD nations as a sample to examine the link between tax revenue and carbon emissions, and the results revealed that there is always a U-shaped relationship between tax revenue and carbon emissions. According to Cheng et al. [33], the effect of carbon taxes on energy innovation stops when a particular threshold is reached. Some researchers have investigated the effects of subsidies on reducing business carbon emissions. Cohen et al. [34] investigated the impact of demand uncertainty on the government’s design of green subsidies and supplier profitability, concluding that if demand uncertainty is ignored, the government’s subsidies will be insufficient and the desired goals will not be met. Zhou et al. [35] established a three-level supply chain comprising suppliers, manufacturers, and retailers and concluded that government emissions reduction subsidy policies can effectively promote the three-level supply chain’s emissions reduction and increase supply chain members’ profits. Some scholars have analyzed the impact of subsidies on reducing corporate carbon emissions. According to Christian and Karol [36], the Pigu Emissions Tax motivated high-carbon-emitting industries to choose clean technology. In addition to assessing the impact of a single policy, Wei et al. [37] investigated the impact of three environmental regulatory policies—innovation subsidies, carbon taxes, and penalties—on the diffusion of low-carbon technologies and observed that enterprises of varying sizes are sensitive to policies to varying degrees.

2.3. Green credit and carbon emissions

Green credit can reduce environmental deterioration by affecting credit allocation and corporate decisions (e.g., technical innovation and green investment) [38]. The introduction of green credit subjects corporations to tougher regulations, causing them to increase their investment in environmental governance [39]. However, the influence of green credit on green investment efficiency is determined by the effectiveness with which green credit policies are implemented, as well as the strategies employed by enterprises in reaction to such policies [40].

Previous studies have examined the benefits of green credit. Green credit has a substantial penalizing effect on the financing of heavily polluting firms [41] and a significant hindering effect on investments [42]. Zhou et al. [16] argue that increasing the number of green loans in commercial banks will reduce the credit risk of large state-owned banks while increasing it for commercial banks in smaller cities/regions. According to Su et al. [43], increasing the ratio of green loans assists in reducing credit risk and improving the stability of the financial system. The risk appetite of financial institutions affects their credit lines and environmental performance; thus, an interest subsidy policy is implemented to limit the downside risk of financial institutions [21].

Researchers have employed empirical tests and model analyses to validate the impact mechanisms of green credit schemes. Using differential analysis, Guo and Zhang [44] concluded that green credit policies can effectively boost total factor productivity at the enterprise level. Du and Guo [45] used text analysis to investigate the regulatory influence of green credit policies on green enterprise innovation behaviors, revealing that green credit regulations can encourage both strategic and substantive green enterprise innovation behaviors. Liu et al. [46] developed a dynamic stochastic general equilibrium model and demonstrated that combining transformation insurance and green credit may encourage energy transformation and green economic growth. Lei et al. [47] used the Differences-in-Differences method to examine data from A-share listed businesses and found that implementing green credit regulations might improve Environmental, Social and Governance performance.

2.4. Application of game theory to corporate carbon reduction

In recent years, game theory has emerged as a vital strategy for addressing the challenge of corporate carbon emissions reduction. Wang et al. [48] developed a carbon emissions reduction coordination game model for thermal power supply chain firms based on the Stackelberg model and added the constraint of total carbon quota control. Xu et al. [49] constructed a Stackelberg model with manufacturers and retailers to investigate the impact of carbon policies on manufacturers' emissions reduction investment choices. The traditional game strategy assumes that each participant is rational, which does not match reality, and the traditional game theory focuses on the solution of the game equilibrium while ignoring the strategy evolution of the game participants.

Some researchers have gradually applied evolutionary game theory to explain stakeholder decision making regarding business carbon emissions reduction. First, evolutionary game theory assumes that individuals have limited rationality and incomplete information, which is more realistic. Second, evolutionary game theory presents a dynamic mechanism for investigating the link between game system stability and evolution [50]. Xia et al. [51] used an evolutionary game model including high-energy-consuming firms and the government to investigate the impact of carbon constraint policies on the carbon emissions reduction behaviors of high-energy-consuming enterprises. Li et al. [52] constructed a three-party evolutionary game model involving the government, consumers, and firms and investigated the effects of carbon trading policies and consumers on enterprises' carbon emissions reduction behaviors. Yan and Gong [53] developed a tripartite evolutionary game model comprising banking financial institutions, non-banking financial institutions, and firms to investigate whether green credit can encourage energy savings and emissions reductions in enterprises. Few studies have used three-way evolutionary game theory to investigate the influence of government and financial institutions on enterprise decision-making behaviors regarding carbon emissions reduction, and they do not reflect the novel insights of evolutionary game use in government, finance, and enterprises.

In sum, the existing literature primarily investigates the issue of enterprise carbon emissions reduction from the standpoint of environmental regulation policies and the application effect of green credit, providing an important foundation for low-carbon operating decisions in cold chain logistics. However, existing research focuses on the impact of single policies on low-carbon enterprise development, and there are few dynamic game studies on the adaptation of cold chain logistics enterprises' tactics employing both environmental regulation and green credit policies.

3. Construction of the evolutionary game model

3.1. Behavior description and game mechanism

Cold chain logistics companies, governments, and financial institutions are the three stakeholders in the low-carbon operation of cold chain logistics, and all gameplayers have limited rationality. The mainstay of low-carbon operations is cold chain logistics. On the one hand, low-carbon and ESG governance have gained strategic importance. Under national strategies, an increasing number of cold chain logistics firms actively implement ESG development and view low-carbon operations as essential to enterprise sustainability. On the other hand, the advancement of cold chain technology not only increases logistical efficiency but also lowers costs, creating favorable conditions for firms to conduct low-carbon operations.

Daily operations consume a huge amount of funds owing to the heavy asset nature of cold chain logistics, resulting in insufficient motivation for firms to carry out low-carbon operations. Currently, governments need to use environmental regulation policies to force enterprises to abandon their short-sighted behavior. It remains challenging to address firms' financial demands for low-carbon operations exclusively through governmental environmental regulatory measures. It is vital to investigate the financial avenues for sponsoring green projects. Green credit's special interest rate establishes favorable conditions for corporate financing; however, financial institutions also require government incentives to ensure a sustainable supply of green credit.

This study incorporates cold chain logistics enterprises, governments, and financial institutions into the same evolutionary game model to analyze how they make decisions to achieve the desired equilibrium result.

3.2. Basic assumptions

Assumption 1. Enterprises, governments, and financial institutions have two options: The strategy of cold chain logistics enterprises is low-carbon operation or non-low-carbon operation, with corresponding probabilities of x and $1-x$; the government's strategy is to strictly regulate or loosely regulate, with corresponding probabilities of y and $1-y$; and the strategy of financial institutions is to provide green credit services or conventional credit services, with corresponding probabilities divided of z and $1-z$, x, y, and $z \in [0,1]$, all of which are functions of time t.

