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Evolutionary game analysis of low-carbon behavior credit supervision of logistics enterprises

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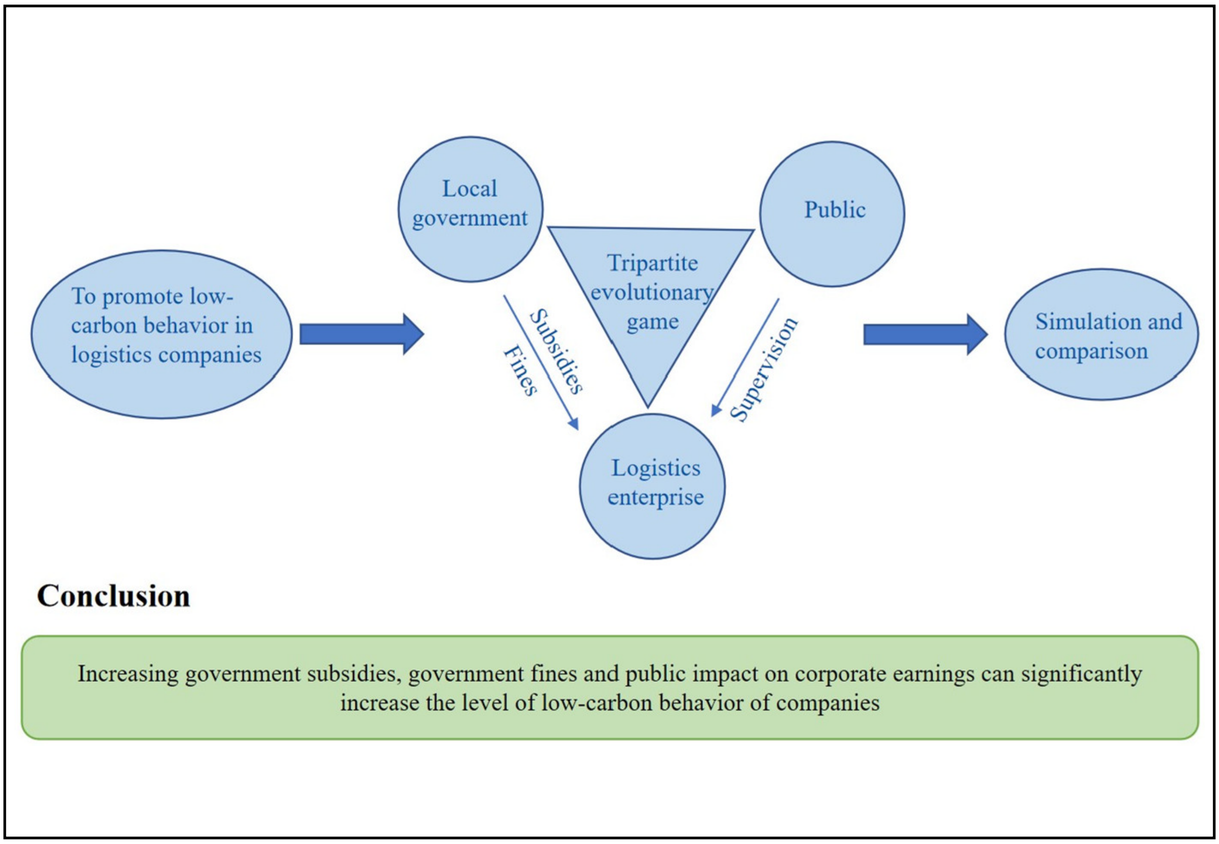
Graphical abstract



Research methods and conclusions based on evolutionary game model.

Public summary

- Reducing government costs can significantly promote the low-carbon behavior of logistics enterprises, while reducing public costs is counterproductive.
- Increasing the low-carbon subsidy of local governments to logistics enterprises has the best effect, and increasing the punishment of higher-level governments to local governments has the worst effect.
- The effect of increasing the public's impact on the income of enterprises is the best, and the effect of increasing the government's subsidy to the public is the worst.

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Abstract: Based on the low-carbon obligation fulfillment of Chinese logistics enterprises, this study constructs a tripartite evolutionary game model to analyze the evolutionary process of the interaction between the local government, logistics enterprises and the public in the process of low-carbon behavior credit supervision. Then using Netlogo software, a parameter simulation experiment is conducted to determine the optimal policy for improving the effect of supervision. The results are as follows: ① The combined influence of the local government and the public can effectively change the strategic choice of enterprises and promote the low-carbon behavior of enterprises. ② In terms of improving the effect of supervision, reducing the cost of government supervision would have a highly significant effect, and reducing the cost of the public would be counterproductive. ③ Increasing the government subsidies to enterprises and the government's fines to enterprises both have a significant effect, and the effect of improving the former is better. However, increasing the severity of higher-level governments punishing local governments will reduce the stability of the system. ④ Supervision can be more effective by increasing the public's impact on enterprises' earnings rather than by increasing government subsidies to the public.

