Government regulation to promote coordinated emission reduction among enterprises in the green supply chain based on evolutionary game analysis

Zheng Liu[1], Qingshan Qian[1], Bin Hu[1], Wen-Long Shang*[,2,5,6], Lingling Li[3], Yuanjun Zhao[4], Zhao Zhao[7], Chunjia Han[8]

1.School of Management, Shanghai University of Engineering Science, Shanghai 201620, China

2.Beijing Key Laboratory of Traffic Engineering, College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, China

3.Department of Central Laboratory, Shanghai Children's Hospital, Shanghai Jiao Tong University, Shanghai 200062, China

4.School of Accounting, Nanjing Audit University, Nanjing 211815, China

5.School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100008, China

6.Centre for Transport Studies, Imperial College London, London SW7 2AZ, United Kingdom

7. Odette School of Business, University of Windsor, N9B 3P4, Canada

8.Department of Management, Birkbeck, University of London, London WC1E 7HX, United Kingdom

*Corresponding author. Email: shangwl_imperial@bjut.edu.cn

Abstract: The green supply chain realizes the unification of economic and environmental benefits through green manufacturing, green circulation and reverse logistics, and represents an important way to reduce emissions. The characteristics of the green supply chain network, however, can encourage some companies to exhibit "free-riding" behavior, participating without being willing to reduce emissions directly themselves. This paper applies an evolutionary game model to a two-level green supply chain composed of green suppliers and green manufacturers in order to analyze a variety of internal and external factors that affect the behavior of both parties in the game, and thence numerically simulate the evolution and stability trend of coordinated reductions in emissions. The results identify many cases of system evolution but the only stable evolution strategy is when both (1) the sum of collaborative emission reduction benefits and government subsidies is greater than the sum of collaborative emission reduction input costs and "free rider" benefits, and (2) the increased rate of unilateral emission reduction benefits is greater than the ratio of costs to original benefits. Income arising from collaborative reductions in emissions, enterprise original income, income from unilateral reductions in emissions increase ratio, government subsidy coefficient and achievement reward base can directly affect the system evolution path. The larger these value, the greater the probability of green suppliers and green manufacturers choosing collaborative reductions in emissions, and the faster the system convergence speed. Only the imposition of regulatory punishments above the threshold will affect the "free riding" behavior of enterprises and drive the upstream and downstream enterprises of the green supply chain to reduce emissions faster.

Keywords: Government regulation; Green supply chain; Coordinated emission reduction; Evolutionary game

1. Introduction

The link between environmental pollution arising from industrialization and global climate change has become increasingly well understood, and subject to government intervention. The EU launched the European Green agreement and the United States returned to the Paris Agreement, announcing that the GDP of carbon neutral countries has exceeded three quarters of the world. At the same time, China put forward the "3060 target" and launched the world's largest carbon trading market. Many scholars have optimized the design of urban transportation system (Bi et al., 2021; Zhang et al., 2018; Shang et al., 2020), buildings (Yan et al., 2019), distributed energy (Qiu et al., 2021; Xing et al., 2019) and oil pipelines (Yuan et al., 2018) to find the path and method of energy conservation and emission reduction. If these efforts are to deliver meaningful change, however, commercial enterprises need to effect significant reductions in carbon emissions across their operations. A key element in such change is the supply chain—an integrated organizational form of many enterprise groups, which can achieve cross-industry and cross-regional collaboration. Traditional supply chains pay attention to the CO_2 reduction of individual and ignore the cooperative emission reduction of the whole system have been difficult to adapt to the low-carbon competition environment, however, and green supply chains have thus become the mainstream direction of future development. There are many enterprises in the upstream and downstream of the green supply chain, and some of these have transformed into intelligent and low-carbon green enterprises through technological change or product structure adjustment. The examples and guidance provided by these enterprises, and technology diffusion, can reduce the overall level of carbon emissions in the supply chain. At the same time, in the processes of pollution control and low-carbon production, they are inseparable from relevant government systems Financial and monetary policy support. How to improve the willingness of green enterprises in the upstream and downstream of the green supply chain to cooperate in emission reductions under the regulation of the government is therefore of great practical significance.

1.1. Literature review

Many scholars have conducted research on how to realize the network design (Wang et al., 2019), optimization and coordination, low-carbon and environmental protection (Zwickl-Bernhard et al., 2020) of the green supply chain. Waltho et al. (2019) pointed out that the conventional green supply chain network design policies mainly include carbon taxes, carbon quotas, carbon offset, and quota transactions. Based on data from a multinational clothing company, Fahimnia et al. (2018) proposed a supply chain network model that is both green and flexible. Guo et al. (2021) used the contract model of cooperative game theory to study the cost-sharing strategy for reducing carbon emission levels in the green supply chain. Luo et al. (2021) constructed a multi-stage game model in multiple scenarios to analyze the changing laws influencing factors such as green after-sales services, product greenness, and equilibrium prices to solve the information-sharing problem of green services provided by manufacturers in two competitive green supply chains. Han et al. (2021) established a Stackelberg game model to study the impact of government subsidies and retailers' fairness concerns on the optimal pricing, greenness decision-making and main profits of the green supply chain. Jamali et al. (2018) and Liu et al. (2021) studied the pricing strategy of green and non-green products by constructing a dual-channel Stackelberg game model. Madani et al. (2017) conducted a sensitivity analysis on key factors such as governance tariffs, green strategies, and pricing policies by constructing a government-led competition game model between green supply chains and non-green supply chains. Ma et al. (2019) studied the green R&D financing issues of green manufacturers and conventional manufacturers by comparing three game models of partial concentration, government subsidies and two-part tariff contract scenarios. Considering the "free rider" behavior of online retailers, Jing et al. (2019) established a contract model for a dual channel green supply chain, arguing that revenue sharing and cost sharing contracts can realize system coordination. Wang (2019) and Zhou (2020) developed the MILP model to help decision makers plan oil pipeline supply chain networks. Yang et al. (2022) and Shang et al. (2020,2022) then studied the green manufacturing process of distribution transformers and the optimization of urban road transport networks.

China is establishing the world's largest carbon dioxide emission trading system (ETS) to achieve the goal of "carbon peak and carbon neutralization" faster through the coordination of environmental regulation objectives and government policies. Many scholars have studied the efficiency with which regulation achieves environmental protection. Springer et al. (2018) used a general equilibrium (CGE) model to simulate the interaction between structural transformation policy and a national ETS. Lin et al. (2019) used a seven scenario equilibrium model of an ETS to study the impact of government fines on carbon emission intensity, the economy and the environment. Shen et al. (2019) studied the impact of different environmental regulations on the total factor energy efficiency of the industrial sector. Ouyang et al. (2020) used provincial panel data to study the relationship between environmental regulations and energy saving and emission reduction technologies. Guo et al. (2019) analyzed data from thirty provinces and cities in China from 2007 to 2016 to find that environmental regulations (ER) have an agglomerative effect on a province's green credit (GC) and green technology innovation (GTI). Jiang et al. (2019) studied the interactive process underpinning the evolution of the environmental regulation strategies of local government regulators (LG), central government planners (CG) and the polluting enterprises (PE) that were regulated. It is inherent in these models that enterprises focus on their own interests, and that the decisions as to whether to carry out energy conservation and emission reduction are affected by the evolution of government policies. Tan et al. (2020) studied the impact of carbon tax policy on the ecological efficiency of China's energy-intensive industries. Axsen et al. (2020) and Shang (2020,2021) summarized the existing combination of climate and road traffic policies, and pointed out that it is rapidly to achieve transportation emission reduction targets through a comprehensive combination of policies, dominated by strict regulations and supplemented by pricing mechanisms. He et al. (2019), however, pointed out that lower government subsidies can still have a significant effect in reducing emissions in the waste incineration power generation industry. Xu et al. (2019) established a game model between government regulation and consumers, to analyze and compare four different government subsidy strategies, finding that the is most profitable approach was to subsidize supply chain members meanwhile. Li et al. (2020) used a DE-SSA algorithm to analyze the impact of four different carbon emission policies (emission cap, carbon tax, carbon trading and carbon offset) on coal supply chain network optimization. From the perspective of cities, rather than organizations, meanwhile, some scholars have also studied the impact and guidance of macroeconomic policies on the development of low-carbon cities (Afzali et al., 2020; Chen et al., 2020; Zhao et al., 2019).

Based on the limited rationality of stakeholders, evolutionary game theory can dynamically evolve to reflect the decision-making behavior of participants, and the influence of the external environment (Liu et al., 2021). It is often used in research into the green supply chain and government environmental regulation. Shao et al. (2021) combined the evolutionary game method and the idea of system dynamics to model the influence paths of government subsidies, policy measures, enterprise green achievement quality and green management level. Xu et al. (2019) applied evolutionary game analysis to the green investment strategies of suppliers and manufacturers in the secondary green supply chain, pointing out the importance of government regulation. Zhu et al. (2021) built a reverse supply chain composed of third-party recyclers and retailers, compared the evolutionary equilibrium strategies of government participation and government non-participation, and found that, when the government participates, the system can achieve cooperation results faster. Tang (2019), meanwhile, compared the differences between dual-species evolutionary game theory and the Nash equilibrium theory, to analyze the issue of how governments, enterprises, and consumers compete in reducing emissions in the green supply chain. Huang et al. (2021) applied the idea of evolutionary game to the practice of construction projects, developing an independent symbiotic density game model of whether developers should build green or traditional buildings. Finally, Dong et al. (2021) studied the optimal boundary problem of the amount of government subsidies by constructing evolutionary game models under different supervision situations, finding that the government's issuance and supervision of low-carbon subsidies should meet certain conditions.

1.2. Bibliometric analysis and literature gaps

In addition to the above literature review, this paper uses VOSviewer software to conduct a bibliometric analysis of the field. This is intended to help grasp the status of research status into green supply chains and low-carbon supply chains as a whole, offering a quantitative summarization of the current practices of carbon emission management, and thus clarifying the research hotspots and frontiers in respect to green supply chains, The data comes from the core collection database of Web of Science (WOS), with "supply chain" and "carbon emission reduction" as keywords, the retrieval time span is nearly ten years, and excludes conference papers, editorial comments, papers unrelated to the research topic. The search returned an initial set of 1214 articles, which were then refined manually by reviewing the dimensions of the research topics of the selected studies according to the abstracts and publication years. The results are shown in Figures 1 and 2. Figure 1 shows the most important and popular research topics in the field of supply chains and carbon reduction, clustered by relevance to form six main clusters, represented in the figure with different colors. In the past ten years, scholars' research has mostly focused on: (1) Low-carbon transformation of energy and manufacturing (Chen et al., 2019; Kim et al., 2019; Tan et al., 2018; Zhu et al., 2020); (2) Calculation of and influencing factors for carbon footprint intensity and carbon emission efficiency (Xu et al., 2014; Long et al., 2016; Yu et al., 2018; Ma et al., 2019); (3) Research on the roles of government, carbon taxes, subsidy mechanisms, carbon trading mechanisms, etc. (Memari et al., 2018; Chen et al., 2018; Zhang et al., 2020); (4) Green supply chain management, supply chain coordination and optimization mechanisms (Pathak et al., 2020; Peng et al., 2018; Safarzadeh et al., 2019); (5) Enterprise strategic decision-making from the perspective of environmental regulation and life cycles (Hedayati et al., 2018; Zhong et al. and Zappa et al., 2019); (6) Game theory analysis among supply chain members, risk preferences and low-carbon consumption behavior of consumers (Zu et al., 2018; Le et al., 2020; Wang X et al., and Wang Z et al., 2018). At the same time, it can be seen from Figure 2 that, in the past five years, the research hotspots of carbon emission reduction have gradually expanded from traditional high-energy-consuming industries such as electricity and energy to the field of consumer services. How to further highlight the key role of innovation and technology and build a resource-sharing platform to promote collaboration between upstream and downstream enterprises has also become an important research topic in the coordination and optimization of green supply chains and low-carbon supply chains.