Assumption 2. Cold chain logistics enterprises manage the entire logistics process of goods in low-temperature environments. When low-carbon operations are not conducted, the profit obtained by enterprises after removing the basic loss cost of fresh agricultural products is P_1. After adopting low-carbon operation, enterprises can increase sales and reduce energy consumption by reducing the decay rate of goods, thereby increasing direct benefits, and gain indirect benefits by improving their corporate image or reputation through low-carbon actions, and the newly added benefits are recorded as P_2. In the early stage of low-carbon transformation, enterprises will purchase energy-saving and environmental protection equipment, introduce digital technology, and record investment capital as C; because of the high investment cost of low-carbon assets, cold chain logistics enterprises will seek credit services from financial institutions. The cost of credit services was set to C_r, the principal of the enterprise loan to m, and the probability of timely repayment to p, which did not change according to the loan method.

Assumption 3. The government benefits from economic growth, stable employment, and credibility, with the basic benefit of B_1, and incurs environmental governance costs of C_{e1}. If cold chain logistics companies adopt low-carbon operating strategies, it will bring environmental benefits to the government B_2 and optimize environmental governance costs to C_{e2} ($C_{e1} > C_{e2}$). At this point, if the government adopts a strict regulatory strategy, it will use subsidy measures to provide positive incentive effects or impose taxes and fees to incentivize cold chain logistics enterprises to take low-carbon actions. The subsidy amount is S_q and the environmental tax fee is T_q. The government provides financial institutions providing green credit services with fiscal subsidies, a discount interest subsidy rate for r, and an interest subsidy amount for mr. If a loose regulatory strategy is adopted, the government will not reward or punish financial institutions or cold chain logistics enterprises, and credibility will decrease to V.

Assumption 4. Financial institutions are primarily responsible for tasks related to financing funds and earn income through traditional credit services Q_1. Green credit refers to banks adopting certain environmental standards to conduct new credit businesses. After receiving a loan application, banks evaluate whether an enterprise or project meets the environmental standards. At this time, training and reviewing personnel, building a database, and continuously tracking and monitoring the situation of the enterprise incur costs C_k. The loan interest rate under green credit is r_1, the credit income obtained is mpr_1; the loan interest rate under conventional credit is r_2, and the credit income obtained is mpr_2. When financial institutions provide green credit services for cold chain logistics enterprises with low-carbon operations, direct and indirect income, such as competitiveness and social praise, increase, and the new income is recorded as Q_2.

3.3. Payment matrix

Based on these assumptions and parameters, we constructed a mixed-strategy game matrix for cold chain logistics enterprises, governments, and financial institutions, as shown in Table 1.

4. Model analysis

4.1. Strategic stability analysis of cold chain logistics enterprises

The expected benefits of a low-carbon operation, expected benefits of a non-low-carbon operation, and dynamic equations for the strategy selection replication of cold chain logistics enterprises are as follows:

$$E_{11} = yz(P_1 + P_2 - C - C_r - mpr_1 + S_q) + y(1-z)(P_1 + P_2 - C - C_r - mpr_2 + S_q) + (1-y)z(P_1 + P_2 - C - C_r - mpr_1) + (1-y)(1-z)(P_1 + P_2 - C - C_r - mpr_2) \tag{1}$$

$$E_{12} = yz(P_1 - T_q) + y(1-z)(P_1 - T_q) + (1-y)zP_1 + (1-y)(1-z)P_1 \tag{2}$$

$$F(x) = x(1-x)(E_{11} - E_{12}) = x(1-x)\left[y(S_q + T_q) + z(mpr_2 - mpr_1) + P_2 - C - Cr - mpr_2\right] \tag{3}$$

Let $G(y) = y(S_q + T_q) + z(-mpr_1 + mpr_2) + P_2 - C - Cr - mpr_2$, $dF(x)/dx = (1-2x)G(y)$, when $y = [C + Cr - P_2 + mpr_2 + z(mpr_1 + mpr_2)]/(S_q + T_q) = y*$, $G(y) = 0$ and $F(x) = 0$, so any value of x is in an evolutionarily stable state. Regardless of the initial proportion of "low-carbon operation" or "non-low-carbon operation" chosen by cold chain logistics enterprises, this proportion will not change over time. $\partial G(y)/\partial y = S_q + T_q > 0$, so $G(y)$ is an increasing function. When $y < y*$, $G(y) < 0$, $F'(x)|_{x=0} < 0$, where $x = 0$ represents the evolutionary stability strategy of cold chain logistics enterprises; when $y > y*$, $G(y) > 0$, $F'(x)|_{x=1} < 0$, and $x = 1$ is the evolutionary stability strategy of cold chain logistics enterprises. The phase diagram of the evolution strategy of cold chain logistics enterprises is shown in Fig. 1.

In Fig. 1, the volume of the probability X_0 for cold chain logistics enterprises choosing non-low-carbon operations is V_{X_0}, and the volume of the probability X_1 for choosing low-carbon operations is $V_{X_1} = 1 - V_{X_0}$. The calculation is as follows:

Table 1
Mixed strategy benefit matrix.

Cold chain logistics enterprises	Government	Financial institution	
		Provide green credit services z	Provide regular credit services $1-z$
Low-carbon operation x	Strict regulation y	$P_1 + P_2 - C - C_r - mpr_1 + S_q$ $B_1 + B_2 - C_{e2} - S_q - mr$ $Q_1 + Q_2 - C_k + mpr_1 + mpr + C_r$	$P_1 + P_2 - C - C_r + S_q - mpr_2 B_1 + B_2 - C_{e2} - S_q$ $Q_1 + mpr_2 + C_r$
	Loose regulation $1-y$	$P_1 + P_2 - C - C_r - mpr_1 - V$ $B_1 + B_2 - C_{e2} - V$ $Q_1 + Q_2 - C_k - R_2$	$P_1 + P_2 - C - C_r - mpr_2$ $B_1 + B_2 - C_{e2} - V$ $Q_1 + mpr_2 + C_2$
Non- low-carbon operations $1-x$	Strict regulation y	$P_1 - T_q$ $B_1 - C_{e1} + T_q$ $Q_1 - C_k$	$P_1 - T_q$ $B_1 - C_{e1} + T_q$ Q_1
	Loose regulation $1-y$	P_1 $B_1 - C_{e1} - V$ $Q_1 - C_k$	P_1 $B_1 - C_{e1} - V$ Q_1

$$V_{X_0} = \int_0^1 \int_0^1 \frac{C + Cr - P_2 + mpr_2 + zmp(r_1 + r_2)}{S_q + T_q} dzdy = \frac{2(C + Cr - P_2) + mpr_1 + 3mpr_2}{2(S_q + T_q)} \tag{4}$$

$$V_{X_1} = 1 - \frac{2(C + Cr - P_2) + mpr_1 + 3mpr_2}{2(S_q + T_q)} \tag{5}$$

Inference 1. The probability of cold chain logistics enterprises choosing low-carbon operations is directly proportional to the new benefits, subsidies, and taxes of low-carbon operations and inversely proportional to the cost of low-carbon operations, credit service costs, credit interest rates, the loan principal, and the probability of timely repayment.