Keywords: low-carbon behavior; logistics enterprises; collaborative governance; evolutionary game

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1 Introduction

The 2009 Copenhagen World Climate Conference, which advocated for green environmental protection, ushered humankind into a new era of "low energy consumption, low pollution, and low emissions". Logistics is an indispensable high-end service industry, and it is imperative that it becomes more dedicated to low-carbon development. According to the National Bureau of Statistics, in 2014 alone, approximately 363 million tons of standard coal was consumed in the transportation, storage and postal industries, and it took only five years for energy consumption to rise from 363 million tons of standard coal to 439 million tons of standard coal. Meanwhile, according to data released by Greenpeace, the global environmental organization, in 2020 alone, the national consumption of express packaging materials reached an astonishing 40 million tons. If it is not controlled, it is expected to reach 41.2705 million tons by 2025. China's logistics market has become the world's largest, and the continuous growth of energy consumption will inevitably result in a large amount of carbon emissions.

However, many logistics companies lack a sense of social responsibility, and their awareness of low-carbon environmental protection is low. To maximize profits and avoid high transportation costs, fuel-guzzling vehicles are often selected for transportation. In the express packaging industry, most companies still use non-degradable materials such as plastics, which release large amounts of greenhouse gases during the decomposition process, and pollution to the atmosphere cannot be ignored. To reduce the carbon emissions of the logistics industry at the source, we must promote low-carbon transportation and packaging.

Several studies have been conducted on the transportation mode of logistics enterprises and carbon emissions. Yang et al.[1] and Ma et al.[2] found that in the transportation industry, more than half of the carbon emissions are caused by the road transportation of trucks. Therefore, it is important to promote cargo transportation among logistics enterprises to implement low-carbon reform as soon as possible to alleviate climate deterioration. Using the logarithmic mean Divisia index decomposition method, Li and Zan[3] found that transportation volume, transportation energy structure, energy consumption intensity, and carbon emission intensity are the main factors affecting transportation carbon emissions, and accordingly provided relevant policy suggestions. Through measurement equations and parameter estimation, Wang and Shen[4] found that electricity can replace gasoline, diesel, and other energy sources, and reduce the dependence on fossil energy in the logistics industry. Using system dynamics, Yang[5] found that the development of new energy technologies and the use of new energy vehicles to replace traditional fuel-consuming vehicles can promote low-carbon development among logistics enterprises.

Several studies have examined low-carbon aspects of pack-

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aging for logistics enterprises. Through research on plastic products, Royer et al.[6] found that plastics not only cause considerable white pollution, but also produce high amounts of carbon emissions during the process of decomposition, increasing air pollution. Zhai[7] demonstrated that the promotion of green packaging can reduce the pollution of plastic packaging from the source. Qu et al.[8] researched the data and found that there are problems such as excessive packaging, low carbon levels of express packaging materials, and the high cost of low-carbon packaging. They recommend that express companies learn advanced packaging technology and actively carry out low-carbon emission reduction. Yang and Pan[9] suggested that it is necessary to promote sustainable development in the express packaging industry and strengthen government supervision and governance.

Research has also been conducted on how to promote low-carbon behavior among logistics enterprises. First, as the makers of low-carbon policy and the governors of carbon emission behavior, local governments both supervise and regulate a carbon emission behavior of logistics enterprises, and encourage changes in that behavior. Li et al.[10] constructed a collaborative network combining the government and the market, and proposed suggestions such as strengthening coordination and guidance, effectively controlling constraints, and insisting on innovation and leadership. Van Dender[11] believe that low-carbon technologies should be widely used in transportation, and government investment and firm commitment to emission reduction policies are important conditions for creating technologies. In recent years, some scholars have used game theory to study the low-carbon game behavior of the government and enterprises. Yang and Xu[12] studied the evolutionary game behavior of the government and logistics enterprises under the carbon tax policy and analyzed the different effects of the adjustment of the carbon tax rate on the evolution of the system strategy. Yu and Chen[13] incorporated the government and consumers into a tripartite evolutionary game model to promote corporate green innovation and mainly analyzed the development of the gradual stability of corporate green innovation diffusion. The tripartite evolutionary game model constructed by Lu and Zhang[14] found that the government's research and development and construction efforts affect the strategic choices of logistics enterprises.

Second, the public, as a stakeholder of consumers and the environment, plays an indispensable role in monitoring the low-carbon behavior of enterprises through public opinion. Cai[15] studied the impact of external pressure on the green management behavior of logistics enterprises and found that the public should reasonably exert the influence of public opinion and cultivate energy-saving awareness. Du et al.[16] and Chen et al.[17] found that with the effective participation of the public, corporate environment and environmental governance can be significantly improved. Fu and Geng[18] demonstrated that public participation significantly affects the development of green technology in enterprises. Deng et al.[19] demonstrated that enhancing public awareness of environmental protection would enhance public low-carbon consumption preference.