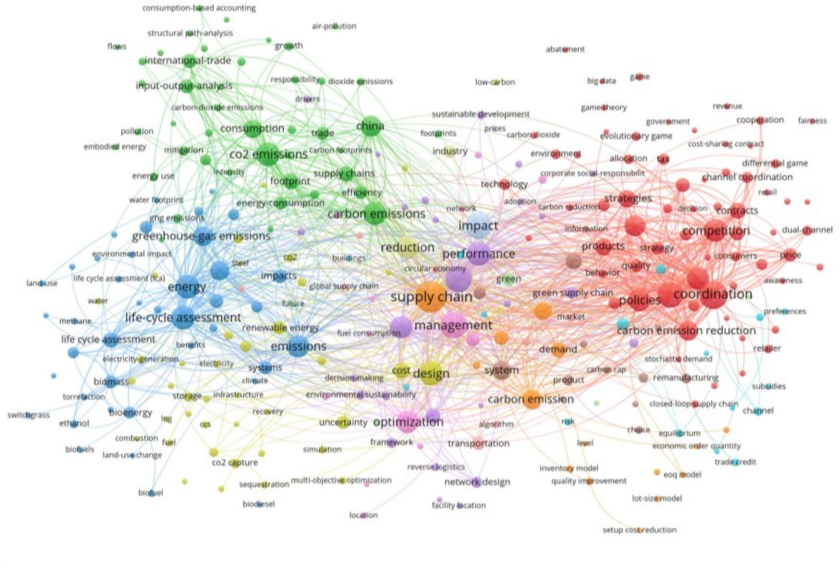


Figure 1. Distribution of research hotspots in the field of supply chain and carbon reduction

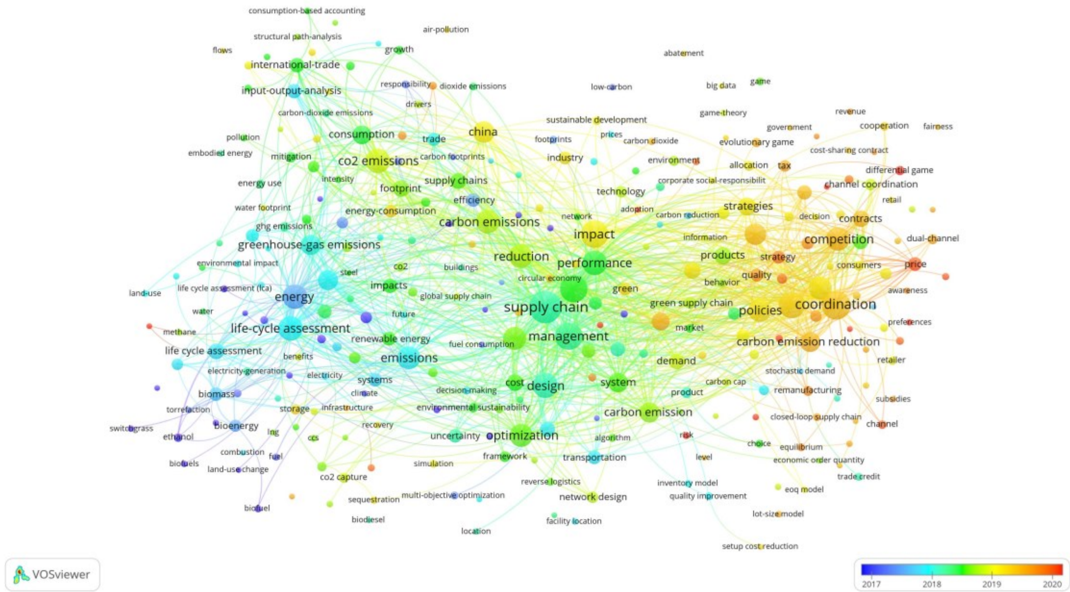


Figure 2. Knowledge mapping of research publication times in the field

Combining the results of the literature review and bibliometric analysis, it is evident that the existing research focuses on the development path of the green supply chain, environmental regulations, and the influence of government policies on the members of the supply chain, but that less attention has been paid to the game behavior between enterprises in the green supply chain. In particular, the following problems are still to be solved.

(i) Scholars mainly use game models and empirical research methods, but most of the research uses static evolutionary game models. The equilibrium strategy between enterprises and enterprises, and enterprises and government is not a static process however, hence the static evolutionary game is inherently not well-suited to the analysis and study of such problems.

(ii) Most of the existing literature focuses on the interaction between government and enterprises to study the impact of government environmental regulation strategies on enterprise energy efficiency and low-carbon investment strategies. Government external policy regulation and supervision on its own, however, is insufficient to effect radical revision of enterprises' emission reduction activities.

(iii) While many scholars use evolutionary game methods to analyze the behavioral decision-making among the government, enterprises and consumers, few consider "free-riding" behavior. How to avoid speculation in emissions reduction by green supply chain members has become an urgent and difficult issue to be addressed.

1.3. Contributions of this work

Relying on external government supervision alone cannot effectively improve the emission reduction efficiency of the green supply chain, and collaboration between upstream and downstream enterprises in the green supply chain is still required if systematic emission reductions are to be achieved. From the internal perspective of the green supply chain, therefore, this paper adopts as its research object the collaborative emission reduction activities of upstream and downstream enterprises, considering the external regulation measures of the government. To this end, the paper constructs an evolutionary game model between green suppliers and green manufacturers, analyzes the factors influencing collaborative emission reductions under different circumstances, and finally obtains the evolutionary stable strategy for collaborative emission reduction of upstream and downstream enterprises in the green supply chain. This work is intended to act as a reference to assist governments seeking to formulate environmental policies and enterprises engaged in low-carbon decision-making. Accordingly, the main contributions of the paper are shown as follows:

(i) Unlike the existing literature, which mostly take the government and enterprises as evolutionary game subjects, this paper constructs an evolutionary game analysis framework between upstream suppliers and downstream manufacturers in the green supply chain. The paper thence investigates the influence of external government subsidies, incentives and other support measures on the evolutionary game results in respect to the coordinated emission reductions of upstream and downstream enterprises.

(ii) The paper builds a mathematical model to analyze the impact of collaborative emission reduction revenue, "free rider" revenue, carbon emission reduction investment and other internal factors of the supply chain on the system evolution results of upstream and downstream enterprises collaboration within the green supply chain under different emission reduction scenarios.

(iii) The paper discusses the evolution of the green supply chain of upstream and downstream enterprises, and intuitively reflects on the evolutionary driving forces and trends in collaborative emission reductions of enterprises under government control. From this basis the paper proposes ways in which government regulation could help to promote the cooperation of upstream and downstream enterprises in respect to emission reductions.

The rest of this paper is organized as follows: Section 2 outlines the research framework and basic assumptions, and then establishes the payment matrix of upstream and downstream enterprises in the green supply chain. Section 3 analyzes the stable strategy of system evolution and identifies the influences of each parameter on the result of dynamic evolution. Section 4 verifies the above model and theorem through the simulation of an actual case. Finally, section 5 summarizes the conclusions of the study, and makes suggestions for management and government, as well as identifying avenues for future research.

2. Methodology

The main body of the game model presented in this paper is the upstream green supplier and downstream green manufacturer groups in the green supply chain. Each time, a pair is randomly selected from these two groups to conduct multiple cooperative emission reduction games. Both the green supplier group and the green manufacturer group are rationally bounded, and cannot accurately know each other's income function and strategy choice. This makes it difficult to make the optimal decision and carry out long-term cooperation and thus the process of adjusting and improving the strategy to reach evolutionary stability can take some time (Zhang et al., 2019, 2020). The corporate behavior strategy space for collaborative emission reduction in the model is abbreviated as (T, N). Collaborative emission reduction includes low-carbon technology research and development, low-carbon environmental protection of raw materials, and transportation of parts and products, and the greening of the production processes so as to reduce the overall carbon emission intensity of the green supply chain. At the same time, based on the double carbon goal, all levels of government have strengthened their support for the green supply chain and actively promoted the low-carbon transformation of traditional industries. This comes in the form of policy guarantees from government subsidies, technology investment, risk compensation and other aspects (Chen et al., 2018; Sun et al., 2019). Governments are also constantly strengthening their supervision, hoping to guide upstream and downstream enterprises of the green supply chain to reduce emissions and improve social benefits through macro-control. The research framework is shown in Figure 3, followed by a statement of the corresponding assumptions:

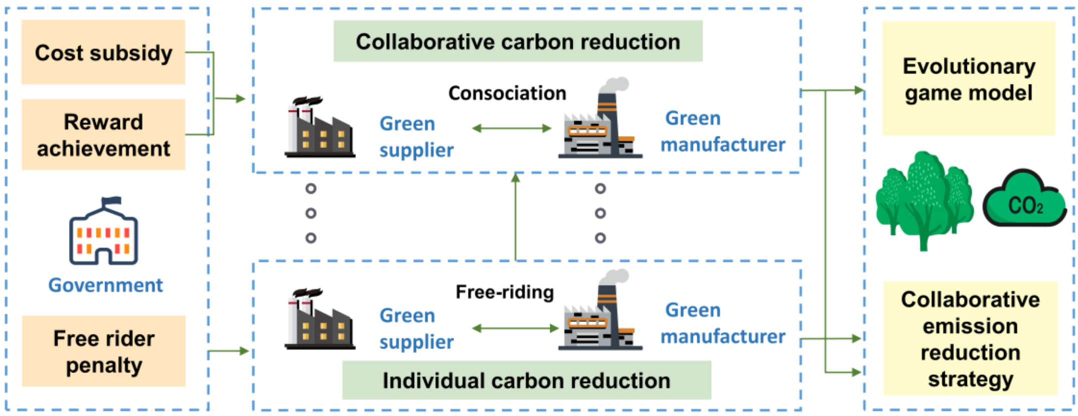


Figure 3. Analytical framework for carbon reduction by upstream and downstream enterprises in green supply chains under government regulation

(1) If neither the green supplier nor the green manufacturer is willing to carry out coordinated emission reduction in respect to the product provided by the green supply chain, the unit product carbon footprint has not changed, the low-carbon level of the product has not been significantly improved, and consumers will not pay higher prices. At this time the income of the green supplier and the manufacturer are v_1 and v_2 respectively.

(2) When only one of the green supplier or green manufacturer hopes to break through the existing green level to reduce carbon emissions through measures such as new technology research and development, process optimization, the party that does not carry out coordinated emission reduction will nonetheless get shared benefits, and thus a "free rider" effect (Guo et al., 2020; Ke et al., 2021; Liu et al., 2020). This is because consumers want to buy more green products, and both parties in the supply chain will benefit from this. It is assumed that the green

supplier and manufacturer who carry out coordinated emission reduction, that is, increase the low-carbon input, obtain the benefits respectively as $(1+\lambda)v_1,(1+\mu)v_2,\lambda>\mu$,where λ,μ is the rate of increase in revenue, and the shared benefit for the party that does not invest in low-carbon emission reduction is $k_i(i=1,2)$.