Proof: Calculate the first-order partial derivatives of V_{X_1} concerning each element, and obtain: $\partial V_{X_1}/\partial C < 0$, $\partial V_{X_1}/\ \partial C_r < 0, \partial V_{X_1}/\partial P_2 > 0, \partial V_{X_1}/\partial S_q > 0, \partial V_{X_1}/\partial T_q > 0, \partial V_{X_1}/\partial r_1 < 0, \partial V_{X_1}/\partial r_2 < 0, \partial V_{X_1}/\partial r_2 < 0, \partial V_{X_1}/\partial p < 0$。

4.2. Analysis of government strategy stability

The replication dynamic equations for the expected benefits of strict government regulation, the expected benefits of loose regulation, and the strategy selection are as follows:

$$E_{21} = xz(B_1 + B_2 - C_{e2} - S_q - mr) + x(1 - z)(B_1 + B_2 - C_{e2} - S_q) + (1 - x)z(B_1 - C_{e1} + T_q) + (1 - x)(1 - z)(B_1 - C_{e1} + T_q) \tag{6}$$

$$E_{22} = xz(B_1 + B_2 - C_{e2} - V) + x(1 - z)(B_1 + B_2 - C_{e2} - V) + (1 - x)z(B_1 - C_{e1} - V) + (1 - x)(1 - z)(B_1 - C_{e1} - V) \tag{7}$$

$$F(y) = y(1 - y)(E_{21} - E_{22}) = y(1 - y)[-x(S_q + T_q) + T_q + V - xzmr] \tag{8}$$

If $G(x) = -x(S_q + T_q) + T_q + V - xzmr$, then $dF(x)/dx = (1 - 2y)G(x)$. During $x = T_q + V/\ S_q + T_q + zmr = x*$, $G(x) = 0$, and $F(y) = 0$, all values of y were in an evolutionarily stable state. Regardless of the initial ratio of "regulated" and "unregulated" chosen by the government, this ratio will not change over time. $\partial G(x)/\partial x = -S_q - T_q - zmr < 0$, so $G(x)$ being a decreasing function, when $x < x*$, $G(x) > 0$, $F'(y)|_{y=1} < 0$, where $y = 1$ is the government's evolutionary stability strategy; when $x > x*$, $G(x) < 0$, $F'(y)|_{y=0} < 0$, and $y = 0$ is the government's evolutionary stability strategy. A phase diagram of the government's strategic evolution is shown in Fig. 2.

The volume V_{Y_1} of the probability Y_1 of government regulations in Fig. 2 is calculated as follows:

$$V_{Y_1} = \int_0^1 \int_0^1 \frac{T_q + V}{S_q + T_q + zmr} dzdx = \frac{T_q + V}{mr} In\left(1 + \frac{mr}{S_q + T_q}\right) \tag{9}$$

Inference 2. The probability of strict government regulation is positively correlated with the negative impact of decreased credibility, non-low-carbon operation taxes, and fees for cold chain logistics enterprises and negatively correlated with low-carbon operation subsidies for cold chain logistics enterprises and interest subsidies for financial institutions.

Proof: Calculate the first-order partial derivatives of each element for V_{Y_1}, and obtain the following: $\partial V_{Y_1}/\partial T_q > 0$, $\partial V_{Y_1}/\ \partial V > 0$, $\partial V_{Y_1}/\partial S_q < 0$, $\partial V_{Y_1}/\partial mr < 0$. Therefore, when V and T_q increase, or S_q and mr decrease, both can increase the probability of the government choosing strict regulations.

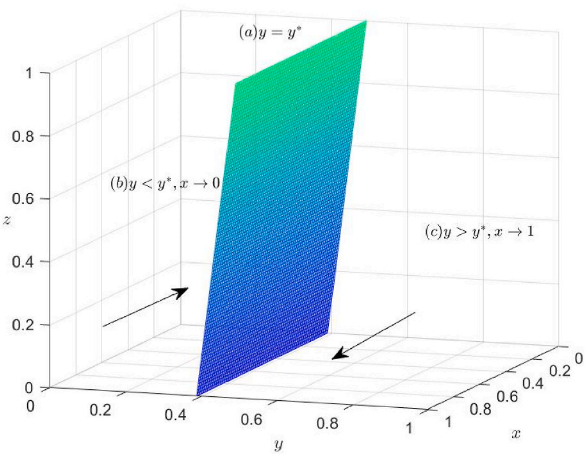

Fig. 1. Dynamic evolution trend of cold chain logistics enterprises.

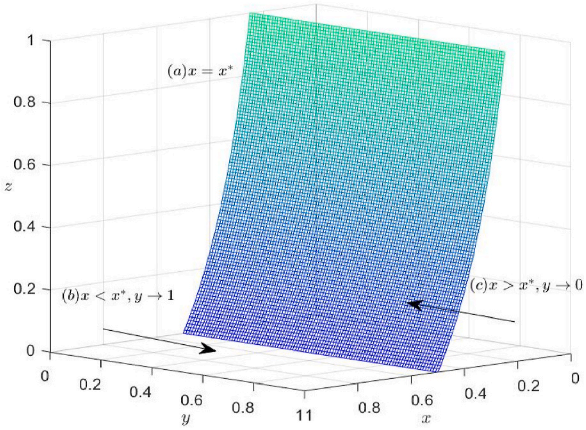

Fig. 2. Dynamic trend of government evolution.

4.3. Analysis of strategic stability of financial institutions

The replication dynamic equations for the expected benefits of green credit services provided by financial institutions, the expected benefits of conventional credit services provided, and the strategy selection are as follows:

$$E_{31} = xy(Q_1 - C_k + mpr_1 + Q_2 + mr + C_r) + x(1-y)(Q_1 - C_k + mpr_1 + Q_2 + C_r) + (1-x)y(Q_1 - C_k) + (1-x)(1-y)(Q_1 - C_k) \quad (10)$$

$$E_{32} = xy(Q_1 + mpr_2 + C_r) + x(1-y)(Q_1 + mpr_2 + C_r) + (1-x)yQ_1 + (1-x)(1-y)Q_1 \quad (11)$$

$$F(z) = z(1-z)(E_{31} - E_{32}) = z(1-z)[x(Q_2 + mpr_1 - mpr_2) + xymr - C_k] \quad (12)$$

If $G(x) = x(Q_2 + mpr_1 - mpr_2) + xymr - C_k$, then $dF(z)/dz = (1-2z)G(x)$. During $x = C_k/(Q_2 + mpr_1 - mpr_2 + ymr) = x*$, $G(x) = 0$, and $F(z) = 0$, then all values of z were in an evolutionarily stable state. Regardless of the initial proportion of "green financial services" and "conventional credit services" chosen by financial institutions, this proportion did not change over time. $\partial G(x)/\partial x > 0$, $G(x)$ is an increasing function of $x < x*$, $G(y) < 0$, and $F'(z)|_{z=0} < 0$, where $z = 0$ represents the evolutionary stability strategy of financial institutions. $x > x*$, $G(y) > 0$, $F'(z)|_{z=1} < 0$, and $z = 1$ represent financial institutions' evolutionary stability strategies. Fig. 3 shows a phase diagram of the financial institutions' evolutionary strategy.

The volume of probability Z_0 for financial institutions to choose conventional credit services in Fig. 3 is V_{Z_0}, and the volume of probability Z_1 for choosing green credit services is $V_{Z_1} = 1 - V_{Z_0}$. The calculation is as follows:

$$V_{Z_0} = \int_0^1 \int_0^1 \frac{C_k}{(Q_2 + mpr_1 - mpr_2 + ymr)} dxdz = \frac{C_k}{mr} In\left(1 + \frac{mr}{Q_2 + mpr_1 - mpr_2}\right) \quad (13)$$

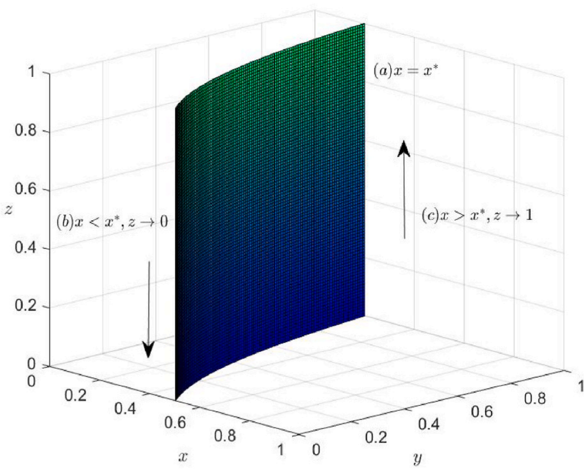

Fig. 3. Dynamic trends in the evolution of financial institutions.

$$V_{z_1} = 1 - \frac{C_k}{mr} In\left(1 + \frac{mr}{Q_2 + mpr_1 - mpr_2}\right) \tag{14}$$

Inference 3. The probability that financial institutions choose to provide green credit services is directly proportional to the new income, green credit interest rate, government discount interest rate, cold chain logistics enterprise loan principal, and probability of timely repayment, and inversely proportional to the cost of green credit evaluation and the conventional credit interest rate.

Proof: Calculate the first-order partial derivatives of each element for V_{Z_1}, and obtain the following: $\partial V_{Z_1}/\partial C_k < 0$, $\partial V_{Z_1}/\partial m > 0$, $\partial V_{Z_1}/\partial r > 0$, $\partial V_{Z_1}/\partial Q_2 > 0$, $\partial V_{Z_1}/\partial p > 0$, $\partial V_{Z_1}/\partial r_1 > 0$, and $\partial V_{Z_1}/\partial r_2 < 0$. Therefore, when Q_2、 m、 r、 p、 r_1 increase or C_k、 r_2 decrease, both can increase the probability of financial institutions choosing to provide green credit.

4.4. Stability analysis of equilibrium points in tripartite evolutionary game systems

Based on an analysis of the stability of the individual strategies of the government, financial institutions, and cold chain logistics enterprises, a comprehensive analysis of the tripartite system was conducted. The system equilibrium point can be obtained from $F(x) = 0$, $F(y) = 0$, $F(z) = 0$:

$$E_1(0,0,0), E_2(1,0,0), E_3(0,1,0), E_4(0,0,1), E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), E_8(1,1,1),$$
$$E_9\left(\frac{C_k}{Q_2 + mpr_1 - mpr_2}, 0\ , \frac{C + C_r - P_2 + mpr_2}{mpr_2 - mpr_1}\right), E_{10}\left(\frac{T_q + V}{S_q + T_q}, \frac{C + C_r - P_2 + mpr_2}{S_q + T_q}, 0\right),$$
$$E_{11}\left(1, \frac{C_k - Q_2 - mpr_1 + mpr_2}{mr}, \frac{-S_q + V}{mr}\right), E_{12}\left(\frac{T_q + V}{S_q + T_q + mr}, \frac{C + C_r - P_2 + mpr_1}{S_q + T_q}, 1\right),$$
$$E_{13}\left(\frac{C_k}{Q_2 + mr + mpr_1 - mpr_2}, 1, \frac{C + C_r - P_2 - S_q - T_q + mpr_2}{mpr_2 - mpr_1}\right)$$

The Jacobian matrix of a tripartite evolutionary game system is as follows:

$$J = \begin{pmatrix} (1-2x)(P_2 - C - C_r - mpr_2 + y(S_q + T_q) + z(-mpr_1 + mpr_2)) & x(1-x)(S_q + T_q) & x(1-x)(mpr_2 - mpr_1) \\ -y(1-y)(S_q + T_q - zmr) & (1-2y)(T_q + V - xzmr - x(S_q + T_q)) & -y(1-y)(xmr) \\ z(1-z)(Q_2 + mpr_1 - mpr_2 + ymr) & z(1-z)(xmr) & (1-2z)(x(Q_2 + mpr_1 - mpr_2) + xymr - C_k) \end{pmatrix} \tag{15}$$

Using Lyapunov's first method, if all eigenvalues of the Jacobian matrix have negative real parts, then the equilibrium point is asymptotically stable; if at least one eigenvalue of the Jacobian matrix has a positive real part, then the equilibrium point is an unstable fixed point; and if the Jacobian matrix has eigenvalues with zero real parts, and all other eigenvalues have negative real parts, then the equilibrium point is in a critical state and stability cannot be determined by the sign of the eigenvalues. Because of the presence of characteristic values with different signs in the Jacobian matrix from E_9 to E_{13}, the equilibrium points from E_9 to E_{13} are unstable. A stability analysis of the equilibrium points from E_1 to E_8 is presented in Table 2.

The analysis of the system equilibrium points can be discussed in the following two situations:

(1) An analysis of a poor stability situation

When Condition 1 is satisfied, the equilibrium point $E_2(0,1,0)$ is stable, and the cold chain logistics enterprise chooses a non-low-carbon operating strategy. This can be considered a poor stability situation. In this situation, even if cold chain logistics companies are strictly regulated by the government, their profits will still be negative, so they will still choose non-low-carbon operations.