(3) When both green suppliers and green manufacturers have reached a cooperative willingness to reduce emissions, they have both contribute to reducing carbon dioxide emissions across the supply chain, thereby enhancing the green competitiveness of their products and consumers' desire to buy. At this time, the green supplier and green manufacturer's collaborative emission reduction input cost is $c_i(i=1,2)$, the added benefit is w_1,w_2, and $w_1>\lambda v_1, w_2>\mu v_2$.

(4) In order to encourage the green supply chain game, the government wants to support collaborative emission reduction, and thus subsidizes $\alpha c_i(i=1,2)$ the costs incurred by relevant enterprises when adopting collaborative emission reduction strategies, in which $\alpha\in[0,1]$ is the strength of government subsidies. When the green supply chain members play a leading role in low-carbon environmental protection, sustainable development and social responsibility to create social benefits, the collaborative emission reduction results that meet the conditions are rewarded βb, where b is the reward base set by the government, β is the social benefit coefficient, and the reward is obtained according to the distribution coefficient $\eta\in[0,1]$ distributed between green suppliers and green manufacturers. At the same time, the government will impose a fine of md on the "free rider" party. $m\in[0,1]$ is the government supervision coefficient and d is the maximum fine. If neither party chooses collaborative emission reduction, they will not be punished. Therefore, the payment matrix of both parties in the game of green supply chain members under government regulation is obtained, as shown in Table 1.

Table 1. Payout matrix of both parties in the game

		Green manufacturer	
		Coordinated emission reduction	Uncoordinated emission reduction
Green Supplier	Coordinated emission reduction	$v_1-c_1+w_1+\alpha c_1+\eta\beta b$, $v_2-c_2+w_2+\alpha c_2+(1-\eta)\beta b$	$(1+\lambda)v_1-c_1$, v_2+k_2-md
	Uncoordinated emission reduction	v_1+k_1-md , $(1+\mu)v_2-c_2$	v_1 , v_2

3. Evolutionary game analysis of collaborative emission reductions by enterprises

3.1. Equilibrium point analysis of the evolution process

Assume that the proportion of members of the upstream green supplier group who choose the coordinated emission reduction strategy is x, and the proportion of members who choose the non-coordinated emission reduction strategy is $1-x$. At the same time, the proportion of the members of the downstream green manufacturer group who choose the cooperative emission reduction strategy is y, and the proportion of the members who choose non-coordinated emission reduction is $1-y$. And the proportion of members $x,y\in[0,1]$ is a function of time t.

At this time, the benefits of the collaborative and non-collaborative emission reduction strategies selected by the green supplier group are as follows:

$$\pi_{s1} = y(v_1 - c_1 + w_1 + \alpha c_1 + \eta\beta b) + (1-y)[(1+\lambda)v_1 - c_1] \tag{1}$$

$$\pi_{s2} = y(v_1 + k_1 - md) + (1-y)v_1 \tag{2}$$

The average expected benefit of the green supplier group is:

$$\overline{\pi_s} = x\pi_{s1} + (1-x)\pi_{s2} \tag{3}$$

According to evolutionary game theory, the replication dynamic equation of the green supplier group is obtained by:

$$\begin{aligned} F(x) &= dx/dt = x(\pi_{s1} - \overline{\pi_s}) = x(1-x)(\pi_{s1} - \pi_{s2}) \\ &= x(1-x)[y(w_1 + \alpha c_1 + \eta\beta b + md - k_1 - \lambda v_1) + \lambda v_1 - c_1] \end{aligned} \tag{4}$$

And, the coordinated emission reduction, non-coordinated emission reduction and expected benefit function of the green manufacturer group are:

$$\pi_{m1} = x[v_2 - c_2 + w_2 + \alpha c_2 + (1-\eta)\beta b] + (1-x)[(1+\mu)v_2 - c_2] \tag{5}$$

$$\pi_{m2} = x(v_2 + k_2 - md) + (1-x)v_2 \tag{6}$$

$$\overline{\pi_m} = y\pi_{m1} + (1-y)\pi_{m2} \tag{7}$$

In the same way, the dynamic replication equation of the green manufacturer group is obtained by:

$$\begin{aligned} F(y) &= dy/dt = y(\pi_{m1} - \overline{\pi_m}) = y(1-y)(\pi_{m1} - \pi_{m2}) \\ &= y(1-y)[x(w_2 + \alpha c_2 + (1-\eta)\beta b + md - \mu v_2 - k_2) + \mu v_2 - c_2] \end{aligned} \tag{8}$$

The two-dimensional dynamic system of green suppliers and manufacturers under government regulation is obtained from equations (4) and (8)

$$\begin{cases} F(x) = x(1-x)[y(w_1 + \alpha c_1 + \eta\beta b + md - k_1 - \lambda v_1) + \lambda v_1 - c_1] \\ F(y) = y(1-y)[x(w_2 + \alpha c_2 + (1-\eta)\beta b + md - \mu v_2 - k_2) + \mu v_2 - c_2] \end{cases} \tag{9}$$

Let equation group $F(x)=0$ and $F(y)=0$, hence we can obtain $x=0,1$ or $x = \dfrac{c_2 - \mu v_2}{w_2 + \alpha c_2 + (1-\eta)\beta b + md - \mu v_2 - k_2}$, indicating that the proportion of collaborative emission reduction cooperation with downstream suppliers in the green supplier group is stable. When $y=0,1$ or $y = \dfrac{c_1 - \lambda v_1}{w_1 + \alpha c_1 + \eta\beta b + md - k_1 - \lambda v_1}$, it indicates that the proportion of collaborative emission reduction cooperation with upstream suppliers in the green manufacturer group is stable. That is, five local equilibrium points $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ and (x^*, y^*) of the evolutionary game model are obtained.

3.2. Stability analysis of equilibrium

According to Friedman's discriminant method, the equilibrium point obtained above is not necessarily the evolutionary stable strategy of the system. Instead, the stable collaborative emission reduction strategy of green suppliers and manufacturers based on government regulation can be obtained by judging the local stability of the Jacobian matrix of the system; that is, the local equilibrium point satisfying condition $\det(J)>0$, $tr(J)<0$ is the evolutionary stability strategy (ESS) of the system. We find the partial derivative with respect to the equation system (9) to obtain the following Jacobian matrix:

$$J=\begin{bmatrix}(1-2x)[y(w_1+\alpha c_1+\eta\beta b+md-k_1-\lambda v_1)+\lambda v_1-c_1] & x(1-x)(w_1+\alpha c_1+\eta\beta b+md-k_1-\lambda v_1)\\ y(1-y)[w_2+\alpha c_2+(1-\eta)\beta b+md-\mu v_2-k_2] & (1-2y)[x(w_2+\alpha c_2+(1-\eta)\beta b+md-\mu v_2-k_2)+\mu v_2-c_2]\end{bmatrix} \quad (10)$$

Table 2. The value of the determinant and trace of each equilibrium point

point	det(J)	tr(J)
(0,0)	$(\lambda v_1-c_1)(\mu v_2-c_2)$	$(\lambda v_1-c_1)+(\mu v_2-c_2)$
(0,1)	$-(w_1+\eta\beta b+md+\alpha c_1-c_1-k_1)(\mu v_2-c_2)$	$(w_1+\eta\beta b+md+\alpha c_1-c_1-k_1)-(\mu v_2-c_2)$
(1,0)	$-(\lambda v_1-c_1)[w_2+(1-\eta)\beta b+md+\alpha c_2-c_2-k_2]$	$-(\lambda v_1-c_1)+[w_2+(1-\eta)\beta b+md+\alpha c_2-c_2-k_2]$
(1,1)	$(w_1+\eta\beta b+md+\alpha c_1-c_1-k_1)\times$ $[w_2+(1-\eta)\beta b+md+\alpha c_2-c_2-k_2]$	$-(w_1+\eta\beta b+md+\alpha c_1-c_1-k_1)-$ $[w_2+(1-\eta)\beta b+md+\alpha c_2-c_2-k_2]$
(x^*,y^*)	—	0

Theorem 1: The government participates in the coordinated emission reduction game between upstream and downstream companies in the green supply chain through incentives, cost subsidies, and fines. This means that different reward bases and supervision efforts will have an impact on stable evolution strategies. At the same time, changes in parameters, such as the benefits arising to green suppliers and green manufacturers from cooperative emission reduction, their respective free-riding benefits, and emission reduction input costs will also change the results of the system evolution game. The details are as follows:

(1) When $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$, $\lambda>\frac{c_1}{v_1}$, $w_2+(\eta-1)\beta b+\alpha c_2>c_2+k_2-md$, $\mu>\frac{c_2}{v_2}$ the evolutionary stable strategy of the system is (T, T).

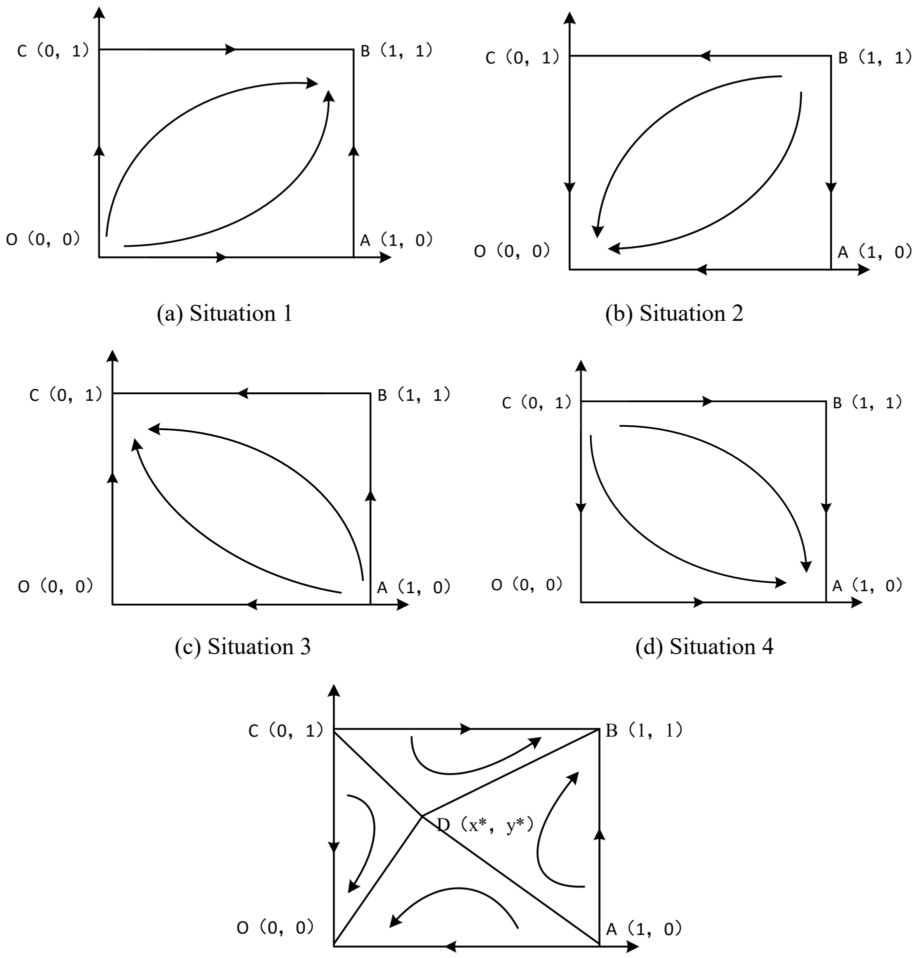
(2) When $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$, $0<\lambda<\frac{c_1}{v_1}$, $w_2+(\eta-1)\beta b+\alpha c_2<c_2+k_2-md$, $0<\mu<\frac{c_2}{v_2}$ the evolutionary stable strategy of the system is (N,N).