Table 2
Stability analysis of equilibrium points.

Equilibrium	Eigenvalue	Symbol	Condition
$E_1(0,0,0)$	$P_2 - C_r - C - mpr_2$, $T_q + V$, $-C_k$	(× ,+,-)	instability
$E_2(0,1,0)$	$P_2 - C - C_r + S_q + T_q - mpr_2$, $-T_q - V$, $-C_k$	(× ,-,-)	Condition①
$E_3(0,0,1)$	$P_2 - C - C_r - mpr_1$, $T_q + V$, C_k	(× ,+,+)	instability
$E_4(0,1,1)$	$P_2 - C - C_r + S_q + T_q - mpr_1$, $-T_q - V$, C_k	(× , × ,+)	instability
$E_5(1,1,0)$	$C + C_r - P_2 - S_q - T_q + mpr_2$, $S_q - V$, $Q_2 - C_k + mpr_1 - mpr_2 + mr$	(× , × , ×)	Condition②
$E_6(1,0,0)$	$C + C_r - P_2 + mpr_2$, $V - S_q$, $Q_2 - C_k + mpr_1 - mpr_2$	(× , × , ×)	Condition③
$E_7(1,0,1)$	$C + C_r - P_2 + mpr_1$, $V - S_q - mr$, $C_k - Q_2 + mpr_2 - mpr_1$	(× , × , ×)	Condition④
$E_8(1,1,1)$	$C + C_r - P_2 - S_q - T_q + mpr_1$, $mr + S_q - V$, $C_k + mpr_2 - mpr_1 + mr - Q_2$	(× , × , ×)	Condition⑤

Note: × Represents uncertainty.

The government subsidy corresponding to Condition 1 was $S_q < C + C_r - P_2 - T_q + mpr_2$. At this time, government subsidies are low and cannot provide significant incentives to enterprises. In the case of high costs and low incomes, enterprises still choose non-low-carbon operations.

(2) An analysis of an optimal stability situation

When Conditions 2–5 are met, the equilibrium points $E_5(1,1,0)$,$E_6(1,0,0)$,$E_7(1,0,1)$, and $E_8(1,1,1)$ are stable, and the cold chain logistics enterprises choose low-carbon operating strategies. These four situations can be considered as having optimal stability. In these four situations, cold chain logistics enterprises, supported by the government and financial institutions, have positive profits from low-carbon operations, but they will still choose non-low-carbon operations.

The government subsidy corresponding to Condition 2 is $C + C_r - P_2 - T_q + mpr_2 < S_q < V$, and the subsidy value is in the median range. Under the positive incentives of the government, the enterprise chooses a low-carbon operating strategy. The government subsidy corresponding to Condition 3 is $S_q > V$, and the subsidy value is in a high range. The government chooses to relax regulations owing to their high costs, but because of $S_q < C + C_r - P_2 - T_q$, the new benefits are higher than the costs. At this time, enterprises will choose low-carbon operations. The government subsidy corresponding to Condition 4 is $S_q > V - mr$, and the subsidy value is in a high-level range. At this time, the government will still choose to relax the regulations. However, because of $C_k < Q_2 + mpr_1 - mpr_2$, the benefits of green credit provided by financial institutions outweigh the costs. With the credit support of financial institutions, the willingness of enterprises to operate with low carbon increases. The government subsidy corresponding to Condition 5 is $S_q < C + C_r - P_2 - T_q + mpr_1$, and the interest subsidy for green credit is $mr < Q_2 - C_k + mpr_1 - mpr_2$. Both values are within the median range. Environmental regulatory policies and green credit have incentive effects on the low-carbon operations of cold chain logistics enterprises.

5. Simulation analysis

This study assigned parameters based on the proportional relationship of real statistical data and used Matlab2016b to simulate the influence of each parameter on the system's convergence to the stable point of $E_8(1,1,1)$. According to the "China Environmental Yearbook 2022," the amount of "pollution discharge fees received" indicates that "enterprises should be subject to environmental taxes before low-carbon operation," "central environmental protection special funds" are "government subsidies provided during low-carbon operation of enterprises," and "the amount of environmental protection investment completed in the current year" is used to indicate "the cost of low-carbon operations." After calculation, the T_q: S_q: C was 1:2:8. According to the 2022 China Green Credit Market Analysis Report, green loans account for approximately 10 % of all loan balances. Therefore, Q_1 and Q_2 were set to 10:1. According to relevant financial institution data, the green credit interest rate is 3.78 % and the interest subsidy rate is 20 % of the green credit ratio.

Assign values based on the proportional relationship of the above parameters, let $P_2 = 80, C = 100, C_r = 5, S_q = 20, T_q = 10, V = 30, Q_1 = 100$, $Q_2 = 10, C_k = 10, m = 30, p = 0.95, r = 0.756\%, r_1 = 3.78\%, r_2 = 4.35\%$, satisfy the conditions for stable point E_8.

5.1. Impact of the initial intentions of the three parties

The initial participation strategy included whether the cold chain logistics enterprise operates on low carbon, whether the government chooses strict or loose regulations, and whether financial institutions provide green credit services. The initial participation probability was set to $x = y = z = \{0.2, 0.5, 0.8\}$, and the evolutionary process and results of the strategy selection of the three-party game subject are shown in Fig. 4, with the other parameters remaining unchanged.

As shown in Fig. 4, with an increase in the initial participation probability of the three parties, the evolutionary process of each subject in the evolutionary system exhibited obvious changes. For the three parties in the game, the change in the initial participation

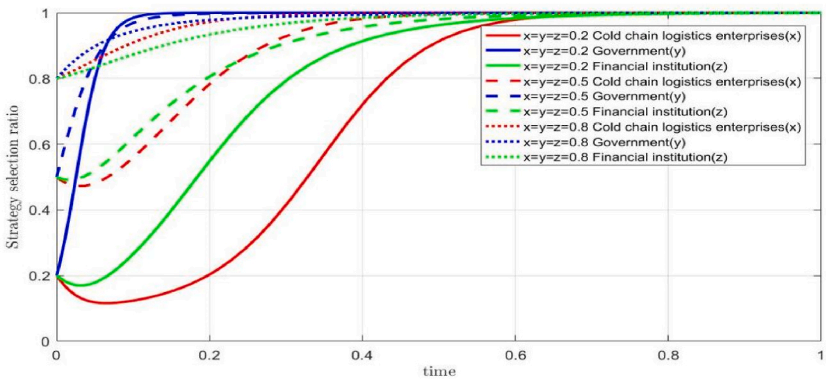

Fig. 4. Evolutionary process and results of simultaneous changes in initial participation probability of three-party game participants.

probability did not change the strategy choice of each subject: cold chain logistics enterprises chose low-carbon operations, the government chose strict regulations, and financial institutions chose to provide green credit services, but this affected the evolutionary stability rate of each subject. As the initial participation probabilities of the three parties increased, the rate at which cold chain logistics firms and financial institutions evolved and stabilized accelerated, whereas the rate at which governments evolved and stabilized increasingly slowed. This shows that diverse organizations engage with one another, and that cold chain logistics firms and financial institutions are incentivized to increase their desire to participate, resulting in a faster rate of action. When cold chain logistics corporations and financial institutions take a wait-and-see approach to implementing low-carbon initiatives, the government swiftly places tight laws and constraints on the behavior of the two entities. However, as their willingness to cooperate increases, the government reduces its action rate to lower its expenditure.

5.2. Impact of enterprise revenue and cost

Cold chain logistics companies can save money by investing in energy-saving and environmental protection equipment, implementing digital technologies, and lowering the cost of credit services. Fig. 5 shows the evolution trajectory.

From Fig. 5(a), it can be seen that the new revenue of a cold chain logistics enterprise after beginning low-carbon operations will directly affect the strategy choice of the subject, when $P_2 = 60$ the enterprise will evolve and stabilize in non-low-carbon operations, and when $P_2 \geq 80$ the enterprise tends toward low-carbon operations, and the rate of evolution becomes faster with the increase in revenue. From Fig. 5(b), it can be seen that cold chain logistics enterprises are more sensitive to the cost of low-carbon operations: the lower the cost required for low-carbon operations, the faster the rate of evolutionary stabilization of the enterprise to low-carbon operations. In the process of C growing from 100 to 120, the strategic choice of the enterprise changes, indicating that there is a critical value between 100 and 120, and because of the high cost of operation that makes the enterprise's profit negative, the enterprise tends to choose a non-low-carbon operating strategy. Fig. 5(c) shows that changes in the cost of credit services do not change the firm's strategy choice, but affect its evolutionary stabilization rate, and the firm's evolutionary stabilization time is prolonged as C_r increases.

Therefore, before initiating a low-carbon investment, a thorough cost-benefit analysis must be conducted. Companies that obtain an in-depth understanding of low-carbon costs can assess the risks and feasibility of their projects, allowing decision makers to make educated investment decisions with limited resources. Furthermore, cost-benefit studies can help businesses track the success of low-carbon operations. Comparing actual and predicted expenses helps to identify potential cost risks in a timely manner, whereas a benefit analysis assists managers in assessing the total benefits of low-carbon operations and making timely modifications and optimizations.

5.3. Impact of government environmental regulations

5.3.1. The impact of government subsidies on evolutionary strategies

To examine the impact of government subsidy behavior on the evolutionary game process and game subject outcomes, $S_q = \{0, 20, 40\}$ values were assigned, and the simulation results are displayed in Fig. 6.

As Fig. 6 illustrates, changes in government subsidies for cold chain logistics firms substantially impact the evolution of these three entities. When the government's subsidy value for cold chain logistics firms is zero, the three parties' strategic choice is "non-low-carbon operation, strict regulation, and green credit services." When S_q reaches 20, the development of cold chain logistics enterprises stabilizes in low-carbon operations. When S_q exceeds a certain threshold, cold chain logistics companies continue to choose low-carbon activities, and the evolution stabilization time is reduced. However, the strategic choices of governments and financial institutions fluctuate and are unable to achieve stability.

Through the simulation of government subsidy values, it was found that subsidies can indeed play an incentive role in cold chain

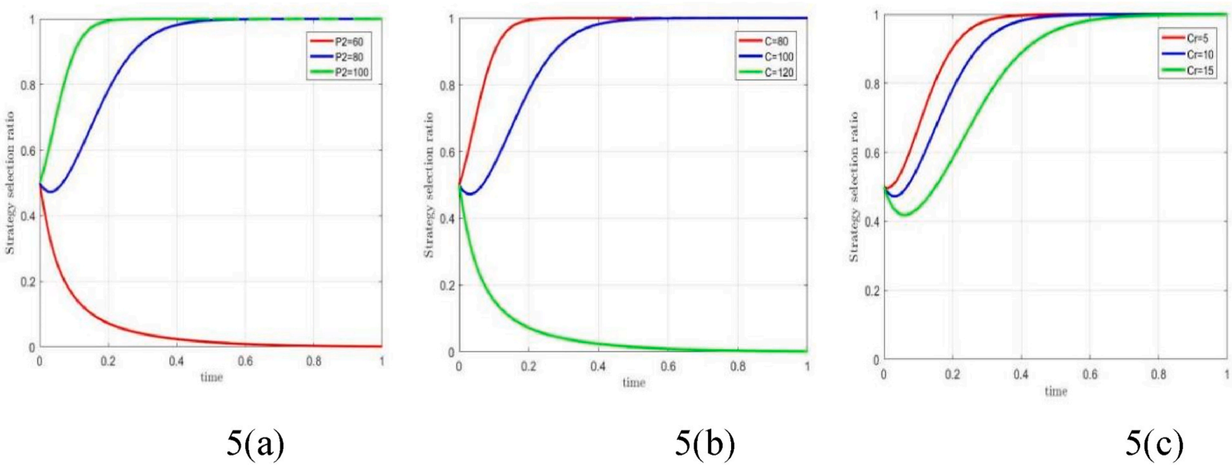

Fig. 5. Strategic evolutionary process and results of cold chain logistics enterprises with changes in P_2, C, and C_r

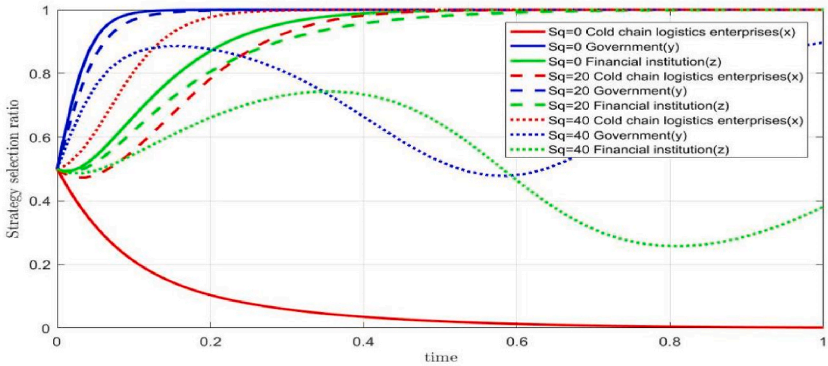

Fig. 6. Evolutionary process and results of the three entities when the government subsidies for cold chain logistics enterprises change.

logistics enterprises and financial institutions, but a moderate subsidy value will achieve a better incentive effect. If the subsidy value is too high and exceeds a specific threshold, the cost burden on the government will increase, which is not conducive to participants reaching a stable state.