(3) When $w_1+\eta\beta b+\alpha c_1<c_1+k_1-md$, $0<\lambda<\frac{c_1}{v_1}$, $w_2+(\eta-1)\beta b+\alpha c_2<c_2+k_2-md$, $\mu>\frac{c_2}{v_2}$ the evolutionary stable strategy of the system is (N,T).

(4) When $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$, $\lambda>\frac{c_1}{v_1}$, $w_2+(\eta-1)\beta b+\alpha c_2<c_2+k_2-md$, $\mu>\frac{c_2}{v_2}$ the evolutionary stable strategy of the system is (T,N).

(5) When $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$, $0<\lambda<\frac{c_1}{v_1}$, $w_2+(\eta-1)\beta b+\alpha c_2>c_2+k_2-md$, $0<\mu<\frac{c_2}{v_2}$ the evolutionary stable strategy of the system is (N,N) or (T,T).

Proof: bring in the value of the equilibrium point and judge the positive and negative symbols of the matrix determinant and trace values at each equilibrium point; get five typical evolutionary game processes of whether green suppliers and green manufacturers carry out collaborative emission reduction cooperation; and draw the game phase diagram, as shown in Figure 4.



(a) Situation 1

(b) Situation 2

(c) Situation 3

(d) Situation 4

(e) Situation 5

Figure 4. Phase diagram of the evolutionary game between the two parties of the system in different situations

3.3. Evolutionary game analysis

The following analysis results can be obtained from the above phase diagram:

(1) If the income from collaborative emission reduction by green suppliers and green manufacturers, plus the income from government subsidies and incentives for green supply chains, is greater than the difference between the input cost of collaborative emission reduction and the balance of the free rider income and penalty, i.e. $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$, $w_2+(\eta-1)\beta b+\alpha c_2>c_2+k_2-md$. At the same time, the income increase ratio of green suppliers and manufacturers for separate emission reductions is greater than the ratio of emission reduction input costs and income, that is, $\lambda>\frac{c_1}{v_1}$, $\mu>\frac{c_2}{v_2}$. As shown in Fig 4 (a), the carbon emission of the green supply chain is reduced and the income increases greatly. Finally, both sides of the game are willing to cooperate in emission reduction.

(2) If the government gives more support to upstream green suppliers by increasing cost subsidies and achievement incentives, i.e. $w_1+\eta\beta b+\alpha c_1>c_1+k_1-md$. Yet, on the other hand, the support for downstream retail is small and the free rider income is high, i.e. $w_2+(\eta-1)\beta b+\alpha c_2<c_2+k_2-md$, and at the same time, green suppliers and manufacturers

increase the income ratio after carbon emission reduction, that is, there is $0 < \lambda < \frac{c_1}{v_1}$, $0 < \mu < \frac{c_2}{v_2}$. As shown in Fig 4 (b), the evolutionarily stable point is (0,0). In this circumstance, neither upstream green suppliers nor downstream green manufacturers will choose a collaborative emission reduction strategy.

(3) If green suppliers and green manufacturers cooperate, the income from emission reductions will be less than the sum of the emission reduction input cost and free rider income, and the government does not give sufficient supervision to the emission reduction behavior of the green supply chain, that is, $w_1 + \eta\beta b + \alpha c_1 < c_1 + k_1 - md$, $w_2 + (\eta - 1)\beta b + \alpha c_2 < c_2 + k_2 - md$; Moreover, due to technical or management differences, the benefits of carbon emission reductions by green manufacturers alone will be greater than those by green suppliers alone, i.e. $0 < \lambda < \frac{c_1}{v_1}$, $\mu > \frac{c_2}{v_2}$. As shown in Fig 4 (c), in this event, the evolutionarily stable point of the system is (0,1): the upstream green suppliers will not choose collaborative emission reduction, and the downstream green manufacturers will choose collaborative emission reduction.

(4) If the increased income ratio of green suppliers or green manufacturers is greater than the ratio of input cost to original income, i.e. $\lambda > \frac{c_1}{v_1}$, $\mu > \frac{c_2}{v_2}$. At the same time, when the government focuses on supporting the emission reduction investment of upstream green suppliers and ignores the emission reduction efforts of green manufacturers, downstream enterprises get a higher "free ride" income, that is, $w_1 + \eta\beta b + \alpha c_1 > c_1 + k_1 - md$, $w_2 + (\eta - 1)\beta b + \alpha c_2 < c_2 + k_2 - md$. As shown in Fig 4 (d), in this circumstance, the evolutionarily stable point of the system is (1,0): the upstream green suppliers will carry out collaborative emission reductions, but the downstream green manufacturers will not.

(5) If green suppliers and green manufacturers meet the conditions of $w_1 + \eta\beta b + \alpha c_1 > c_1 + k_1 - md$, $w_2 + (\eta - 1)\beta b + \alpha c_2 > c_2 + k_2 - md$, it indicates that the benefits of enterprise collaborative emission reduction will be greater than the "free rider" benefits. At the same time, the increase in the green suppliers and green manufacturers income from emission reductions alone will be less than the ratio of input cost to original income, i.e. $0 < \lambda < \frac{c_1}{v_1}, 0 < \mu < \frac{c_2}{v_2}$. As shown in Fig 4 (e), in this circumstance, the evolutionarily stable points of the system are (1,1), (0,0). Both upstream green suppliers and downstream green manufacturers carry out collaborative emission reduction or do not carry out collaborative emission reduction. The specific choice of which path converges to which equilibrium point is related to the payment matrix and the initial state of the system.

Analyzing the situation in Fig 4 (e) further, no matter what the initial decision of the two parties in the game is, after a long-term game, they will evolve towards the equilibrium point of (1,1) and (0,0). If we record the area of the quadrilateral $OADC$ as H_1 and the area of quadrilateral $ABCD$ as H_2 it is found that the final strategy chosen by the two parties in the game is related to the relative size of H_1 and H_2. When $H_1 > H_2$, the probability of the system converging to (0,0) is greater than the probability of converging to (1,1). On the contrary, when $H_1 < H_2$, the probability of the system converging to (1,1) is greater than the probability of converging to (0,0).

$$H_1=\frac{1}{2}(x^*+y^*)=\frac{1}{2}(\frac{c_2-\mu v_2}{w_2+\alpha c_2+(1-\eta)\beta b+md-\mu v_2-k_2}+\frac{c_1-\lambda v_1}{w_1+\alpha c_1+\eta\beta b+md-k_1-\lambda v_1}) \quad (11)$$

Theorem 2: As green suppliers and green manufacturers increase the input cost of coordinated emission reductions, the probability that the two sides of the game will not implement a cooperative emission reduction strategy increases.

Proof: Find the partial derivatives of c_1,c_2 in equation (11), and get $\frac{\partial H_1}{\partial c_1}=\frac{\eta\beta b+w_1+dm-k_1}{2(w_1-k_1+\alpha c_1+dm-\lambda v_1+\eta\beta b)^2}>0$, $\frac{\partial H_1}{\partial c_1}=\frac{w_2+dm-k_2-(\eta-1)\beta b}{2[k_2-w_2-\alpha c_2-dm+\mu v_2+(\eta-1)\beta b)]^2}>0$ .That is, H_1 is a monotonically increasing function of c_1,c_2. The larger c_1,c_2 is, the larger the area of the quadrilateral $OADC$ is, and the faster the system evolves to the (0,0) point. With the rise of technologies and concepts for smart manufacturing, energy saving and emission reductions, more and more traditional supply chains are turning to green supply chains. It cannot be ignored, however, that there are differences in productivity and environmental awareness between upstream and downstream members of the green supply chain. When the input cost is too large and the payback period is too long, the two sides of the game will reduce their willingness to cooperate in reducing emissions (Liu et al., 2020; Long et al., 2021).

Theorem 3: as the value of collaborative emission reduction income, w_1,w_1, of green suppliers and green manufacturers increases, the probability of both sides of the game choosing a collaborative emission reduction strategy increase.

Proof: Find the partial derivatives of w_1,w_1 in equation (11) and get $\frac{\partial H_1}{\partial w_1}=-\frac{c_1-\lambda v_1}{2(w_1-k_1+\alpha c_1+dm-\lambda v_1+\eta\beta b)^2}$. From the above assumptions, it is easy to know that $c_1-\lambda v>0$, $\frac{\partial H_1}{\partial w_1}<0$ and $\frac{\partial H_1}{\partial w_2}<0$ can be obtained in the same way. Therefore, H_1 is a monotonic decreasing function of w_1,w_1. The larger the w_1,w_1, the larger the area of the quadrilateral $ABCD$, and the faster the system evolves to the point (1,1). Compared with a company in the green supply chain that independently bears the cost of emission reductions, upstream and downstream companies carry out coordinated emission reduction to achieve cost sharing, which benefits the entire industry chain.

Theorem 4: As green suppliers or manufacturers increase the rate of unilateral carbon emission reduction revenue, and increase the original revenue of the enterprise without implementing any low-carbon strategy, the probability of both parties in the game choosing a coordinated emission reduction strategy will increase.

Proof: Find the partial derivative of λ,μ,v_1,v_2 in equation (11) to get $\frac{\partial H_1}{\partial\lambda}=-\frac{v_1(w_1+ac_1+dm+n\beta b-k_1-c_1)}{2(w_1-k_1+\alpha c_1+dm-\lambda v_1+\eta\beta b)^2}$, $\frac{\partial H_1}{\partial v_1}=-\frac{\lambda(w_1-k_1+\alpha c_1-c_1+dm+\eta\beta b)}{2(w_1-k_1+\alpha c_1+dm-\lambda v_1+\eta\beta b)^2}<0$. It is easy to know that $\frac{\partial H_1}{\partial\lambda}<0,\frac{\partial H_1}{\partial v_1}<0$ from the previous assumptions and Theorem 1. Similarly, we get $\frac{\partial H_1}{\partial\mu}<0,\frac{\partial H_1}{\partial v_2}<0$, that is, H_1 decreases with the increase of λ,μ,v_1,v_2, and the area $ABCD$ increases, the probability of the system evolving to the equilibrium point (1,1) increases.

Theorem 5: When one party in the game chooses to coordinate emission reductions and the other party chooses to "free ride", as the revenue of free riders increases, the probability that both green suppliers and green manufacturers will not perform coordinated emission reductions increases.

Proof: Finding the partial derivative of k_1, k_2, it is easy to get $\frac{\partial H_1}{\partial k_1} = \frac{c_1 - \lambda v_1}{2(w_1 - k_1 + \alpha c_1 + dm - \lambda v_1 + \eta \beta b)^2} > 0$. Similarly, knowing that $\frac{\partial H_1}{\partial k_2} > 0$, that is, the parameter k_1, k_2 and H_1 are positively correlated, the probability of the system evolving to the equilibrium point (0,0) increases. Given the speculative behavior of some companies in green supply chains, it is inevitable that appropriate government regulation (penalties, incentives) is needed to create a level playing field (Encarnacao et al., 2018).

Theorem 6: with the increase of government cost subsidies, incentive base, social welfare coefficient, supervision and fines; that is, where the government fully participates in the low-carbon transformation process of the green supply chain, the probability of collaborative emission reduction between upstream green suppliers and downstream green manufacturers increases.

Proof: Find the partial derivatives of $b, m, \eta, d, \alpha, \beta$ in equation (10) respectively, and get:

$$\frac{\partial H_1}{\partial b} = \frac{\beta(c_2 - \mu v_2)(\eta - 1)}{2[k_2 - w_2 - \alpha c_2 - dm + \mu v_2 + (\eta - 1)\beta b)]^2} - \frac{\beta \eta (c_1 - \lambda v_1)}{2(w_1 - k_1 + \alpha c_1 + dm - \lambda v_1 + \eta \beta b)^2},$$

$$\frac{\partial H_1}{\partial m} = -\frac{d(c_2 - \mu v_2)}{2[k_2 - w_2 - \alpha c_2 - dm + \mu v_2 + (\eta - 1)\beta b)]^2} - \frac{d(c_1 - \lambda v_1)}{2(w_1 - k_1 + \alpha c_1 + dm - \lambda v_1 + \eta \beta b)^2},$$

$$\frac{\partial H_1}{\partial \eta} = \frac{\beta b(c_2 - \mu v_2)}{2[k_2 - w_2 - \alpha c_2 - dm + \mu v_2 + (\eta - 1)\beta b)]^2} - \frac{\beta b(c_1 - \lambda v_1)}{2(w_1 - k_1 + \alpha c_1 + dm - \lambda v_1 + \eta \beta b)^2},$$

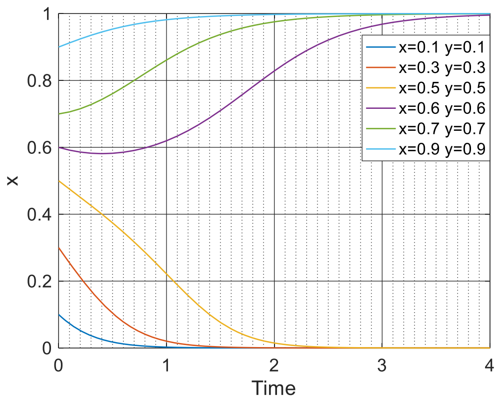
Because $\eta - 1 > 0$ it is easy to know that $\frac{\partial H_1}{\partial b} < 0$, $\frac{\partial H_1}{\partial m} < 0$, and $\frac{\partial H_1}{\partial d} < 0$, $\frac{\partial H_1}{\partial \alpha} < 0$. $\frac{\partial H_1}{\partial \beta} < 0$ can be obtained in the same way, that is, the parameter b, m, d, α, β is positively correlated with H_1, and the system moves toward the equilibrium point (1,1). The probability of evolution increases, and the influence of the reward distribution coefficient η needs to be discussed separately.

4. Case studies and numerical simulations

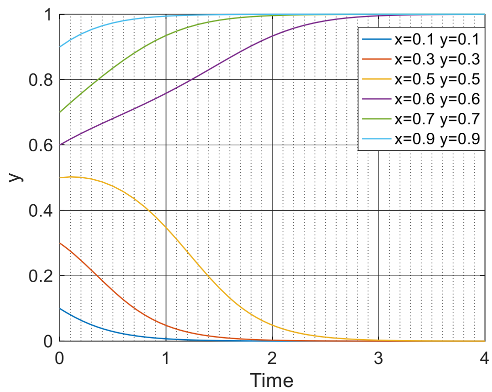
In order to further verify the effectiveness of the evolutionary game model, clarify the relationship between various influencing factors and system stability, and thus model the evolution of whether upstream green suppliers and downstream green manufacturers will choose a collaborative emission reduction strategy, MATLAB software is combined with examples to simulate and analyze the evolution trajectory of the equilibrium point in situation 5. Sinopec East China Petroleum Bureau, East China Oil and Gas Branch (referred to as East China Oil and Gas Field) and Sinopec Nanjing Chemical Industry Co., Ltd. (referred to as Nanhua Company) are taken as examples for the numerical simulation analysis. East China Oil and Gas Field is an upstream enterprise of Sinopec Group engaged in the exploration and development of unconventional oil and gas resources such as shale gas, shale oil, and coalbed methane, as well as conventional oil and gas exploration and development in the eastern part of the North Jiangsu Basin. Nanhua Company is an important downstream base for the research and development of inorganic chemicals, organic chemicals, fine chemicals, chemical machinery and catalysts for use by Sinopec Group. It is reported that the carbon capture, utilization and storage (CCUS) demonstration base jointly constructed by the two parties can capture more than100000 tons of carbon dioxide per year, while also helping upstream oilfields to increase production by about 50,000 tons. There is a plan to build a million-ton CCUS demonstration project in 2025. Assuming that East China Oil and Gas Field is the main body 1 (upstream green supplier) and Nanhua Company is the main body 2 (downstream green manufacturer), the local government will subsidize and reward CCUS projects and R&D products while monitoring their carbon emission levels. Referring to previous studies, and combining with the actual data for these projects, this paper tries to generalize the conclusion and assign values to each parameter: $w_1 = 3$, $w_2 = 5$, $c_1 = 6$, $c_2 = 6.5$, $k_1 = 2$, $k_2 = 2.5$, $v_1 = 10$, $v_2 = 12$, $\lambda = 0.2$, $\mu = 0.3$, $\alpha = 0.5$, $\beta = 1$, $b = 4$, $m = 0.5$, $d = 4$, $\eta = 0.5$.

4.1. The impact of the cooperation ratio of green supply chain members on the outcome of the evolutionary game

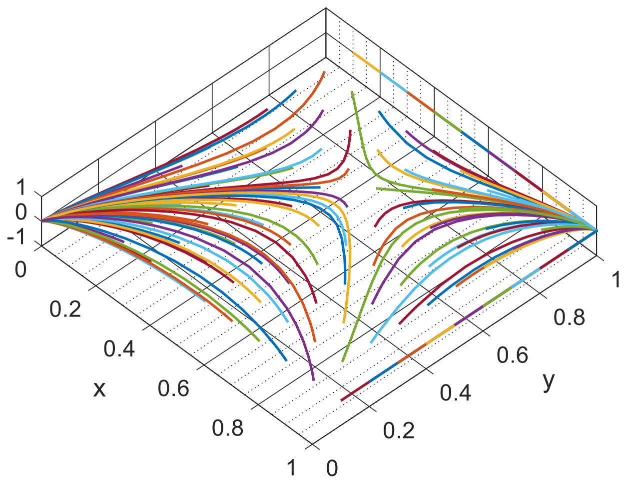
There are many green suppliers and green manufacturers in the green supply chain system. Due to the different proportion of members who initially choose collaborative emission reduction, the final evolution result of the system may be (collaborative emission reduction, collaborative emission reduction) or (non-collaborative emission reduction, non-collaborative emission reduction). Set the initial value of the participation proportion (x, y) as $(0.1,0.1),(0.3,0.3),(0.5,0.5),(0.7,0.7),(0.9,0.9)$ to obtain the relationship between t and x, y, as shown in Figure 5 (a) and Figure 5 (b); At the same time, set the step size as 0.1 to obtain the trajectory of the evolution from different initial value points to equilibrium points, as shown in Figure 5 (c).



(a) The evolution result of different initial values of x



(b) Evolution results of different initial values of y



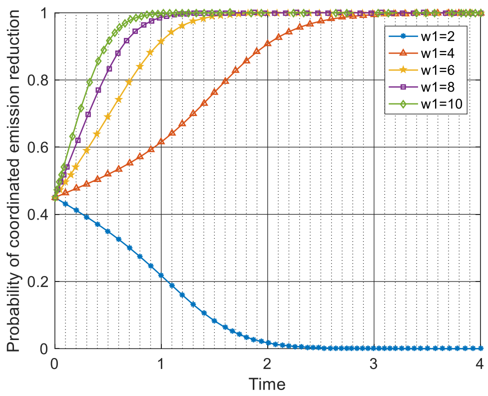
(c) Evolution results of different initial values of (x, y)

Figure 5. Dynamic evolution process of the cooperative emission reduction strategies of both parties in the game

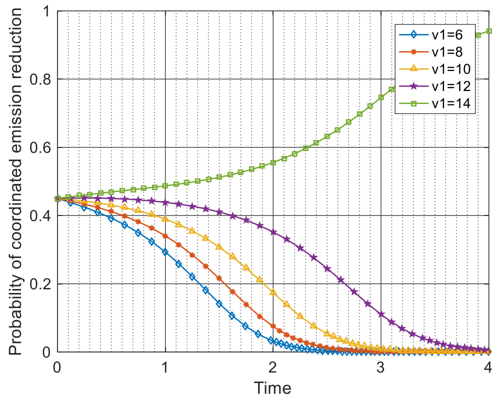
As can be seen from Figure 5, when the upstream green suppliers and downstream green manufacturers of the green supply chain carry out collaborative emission reductions, the income obtained is greater than the sum of "free rider" income and input cost. At the same time, when the green supplier or green manufacturer does not cooperate, and the rate of return is less than the cost, regardless of the proportion of green supply members who choose collaborative emission reduction at the beginning, the final game evolution result can only converge to (1,1) or (0,0). At this time, the value of saddle point D is about $(0.417, 0.666)$.Thus, it is verified that the stable strategy selected by both sides of the game is closely related to the initial value of (x, y). In this case, since there are only two entities involved, namely East China Oil and Gas Field and Nanhua Company, there is only a zero-sum game and a win-win situation. When there are multiple entities in the upstream and downstream of the supply chain, however, the higher the ratio of cooperation among members, the easier it is to form a multi-channel, multi-form and multi-level strategic alliance for coordinated emission reduction.

4.2. The influence of the internal parameters of the enterprise on the outcome of the evolutionary game

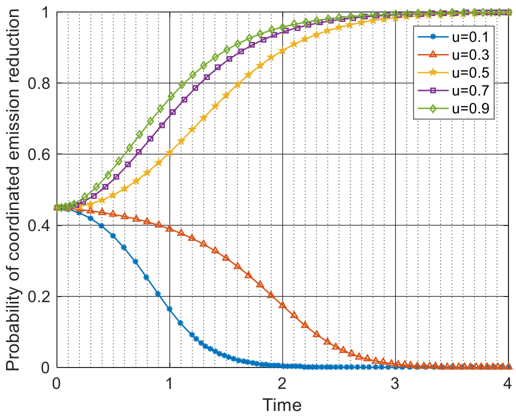
In the evolutionary game model between upstream and downstream enterprises in the green supply chain constructed above, the two parties need to take account of the game equilibrium strategy of other green suppliers and green manufacturers, as well as the government's attitude towards green supply chain enterprises' collaborative emission reduction. Therefore, sensitivity analysis of many influencing factors is needed. Firstly, consider the impact of the internal parameters of green supply chain enterprises on the results of the evolutionary game. Because the decisions of green suppliers and green manufacturers are consistent in situation 5, only the evolutionary direction of (1) the benefits to green suppliers of collaborative emission reductions, (2) the original benefits of enterprises, and (3) the increase ratio of the benefits arising from carbon emission reductions are simulated here. The results are shown in Fig 6.