5.3.2. *The impact of government taxation on evolutionary strategies*

To examine the impact of government taxation behavior on the evolutionary process and outcomes of the game subjects, the value of $T_q = \{0, 10, 20\}$ was chosen, and the simulation results are shown in Fig. 7.

Fig. 7 shows that while the government's tax on cold chain logistics firms increased from 0 to 10 and then to 20, the evolutionary stability strategies employed by the three entities remained constant. However, the rate at which cold chain logistics firms tend to function at a low-carbon level greatly increased. For governments and financial institutions, the rate of evolution did not change significantly. The simulation of the government tax value indicated that while taxes put financial pressure on cold chain logistics firms, they had a positive effect on motivating them to take low-carbon measures.

A balance between reducing carbon emissions and sustaining economic development must be established when determining environmental subsidies and carbon taxes. The unique circumstances of various businesses and regions must be fully considered to prevent undue pressure on a particular business. If necessary, the two policy tools can be combined to fulfill their respective roles.

5.4. *The impact of government green credit subsidies*

To analyze the impact of government green credit interest subsidies on the evolutionary process and results of the game subjects, values of $m * r = \{0, 10, 20\}$ were assigned, and the simulation results are shown in Fig. 8.

As the figure shows, when the interest subsidy amount for green credit is in the low range, there is no incentive effect and financial institutions cannot reach the evolutionary stability point. When the discount interest rate increases to a certain extent, financial institutions tend to provide green credit services and gradually accelerate the rate of evolution. For cold chain logistics enterprises and the government, the change in the interest subsidy amount has no significant influence on the evolution strategy and rate of the two entities. However, preserving the supply of discounted interest subsidies benefits enterprises; on the one hand, fiscal funds can successfully motivate banking institutions to provide green loans. After the green credit policy was rapidly implemented in the market, the availability of financing for cold chain logistics enterprises increased. However, financial institutions are more proactive in credit approval and information screening for enterprises after receiving fiscal incentives, encouraging them to better fulfill their social

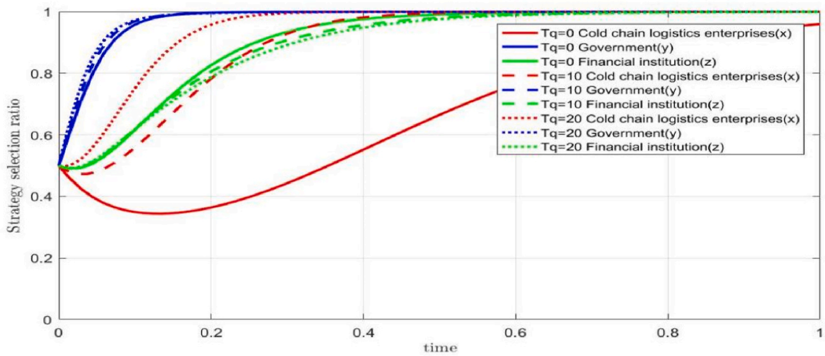

Fig. 7. Evolutionary process and results of the three entities when the government changes taxation on cold chain logistics enterprises.

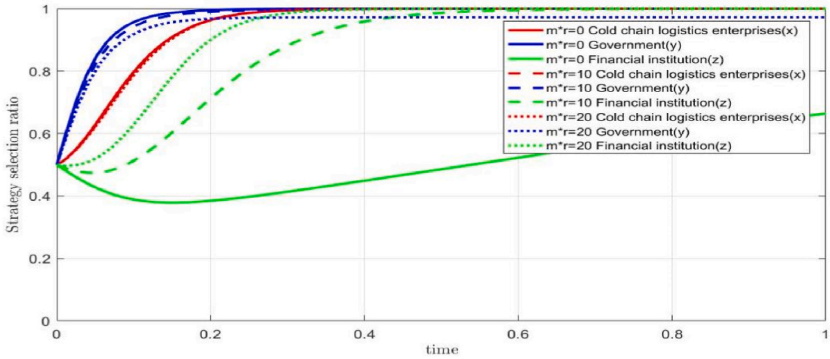

Fig. 8. Evolutionary Process and Results of the Three Entities when the Government's Interest Subsidy amount Provided to Financial Institutions Changes.

responsibilities and obtain credit funds.

5.5. *The impact of credit interest rates on financial institutions*

5.5.1. *The impact of green credit interest rates*

To analyze the impact of green credit interest rates on the evolutionary process and results, a value of $r_1 = \{1.78\%, 3.78\%, 5.78\%\}$ was assigned, and the simulation results are shown in Fig. 9.

Fig. 9 shows that changes in the green credit interest rates do not affect the evolutionary stability strategies of the three parties in the game; that is, the three parties tend to operate on low carbon, strictly regulate, and provide green credit services. However, this has an impact on the evolutionary stability rate. As r_1 gradually increases, the evolution rate of cold chain logistics enterprises toward low-carbon operations will slow, and the evolution rate of financial institutions toward green credit will accelerate. This finding indicates that the green credit interest rates affect the operations of low-carbon firms. When green credit interest rates are low, businesses are more inclined to meet their social duties, allowing them to acquire cheaper interest rate financing, as well as more credit sources.

5.5.2. *Impact of conventional credit interest rates*

To analyze the impact of conventional credit interest rates on the evolutionary process and results, a value of $r_2 = \{2.35\%, 4.35\%, 6.35\%\}$ was assigned, and the simulation results are shown in Fig. 10.

Fig. 10 shows that the conventional credit interest rate has a significant impact on cold chain logistics enterprises and financial institutions. When the conventional credit interest rate increases, the rate at which cold chain logistics enterprises tend to operate in a low-carbon manner decreases, and the rate at which financial institutions evolve and develop green credit initially slows down. When the conventional credit interest rate is 6.35 %, the entity does not tend to evolve or stabilize. This indicates that when the regular credit interest rate increases, financial institutions can maintain good returns by providing regular credit services alone, without incurring the extra costs of developing new businesses. For cold chain logistics enterprises, the lower the regular credit interest rate, the lower the cost of obtaining funds, and the greater the willingness to pay attention to environmental governance issues.