(a) Benefits of collaborative emission reductions



（b）Original income

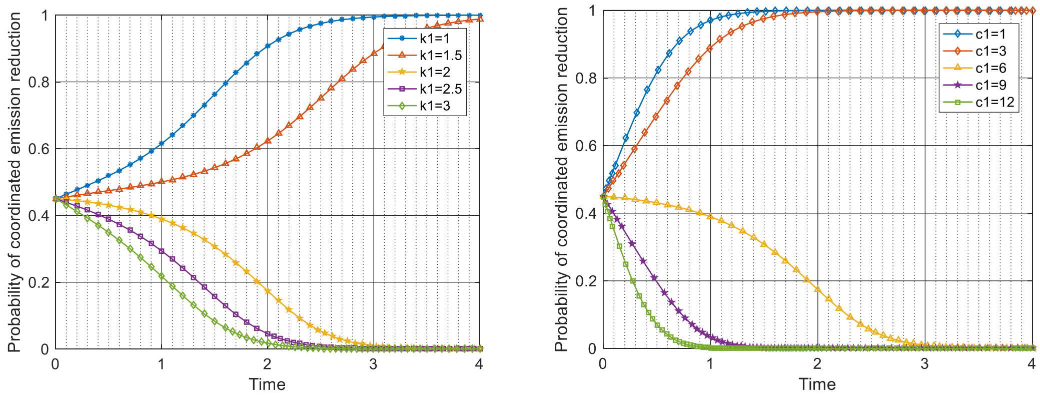


（c）Rate of increase in benefits from carbon emission reductions

Figure 6. The influence of parameter w_1, v_1, μ on the equilibrium probability (T,T)

The numerical simulation results in Figure 6 verify the conclusions of Theorem 3 and Theorem 4 in section 3. The rate of increase of benefits arising from collaborative emission reductions, original corporate benefits, and carbon emission reduction benefits is in each case positively correlated with the probability of the upstream and downstream members of the green supply chain choosing coordinated emission reduction. By comparing Figure 6 (a) and Figure 6 (b), it can be seen that the threshold at which collaborative emission reduction benefits start to affect the evolution game results is lower than the threshold in the case of the enterprise's original income. This is because the income obtained through collaborative emission reductions will not be higher than the income of the enterprise's original business, and the enterprise's high income is the premise and basis for increasing carbon emission reduction investment. At the same time, it can be seen that, in the early stage of evolution, the benefits of collaborative emission reduction will be (1,1) The convergence speed of the point is significantly higher than the original income of the enterprise, and the higher the value, the faster the evolution speed. As can be seen from Figure 6 (c), meanwhile, the threshold at which the rate of increase of the benefits from carbon emission reduction affects both sides of the game is between 0.3 and 0.5. A high income from carbon emission reductions will stimulate the willingness of enterprises to cooperate in collaborative emission reductions; that is, it will improve the probability of cooperation between upstream and downstream enterprises in the green supply chain. Low income from carbon emission reductions, however, encourages enterprises to abandon the collaborative emission reduction strategy.

Based on the position of the saddle point, it is consistent with the above assumption that $x = 0.45$, $y = 0.65$. Under the condition that other parameters remain unchanged, the value of "free rider" income k_1 for green suppliers is 1, 1.5, 2, 2.5, 3; the cost of coordinated emission reductions for for green suppliers, c_1, takes the value 1, 3, 6, 9, 12, and the simulation result is shown in Figure 7.



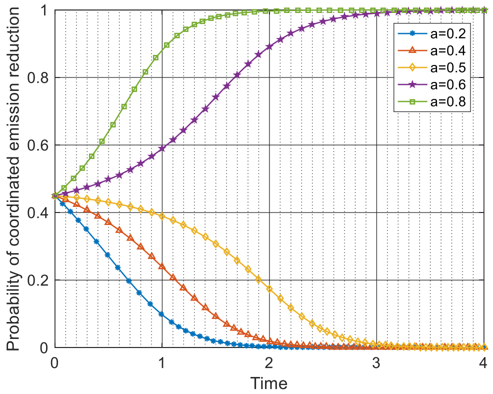
(a) "Free rider" income (b) Collaborative abatement costs

Figure 7. The influence of parameter k_1, c_1 on the equalization probability (N, N)

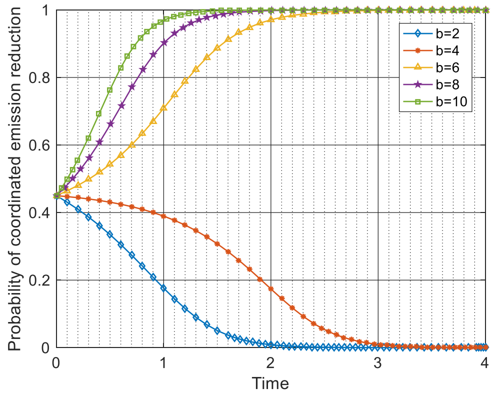
The simulation results in Figure 7 verify the conclusions of Theorem 2 and Theorem 5. It can be seen that with the increase of enterprise "free rider" income and collaborative emission reduction investment cost, the two sides of the game will evolve to point (0,0), and thus there will be no agreement on collaborative emission reduction. At the same time, the convergence rate of the effect of the input cost of collaborative emission reduction is greater than that of the "free rider" income, which shows that in the early stage of the game, green suppliers and green manufacturers are more sensitive to the input costs of collaborative emission reduction. By reducing the input cost of collaborative emission reduction, the probability of collaborative emission reduction in the green supply chain can be improved. Although the impact of reducing the "free rider" income on the evolution results is more long term, the "free rider" behavior of green supply chain members cannot be ignored. This implies that either enterprises will need to develop more internal consciousness of the need for emission reductions, or government macro-control will be needed to ensure fair competition, and stable strategic relationships for emission reduction in the green supply chain.

4.3. The influence of external (government control) parameters on the outcome of the evolutionary game

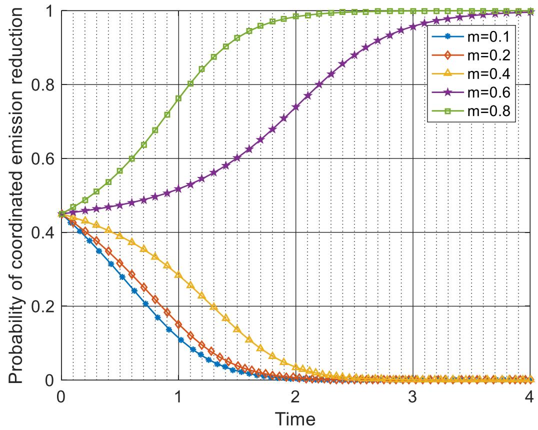
Government departments may influence the coordinated emission reduction mechanism between upstream and downstream enterprises in the green supply chain through financial subsidies, achievement rewards, and regulatory penalties. Under the condition that other parameters remain unchanged, the government subsidy coefficient, the reward base, and the supervision coefficient are here simulated and analyzed with different values. The simulation results are shown in Figure 8.



(a) Government subsidy coefficient



(b) Government rewards



(c) Government supervision coefficient

Figure 8. The influence of parameter α, b, m on the equalization probability (T,T)

The simulation results in Figure 8 verify the conclusion of Theorem 6. As the government subsidy coefficient, government incentive base, and government supervision coefficient increase, the probability that green suppliers and green manufacturers will eventually engage in coordinated emission reductions increases. The speed with which these forms of government influence lead to convergence to the point (1,1) varies, however. Specifically, government rewards lead to a slightly faster convergence than government subsidy coefficients and regulatory coefficients, especially when low-carbon technological innovations are rewarded with high results. In respect to supervision, and the punishment of “free riding” behavior, as can be seen from Figure 8 (c), a low level of supervision and small fines will not weaken the motivation of enterprises to reduce "free riding". Only supervision coefficients higher than the threshold, and fines higher than the "free riding" income will encourage green suppliers or green manufacturers who do not cooperate in emission reduction to do so. In short, diversified government control methods can not only better encourage coordinated emission reduction among green supply chain enterprises, but also have a strong binding force to prevent the rights and interests of any party in the game from being harmed.

5. Conclusions and policy implications

Based on the idea and method of evolutionary games, this paper constructs a dynamic game model of collaborative emission reduction between upstream and downstream enterprises in a green supply chain under government regulation. It analyzes the evolutionary stability of this collaboration, obtains five different evolutionary game strategies, and uses MATLAB software to simulate and verify the evolutionary path of the fifth case. The results show that:

(1) when the sum of collaborative emission reduction benefits and government subsidies is greater than the sum of collaborative emission reduction input costs and "free rider" benefits, and the rate of increase of benefits arising from unilateral emission reductions is less than the ratio of cost to original benefits, the system will only evolve to either (T, T) or (N, N) equilibrium.

(2) The ratio of the increase of income from collaborative emission reductions, enterprise original income and income from unilateral reduction in emissions influences the evolution of the system towards collaborative emission reduction. Increases in "free rider" income and the input costs of collaborative emission reductions increase the probability of green suppliers and green manufacturers choosing non-collaborative approaches to emission reductions, At the same time, in the early stage of the game, the higher the income and input costs of collaborative emission reductions, the faster the system converges. In the later stage of the game, however, the "free rider income" slows down the evolution trend of the system towards collaborative emission reductions.

(3) Increases in the coefficient of government subsidy, achievement reward, social benefit coefficient, supervision coefficient and fines, increase the probability of green suppliers and green manufacturers choosing collaborative emission reductions. The impact of the distribution coefficient, meanwhile, depends on the situation. At the same time, government regulation measures, based on the integration of financial subsidies, achievement rewards, supervision and punishment, have act as stronger incentives for upstream and downstream enterprises of the green supply chain to undertake collaborative emission reductions.

The above conclusions can give some enlightenment to regulators (governments) and participants (upstream and downstream enterprises of the supply chain) implementing collaborative emission reduction strategies:

(1) *Strengthen government supervision, and improve incentive and guidance mechanisms.* Firstly, based on the existing development strategy to promote collaborative emission reductions among upstream and downstream enterprises in the green supply chain, the green industry chain development plan and other documents, there is a need to formulate action guidelines for enterprise energy conservation and emission reduction activities, clarify the strategic objectives and industrial layout of upstream and downstream green industry chain development, and regularly release capacity scales, emissions quotas, green innovation technology patents and other information in order to guide enterprises' low-carbon investment decisions. Secondly, in response to the demand for green collaborative innovation behavior among upstream and downstream enterprises in the supply chain, there is a need for timely adjustment of existing financial subsidies, industrial support, introduction of high-level talent, green technology research and development and other policies to support the green industry supply chain, recognition of the key role of upstream enterprise technology and cost advantages in the green supply chain, and improvement of the green competitiveness of the entire supply chain and corporate profits. Finally, there is a need to improve the service function of the government to promote collaborative emission reduction of enterprises; strengthen the coordination and cooperation of various supporting policies and management measures, constantly improve the green industrial chain and management systems to promote the green innovation behavior of enterprises, standardize the government's behavior in policy releases, industrial regulation and market management, and create a fair environment for the market competition of upstream and downstream enterprises in the supply chain.

(2) *Stimulate the motivation of upstream and downstream enterprises in the green supply*

chain to coordinate emission reduction. When the upstream and downstream enterprises in the supply chain implement energy-saving and emission-reduction behaviors, they should not only consider their own development needs, but also the perspective of the sustainable development of the entire industrial chain, by building a collaborative emission reduction strategic alliance to reduce emission reduction input costs and increase the overall profit of the industrial chain and the green competitiveness of products. At the same time, when implementing coordinated emission reductions, upstream and downstream companies in the supply chain must combine their own advantages in the role of suppliers or manufacturers in the industry chain, actively cooperate with the government, and use green innovative technologies to develop preferential policies and platforms. In addition, under the background of economic and social construction, they need to invest actively in the national carbon emission trading market, use flexibly market means, save costs for enterprises in energy-saving and emission-reduction activities, and improve their green competitiveness and corporate profits.