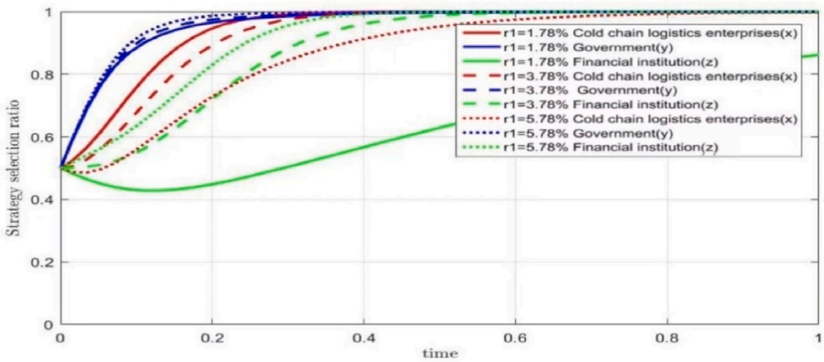

Fig. 9. Evolutionary process and results of the three entities when green credit interest rates change. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

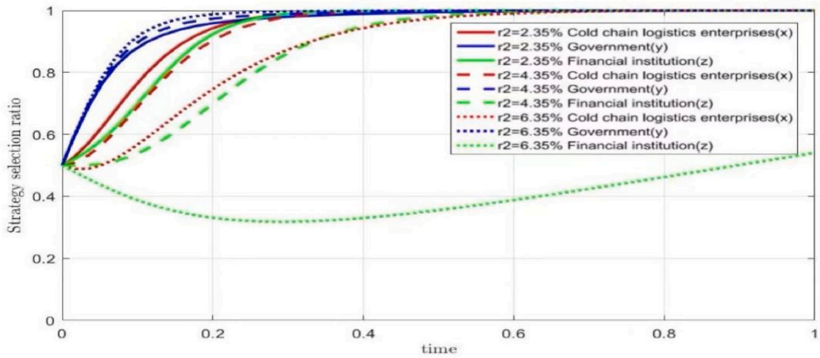

Fig. 10. Evolutionary process and results of the three entities when the conventional credit interest rate changes.

6. Conclusion and recommendations

6.1. Research conclusion

This study established an evolutionary model of the game among cold chain logistics enterprises, governments, and financial institutions to complete the low-carbon operation of cold chain logistics enterprises and find suitable strategic choices for each participating entity. The evolution pathways of each entity were studied via simulations, and the following conclusions were drawn:

(1) The behavioral choices of cold chain logistics enterprises, governments, and financial institutions interact with each other. As the initial willingness of the three parties to participate increases, the evolution and stability rates of cold chain logistics enterprises toward low-carbon operations and financial institutions toward green credit services accelerate. At this time, the government engages in opportunistic behavior, and its rate of approaching strict regulations slows down.
(2) Cold chain logistics enterprises are more sensitive to the new benefits and costs of low-carbon operations, as well as credit service expenses. Both revenue and cost have critical values that determine whether a company will adopt a low-carbon operating strategy, whereas the cost of credit services only affects the evolutionary stability rate of enterprises.
(3) The government's environmental regulatory policies are an important driving force for the low-carbon operations of cold chain logistics enterprises. However, only moderate subsidies and taxes are conducive to the joint participation of the three parties. A subsidy or tax that is too low cannot have a good incentive effect, whereas one that is too high can cause fluctuations in parties' strategic choices. The increase in interest subsidies for green credit has a promoting effect on financial institutions' provision of green credit services.
(4) Reducing green and conventional credit interest rates can boost low-carbon operations in cold chain logistics firms. This indicates that enterprises are unconcerned about the type of credit as long as their financing costs can be reduced. For financial institutions, increasing the green credit interest rate or decreasing the conventional credit interest rate is required to accelerate their implementation of green credit services.

6.2. Managerial recommendations

All social parties must participate in reaching a low-carbon target in cold chain logistics. Effective regulation from the government, acting as policymakers, is necessary to solve the issue; reasonable practice paths from cold chain logistics companies, acting as industry practitioners, hold the key to solving the problem; and flexible financing services from financial institutions, acting as stakeholders, ensure that the problem is solved. The following ideas can help cold chain logistics companies operate more sustainably.

(1) Giving the government credit to take the lead in environmental governance and creating a diverse long-term regulatory framework. First, we must formulate and improve low-carbon operating standards and rules, such as those regarding green supply chains, energy conservation, and emissions reduction, and support cold chain logistics companies in implementing low-carbon operations. Second, financial incentives can be enhanced by tailoring them to the specific requirements of businesses in order to reduce taxes or provide subsidies. Appropriate subsidies can lower the low-carbon operating expenses of cold chain logistics companies, whereas tax policy limitations can effectively curb high-pollution and high-emission practices. Third, we should offer green credit discount interest to financial institutions to incentivize them to provide green credit services, raise the discount rate or scale of interest appropriately, and foster the innovative development of green credit.
(2) Cold chain logistics enterprises should pay attention to energy saving and emissions reduction, considering the social and environmental benefits. First, businesses should increase internal fund management, improve their benefit analysis capabilities, and conserve funds for low-carbon operational inputs by optimizing operations and lowering operating costs. Second, there are various ways to achieve low-carbon operations, such as building new green and high-efficiency cold storage, purchasing new

energy-efficient refrigerated trucks, investing in digital technology, manufacturing energy-saving and environmentally friendly refrigeration equipment, and choosing the path that best suits the enterprise's development. Finally, cold chain logistics companies should seize policy possibilities in green finance and cold chain logistics and layout ahead of time on both the investment and industrial sides to take advantage of the industry's low-carbon development.

(3) Financial institutions should seek new profit growth potential through varied financial services and take advantage of the green credit market's development opportunities. First, the mode of financing of cold chain logistics companies should be rationally analyzed, considering the costs and benefits to each party involved, and the main green credit support areas in the cold chain logistics sector should be identified. Second, financial institutions should improve their environmental credit evaluation systems and promote the standardization of evaluation metrics. Finally, there is a need to improve enterprise financing diversity and facilitation, boost investments in green credit, and deepen the investigation and design of green credit policies. Credit staff and managers of financial institutions serve as investment advisers to businesses, logically directing loans toward them and reinforcing the function of interest rate guidance to boost business financing costs and fund utilization rates.

To cooperatively encourage the adoption of low-carbon operations, governments, cold chain logistics companies, and financial institutions should establish a collaborative mechanism. Governments can provide legislative guidance and oversight, businesses can provide experience and demand feedback, and financial institutions can offer funding and financial products. The three major parties should collaborate to maximize the economic, environmental, and social benefits.

6.3. Limitations and future research directions

This study analyzed the effectiveness of government environmental regulation policies and green credit from financial institutions on the behavioral strategies of the low-carbon operations of cold chain logistics companies, and the influence of related factors on these behavioral strategies. However, this study has several limitations. First, the evolutionary game model in this study involved three subjects, namely cold chain logistics enterprises, the government, and financial institutions, and ignored other subjects, such as consumers, who influence enterprises' low-carbon operation decisions. Future research should consider consumer factors when constructing more realistic models. Second, although the simulation results were consistent with those of the previous model analysis, the parameter value sets were relatively abstract. More real enterprise data will be collected in the future to improve the empirical study.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Rong Wu: Writing – review & editing, Project administration, Funding acquisition. **Lin Zhu:** Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Man Jiang:** Writing – review & editing, Validation, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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