(3) *Build a low-carbon industrial platform for resource sharing*. To promote collaborative emission reductions among upstream and downstream enterprises in the green supply chain, there is a need for resource sharing platform, led by the government but with participation from green enterprises, scientific research institutions and the public. The government needs to actively publicize low-carbon-related laws and regulations, and regularly publish the results of supervision and assessment of green enterprises, so as to provide convenient and up-to-date information for relevant enterprises, realize the openness, transparency and sharing of information, and reduce the cost of supervision. Green enterprises will rely on the platform to build an emission reduction cooperation system, announce the progress and phased achievements of emission reduction cooperation projects, and release information according to their own needs for talents, resources and technology. Various scientific research institutions dedicated to environmental protection and green technology innovation should regularly release the latest research and development projects to provide enterprises with more theoretical and technical support for collaborative emission reduction. The public should be able to obtain the latest green products of various enterprises and relevant data about government supervision and inspection online.

This paper has a number of shortcomings, such as a failure to take account of the risk attitude of enterprises, the market demand for green products and other factors affecting collaborative emission reductions of upstream and downstream enterprises in the green supply chain. Future work will address these limitations and go on to study the four-way evolutionary game of upstream and downstream green enterprises, governments and consumers.

CRediT authorship contribution statement

Zheng Liu: Conceptualization, Methodology, Resources, Writing - original draft, Supervision. **Qingshan Qian:** Investigation, Validation, Software, Formal analysis, Writing - original draft, Writing - review & editing. **Bin Hu:** Conceptualization, Methodology, Investigation. **Wen-Long Shang:** Investigation, Data curation, Writing - original draft, Supervision. **Lingling Li:** Investigation, Visualization, Writing - review & editing. **Yuanjun Zhao:** Investigation, Resources, Writing - review & editing. **Zhao Zhao:** Data curation, Writing - review & editing. **Chunjia Han:** Investigation, Writing - review & editing.

Acknowledgments

The finding is sponsored by the National Natural Science Foundation of China (Grant No.71901141), the soft science research project of Shanghai Science and Technology Committee (Grant No.21692195600, Grant No.22692104000), the Key Lab of Information Network Security of Ministry of Public Security (Grant No.C20609), Postdoctoral Research Foundation in China (Grant No.2021M690341), Municipal Key Curriculum Construction Project of University in Shanghai (Grant No. S202003002), and Shanghai Philosophy and Social Science Planning Project (Grant No.2020BGL007).

Conflict of interest

All authors declare no conflict of interest in this paper.

References

[1] Bi HB, Shang WL, Chen YY, Wang KZ, Yu Q, Sui Y, 2021. GIS aided sustainable urban road management with a unifying queueing and neural network model. Applied Energy. 291:15. https://doi.org/10.1016/j.apenergy.2021.116818.

[2] Zhang HR, Song X, Xia TQ, Yuan M, Fan ZP, Shibasaki R, et al, 2018. Battery electric vehicles in Japan: Human mobile behavior based adoption potential analysis and policy target response. Applied Energy. 220:527-35. https://doi.org/10.1016/j.apenergy.2018.03.105.

[3] Shang WL, Chen YY, Bi HB, Zhang HR, Ma CX, Ochieng WY, 2020. Statistical characteristics and community analysis of urban road networks. Complexity. 2020:21. https://doi.org/10.1155/2020/6025821.

[4] Yan YM, Zhang HR, Meng J, Long Y, Zhou XY, Li ZC, et al, 2019. Carbon footprint in building distributed energy system: An optimization-based feasibility analysis for potential emission reduction. Journal of Cleaner Production. 239:15. https://doi.org/10.1016/j.jclepro.2019.117990.

[5] Qiu R, Liao Q, Yan J, Yan YM, Guo ZC, Liang YT, et al, 2021. The coupling impact of subsystem interconnection and demand response on the distributed energy systems: A case study of the composite community in China. Energy. 228:19. https://doi.org/10.1016/j.energy.2021.120588.

[6] Xing XK, Yan YM, Zhang HR, Long Y, Wang YF, Liang YT, 2019. Optimal design of distributed energy systems for industrial parks under gas shortage based on augmented epsilon-constraint method. Journal of Cleaner Production. 218:782-95. https://doi.org/10.1016/j.jclepro.2019.02.052.

[7] Yuan M, Zhang HR, Long Y, Shen RH, Wang BH, Liang YT, 2019. Economic, energy-saving and carbon-abatement potential forecast of multiproduct pipelines: A case study in China. Journal of Cleaner Production. 211:1209-27. https://doi.org/10.1016/j.jclepro.2018.11.144.

[8] Wang L, Zheng J, 2019. Research on low-carbon diffusion considering the game among enterprises in the complex network context. Journal of Cleaner Production. 210:1-11. https://doi.org/10.1016/j.jclepro.2018.10.297.

[9] Zwickl-Bernhard S, Auer H, 2021. Open-source modeling of a low-carbon urban neighborhood with high shares of local renewable generation. Applied Energy. 282. https://doi.org/10.1016/j.apenergy.2020.116166.

[10] Waltho C, Elhedhli S, Gzara F, 2019. Green supply chain network design: A review focused on policy adoption and emission quantification. International Journal of Production Economics, 208(FEB.):305-318. https://doi.org/10.1016/j.ijpe.2018.12.003.
[11] Fahimnia B, Jabbarzadeh A, Sarkis J, 2018. Greening versus resilience: A supply chain design perspective. Transportation Research. 119(NOV.):129-148. https://doi.org/10.1016/j.tre.2018.09.005.
[12] Guo W, Liang L, 2021. Research on cooperative game of carbon emission reduction cost allocation in supply chain. Forecasting. 40(02): 83-89. http://dx.chinadoi.cn/10.11847/fj.40.2.83.
[13] Luo J, Song H, Yang X, et al, 2021. Research on information sharing of green services provided by manufacturers in competitive green supply chain. Chinese Journal of Management Science. 1-12.
[14] Han T, Liu L, Jin H, 2021. Research on dual-channel green supply chain decision-making considering government subsidies and fairness concerns. Chinese Journal of Management Science. 1-12. http://dx.chinadoi.cn/10.16381/j.cnki.issn1003-207x.2020.2364.
[15] Jamali M, Rasti-Barzoki M, 2018. A game theoretic approach for green and non-green product pricing in chain-to-chain competitive sustainable and regular dual-channel supply chains. Journal of Cleaner Production. 170(jan.1):1029-1043. https://doi.org/10.1016/j.jclepro.2017.09.181.
[16] Liu Z, Guo H, Zhao Y, Hu B, et al., 2021. Optimal pricing decision of composite service offered by network providers in e-commerce environment. Electronic Commerce Research. 22:77–193. https://doi.org/10.1007/s10660-021-09487-8.
[17] Madani S, Rasti-Barzoki M, 2017. Sustainable supply chain management with pricing, greening and governmental tariffs determining strategies: A game-theoretic approach. Computers & Industrial Engineering. 105(Complete):287-298. https://doi.org/10.1016/j.cie.2017.01.017.
[18] Ma W, Zhang R, Cheng Z, 2019. Analysis of internal and external funding mechanisms considering green consumer loyalty: A game-theoretic approach. IEEE Access. PP (99):1-1. https://doi.org/10.1109/ACCESS.2019.2962311.
[19] Jing Y, Meng Y, 2019. Research on coordination mechanism of dual channel green supply chain under free rider behavior. Industrial Engineering and Management. 24(05): 72-80. http://dx.chinadoi.cn/10.19495/j.cnki.1007-5429.2019.05.010.
[20] Wang BH, Liang YT, Zheng TC, Yuan M, Zhang HR, 2019. Optimisation of a downstream oil supply chain with new pipeline route planning. Chemical Engineering Research and Design. 145:300-13. https://doi.org/10.1016/j.cherd.2019.03.009.
[21] Zhou XY, Zhang HR, Xin SC, Yan YM, Long Y, Yuan M, et al, 2020. Future scenario of China's downstream oil supply chain: Low carbon-oriented optimization for the design of planned multi-product pipelines. Journal of Cleaner Production. 244:20. https://doi.org/10.1016/j.jclepro.2019.118866.
[22] Yang Z, Shang W, Zhang H, Garg H, Han C, 2022. Assessing the green distribution transformer manufacturing process using a cloud-based fuzzy multi-criteria framework. Applied Energy. 118687. https://doi.org/10.1016/j.apenergy.2022.118687.
[23] Shang W, Chen Y, Ochieng W, 2020. Resilience analysis of transport networks by combining variable message signs with agent-based day-to-day dynamic learning. IEEE ACCESS. https://doi.org/10.1109/ACCESS.2020.2999129.
[24] Shang W, Gao Z, Nicolo D, Long Y, Zhang H, Guo Z, Ochieng, W, 2022. Benchmark analysis

for robustness of multi-Scale urban road networks under global disruptions. IEEE Transactions on Intelligent Transportation Systems. https://doi.org/10.1109/TITS.2022.3149969.
[25] Springer C, Evans S, Lin J, Roland-Holst D, 2019. Low carbon growth in China: The role of emissions trading in a transitioning economy. Applied Energy. 235:1118-25. https://doi.org/10.1016/j.apenergy.2018.11.046.
[26] Lin B, Jia Z, 2019. Energy, economic and environmental impact of government fines in China's carbon trading scheme. Science of the Total Environment. 667:658-70. https://doi.org/10.1016/j.scitotenv.2019.02.405.
[27] Shen N, Liao H, Deng R, Wang Q, 2019. Different types of environmental regulations and the heterogeneous influence on the environmental total factor productivity: Empirical analysis of China's industry. Journal of Cleaner Production. 211:171-84. https://doi.org/10.1016/j.jclepro.2018.11.170.
[28] Ouyang X, Li Q, Du K, 2020. How does environmental regulation promote technological innovations in the industrial sector? Evidence from Chinese provincial panel data. Energy Policy. 139. https://doi.org/10.1016/j.enpol.2020.111310.
[29] Guo Q, Zhou M, Liu N, Wang Y, 2019. Spatial effects of environmental regulation and green credits on green technology innovation under low-carbon economy background conditions. International Journal of Environmental Research and Public Health. 16. https://doi.org/10.3390/ijerph16173027.
[30] Jiang K, You D, Merrill R, Li Z, 2019. Implementation of a multi-agent environmental regulation strategy under Chinese fiscal decentralization: An evolutionary game theoretical approach. Journal of Cleaner Production. 214:902-15. https://doi.org/10.1016/j.jclepro.2018.12.252.
[31] Tan R, Lin B, 2020. The influence of carbon tax on the ecological efficiency of China's energy intensive industries-A inter-fuel and inter-factor substitution perspective. Journal of Environmental Management. 261. https://doi.org/10.1016/j.jenvman.2020.110252.
[32] Axsen J, Ploetz P, Wolinetz M, 2020. Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport. Nature Climate Change. 10:809-18. https://doi.org/10.1038/s41558-020-0877-y.
[33] Shang WL, Chen JY, Bi HB, Sui Y, Chen YY, Yu HT, 2021. Impacts of COVID-19 pandemic on user behaviors and environmental benefits of bike sharing: A big-data analysis. Applied Energy. 285:14. https://doi.org/10.1016/j.apenergy.2020.116429.
[34] Shang WL, Chen YY, Li XG, Ochieng WY, 2020. Resilience analysis of urban road networks based on adaptive signal controls: Day-to-day traffic dynamics with deep reinforcement learning. Complexity. 2020:19. https://doi.org/10.1155/2020/8841317.
[35] Shang WL, Chen YY, Song CC, Ochieng WY, 2020. Robustness analysis of urban road networks from topological and operational perspectives. Mathematical Problems in Engineering. 2020:12. https://doi.org/10.1155/2020/5875803.
[36] He J, Lin B, 2019. Assessment of waste incineration power with considerations of subsidies and emissions in China. Energy Policy. 126:190-9. https://doi.org/10.1016/j.enpol.2018.11.025.
[37] Xu L, Wang C, Miao Z, Chen J, 2019. Governmental subsidy policies and supply chain decisions with carbon emission limit and consumer's environmental awareness. Rairo-Operations Research. 53:1675-89. https://doi.org/10.1051/ro/2018094.
[38] Li J, Wang L, Tan X, 2020. Sustainable design and optimization of coal supply chain network

under different carbon emission policies. Journal of Cleaner Production. 250. https://doi.org/10.1016/j.jclepro.2019.119548.
[39] Afzali SF, Cotton JS, Mahalec V, 2020. Urban community energy systems design under uncertainty for specified levels of carbon dioxide emissions. Applied Energy. 259. https://doi.org/10.1016/j.apenergy.2019.114084.
[40] Chen S, Long H, Chen B, Feng K, Hubacek K, 2020. Urban carbon footprints across scale: Important considerations for choosing system boundaries. Applied Energy. 259. https://doi.org/10.1016/j.apenergy.2019.114201.
[41] Zhao Z-Y, Gao L, Zuo J, 2019. How national policies facilitate low carbon city development: A China study. Journal of Cleaner Production. 234:743-54. https://doi.org/10.1016/j.jclepro.2019.06.116.
[42] Liu Z, Lang L, Li L, Zhao Y, Shi L, 2021. Evolutionary game analysis on the recycling strategy of household medical device enterprises under government dynamic rewards and punishments. Mathematical Biosciences and Engineering. 18(5): 6434-6451. https://doi.org/10.3934/mbe.2021320.
[43] Shao B, Hu L, 2021. Evolutionary game analysis of green supply chain participation behavior -- from the perspective of system dynamics. Science Research Management. 09:1-11. http://dx.chinadoi.cn/10.19571/j.cnki.1000-2995.2021.11.020.
[44] Xu Y, Cheng L, Zheng Y, 2019. Research on evolutionary game of product green investment in secondary green supply chain. Journal of Harbin University of Commerce (Social Science Edition), 000(006):29-39.
[45] Zhu C, Zhang J, 2021. Evolutionary game analysis of reverse supply chain cooperation based on government participation. Statistics & Decision. 37(18): 180-184. http://dx.chinadoi.cn/10.13546/j.cnki.tjyjc.2021.18.041.
[46] Tang H, 2019. Research on the game between government and enterprises in green supply chain under the background of low-carbon economy -- Based on the goal of enterprise independent emission reduction. Modern Economic Science. 41(06): 108-119.
[47] Huang D, Li S, Wu Y, et al, 2021. Study on Symbiosis between green buildings and Traditional Buildings Considering game payment and limited market capacity. Chinese Journal of Management Science. 29(08): 94-105. http://dx.chinadoi.cn/10.16381/j.cnki.issn1003-207x.2019.0224.
[48] Dong L, Fan R, 2021. Optimal regulatory strategy and optimal boundary problem of government low carbon subsidies. China Population, Resources and Environment. 31(08): 13-22.
[49] Chen Y, Wang Z, Zhong Z, 2019. CO2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in China. Renewable Energy. 131:208-16. https://doi.org/10.1016/j.renene.2018.07.047.
[50] Kim Hanh N, Kakinaka M, 2019. Renewable energy consumption, carbon emissions, and development stages: Some evidence from panel cointegration analysis. Renewable Energy. 132:1049-57. https://doi.org/10.1016/j.renene.2018.08.069.
[51] Tan X, Lai H, Gu B, Zeng Y, Li H, 2018. Carbon emission and abatement potential outlook in China's building sector through 2050. Energy Policy. 118:429-439. https://doi.org/10.1016/j.enpol.2018.03.072.
[52] Zhu J, Sun H, Zhou D, Peng L, Sun C, 2020. Carbon emission efficiency of thermal power in different regions of China and spatial correlations. Mitigation and Adaptation Strategies for Global Change. 25:1221-1242. https://doi.org/10.1007/s11027-019-09901-5.

[53] Xu S-C, He Z-X, Long R-Y, 2014. Factors that influence carbon emissions due to energy consumption in China: Decomposition analysis using LMDI. Applied Energy. 127:182-193.https://doi.org/10.1016/j.apenergy.2014.03.093
[54] Long R, Shao T, Chen H, 2016. Spatial econometric analysis of China's province-level industrial carbon productivity and its influencing factors. Applied Energy. 166:210-9. https://doi.org/10.1016/j.apenergy.2015.09.100.
[55] Yu F, Yang Y, Chang D, 2018. Carbon footprint based green supplier selection under dynamic environment. Journal of Cleaner Production. 170:880-889. https://doi.org/10.1016/j.jclepro.2017.09.165.
[56] Ma X, Wang C, Dong B, Gu G, Chen R, Li Y, et al, 2019. Carbon emissions from energy consumption in China: Its measurement and driving factors. Science of the Total Environment. 648:1411-1420. https://doi.org/10.1016/j.scitotenv.2018.08.183.
[57] Memari A, Ahmad R, Rahim ARA, Jokar MRA, 2018. An optimization study of a palm oil-based regional bio-energy supply chain under carbon pricing and trading policies. Clean Technologies and Environmental Policy. 20:113-125.https://doi.org/10.1007/s10098-017-1461-7.
[58] Chen J, Wang P, Cui L, Huang S, Song M, 2018. Decomposition and decoupling analysis of CO2 emissions in OECD. Applied Energy. 231:937-50. https://doi.org/10.1016/j.apenergy.2018.09.179.
[59] Zhang X, Loeschel A, Lewis J, Zhang D, Yan J, 2020. Emissions trading systems for global low carbon energy and economic transformation. Applied Energy. 279. https://doi.org/10.1016/j.apenergy.2020.115858.
[60] Pathak U, Kant R, Shankar R, 2020. Analytics of cap-and-trade policy for dual supply chain network structures. Clean Technologies and Environmental Policy. 22:1999-2021. https://doi.org/10.1007/s10098-020-01937-5.
[61] Peng H, Pang T, Cong J, 2018. Coordination contracts for a supply chain with yield uncertainty and low-carbon preference. Journal of Cleaner Production. 205:291-302. https://doi.org/10.1016/j.jclepro.2018.09.038.
[62] Safarzadeh S, Rasti-Barzoki M, 2019. A game theoretic approach for assessing residential energy-efficiency program considering rebound, consumer behavior, and government policies. Applied Energy. 233:44-61. https://doi.org/10.1016/j.apenergy.2018.10.032.
[63] Hedayati M, Brock PM, Nachimuthu G, Schwenke G, 2019. Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: An Australian perspective. Journal of Cleaner Production. 212:974-85. https://doi.org/10.1016/j.jclepro.2018.11.190.
[64] Zhong H, Hu Z, Yip TL, 2019. Carbon emissions reduction in China's container terminals: Optimal strategy formulation and the influence of carbon emissions trading. Journal of Cleaner Production. 219:518-530. https://doi.org/10.1016/j.jclepro.2019.02.074.
[65] Zappa W, Junginger M, van den Broek M, 2019. Is a 100% renewable European power system feasible by 2050? Applied Energy. 233:1027-1050. https://doi.org/10.1016/j.apenergy.2018.08.109.
[66] Zu Y, Chen L, Fan Y, 2018. Research on low-carbon strategies in supply chain with environmental regulations based on differential game. Journal of Cleaner Production. 177:527-546. https://doi.org/10.1016/j.jclepro.2017.12.220.
[67] Le Quere C, Jackson RB, Jones MW, Smith AJP, Abernethy S, Andrew RM, et al, 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nature Climate Change. 10:647-+. https://doi.org/10.1038/s41558-020-0797-x.

[68] Wang X, Zhu Y, Sun H, Jia F, 2018. Production decisions of new and remanufactured products: Implications for low carbon emission economy. Journal of Cleaner Production. 171:1225-1243. https://doi.org/10.1016/j.jclepro.2017.10.053.

[69] Wang Z, Hu S, Zhang B, Wang B, 2018. Optimizing cooperative carbon emission reduction among enterprises with non-equivalent relationships subject to carbon taxation. Journal of Cleaner Production. 172:552-565.https://doi.org/10.1016/j.jclepro.2017.10.196.

[70] Zhang S, Wang C, Yu C, 2019. The evolutionary game analysis and simulation with system dynamics of manufacturer's emissions abatement behavior under cap-and-trade regulation. Applied Mathematics and Computation. 355:343-55. https://doi.org/10.1016/j.amc.2019.02.080.

[71] Zhang Z, Xue Y, Li J, Gong L, Wang L, 2020. Supply chain logistics information collaboration strategy based on evolutionary game theory. IEEE Access. 8:46102-20. https://doi.org/10.1109/access.2020.2978943.

[72] Chen W, Hu Z-H, 2018. Using evolutionary game theory to study governments and manufacturers' behavioral strategies under various carbon taxes and subsidies. Journal of Cleaner Production. 201:123-41. https://doi.org/10.1016/j.jclepro.2018.08.007.

[73] Sun H, Wan Y, Zhang L, Zhou Z, 2019. Evolutionary game of the green investment in a two-echelon supply chain under a government subsidy mechanism. Journal of Cleaner Production. 235:1315-26. https://doi.org/10.1016/j.jclepro.2019.06.329.

[74] Guo J, Zhou Y, Li B, 2020. The optimal pricing and service strategies of a dual-channel retailer under free riding. Journal of Industrial and Management Optimization. https://doi.org/10.3934/jimo.2021056.

[75] Ke H, Jiang Y, 2021. Equilibrium analysis of marketing strategies in supply chain with marketing efforts induced demand considering free riding. Soft Computing. 25:2103-14. https://doi.org/10.1007/s00500-020-05281-0.

[76] Liu C, Dan Y, Dan B, Xu G, 2020. Cooperative strategy for a dual-channel supply chain with the influence of free-riding customers. Electronic Commerce Research and Applications. 43. https://doi.org/10.1016/j.elerap.2020.101001.

[77] Liu L, Zhu Y, Guo S, 2020. The evolutionary game analysis of multiple stakeholders in the low-carbon agricultural innovation diffusion. Complexity. 2020. https://doi.org/10.1155/2020/6309545.

[78] Long Q, Tao X, Shi Y, Zhang S, 2021. Evolutionary game analysis among three green-sensitive parties in green supply chains. IEEE Transactions on Evolutionary Computation. 25:508-23. https://doi.org/10.1109/tevc.2021.3052173.

[79] Encarnacao S, Santos FP, Santos FC, Blass V, Pacheco JM, Portugali J, 2018. Paths to the adoption of electric vehicles: An evolutionary game theoretical approach. Transportation Research Part B-Methodological. 113:24-33. https://doi.org/10.1016/j.trb.2018.05.002.