Third, the credit supervision system in the context of collaborative governance is an important model that reflects the country's modern governance capabilities and integrated governance system. Ren[20] believed that accelerating the low-carbon transformation of the logistics industry is an important part of the development of the national economy, and it is a mission and task that should be shouldered by the government and the whole society. Wang and Guo[21] found that the collaborative governance model and the credit system construction are complementary to each other. They suggest that a new market supervision mechanism that strengthens information sharing and information sharing can be built with credit supervision as the core. Zhang et al.[22] suggested that the establishment of comprehensive and multi-dimensional assessment indicators, giving full play to the supervision power of the public and the third party of the media, can effectively restrain government and enterprises from collusion.

In sum, there are relatively few studies on the tripartite strategic behavior game between the government, logistics enterprises, and the public in the relevant literature, and most existing studies analyze the role of the public as a consumer rather than as a supervisor. Therefore, this study incorporated the government as a regulator and the public as a supervisor into an evolutionary game study to analyze the evolutionary stability of the three parties. Then, NetLogo software was used to simulate the game, show the game interaction of each subject from a micro perspective, discuss the promotion of external regulatory forces on the low-carbon behavior of enterprises, and provide corresponding policy suggestions on the effectiveness of supervision.

2 Game mechanism

The current phenomenon suggests that, driven by a sense of social responsibility, the logistics industry has begun to realize the importance of carbon emission reduction. In recent years, some logistics companies have made progress in low-carbon packaging and transportation. However, under the price-led market mechanism, low-carbon packaging and transportation not only make companies pay high low-carbon costs but also prevent companies from gaining more market share by raising prices. This not only reduces the enthusiasm of enterprises for low-carbon behavior but also increases the possibility of enterprises engaging in fraudulent low-carbon behavior to meet government regulations. Because of the lack of internal motivation for low-carbon behavior, enterprises must be restrained by external forces. As the promulgator and advocate of low-carbon policies, the government is duty-bound to promote low-carbon behavior among logistics enterprises. As the most direct beneficiary of the low-carbon environment, the public must also supervise this behavior of logistics enterprises. Based on the above background, this study designed a game mechanism of the government, enterprises, and the public as follows:

① Under the strong supervision of local governments, the central government will increase supervision and invest more human, material, and financial support. At the same time, the carbon emissions of logistics enterprises are included in the assessment indicators, and fines are imposed for excessive emissions of greenhouse gases caused by the non-low-carbon behavior of logistics enterprises. Under weak supervision, the

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government relaxes the supervision of carbon emissions of logistics enterprises, and mainly implements policies based on subsidies to encourage and guide logistics enterprises to engage in low-carbon behavior.

② Participation in the supervision by the public positively impacts the low-carbon behavior of enterprises, and improving the green reputation of enterprises creates more business opportunities for them. There is a negative impact on the consequences of high-carbon emissions caused by the non-low-carbon behavior of enterprises, reducing the green reputation of enterprises, thereby reducing the business opportunities of enterprises.

③ The government and the public share similar demands with regard to restraining the low-carbon behavior of enterprises. In principle, government supervision and public participation can play a joint role in restraining the low-carbon behavior of enterprises. The government encourages and rewards the public for its participation in the supervision of the low-carbon behavior of logistics enterprises. At the same time, to enhance the coordinated supervision of the local government and the public, the higher-level government supervises the local government and punishes the local government when there is a dereliction of duty. The game mechanism is shown in Fig. 1.

3 Model assumptions and model building

3.1 Model assumptions

According to the aforementioned game mechanism, five assumptions are made as follows.

Hypothesis 1. The strategic space of the local government is strong supervision/weak supervision. The strategic space of logistics enterprises is low-carbon behavior/non-low-carbon behavior. The strategic space of the public is participation/non-participation. Local governments, logistics enterprises and the public are all bounded rational subjects, and they carry out strategy learning and strategy improvement according to their own interests in the process of the game.

Hypothesis 2. The company's own operating income is R_E. Enterprises can save low-carbon costs C_E by implementing non-low-carbon behavior strategies, but they may be subject to government fines P_E and the public's negative impact ΔP on corporate earnings. Enterprises will pay low-carbon behavior costs C_E when implementing low-carbon behavior strategies, and will also receive low-carbon subsidies A from the government and the positive impact ΔP of the public on enterprise income.

Hypothesis 3. When local governments implement weak supervision strategies, they only need to provide low-carbon subsidies A to enterprises, but they are likely to be punished by higher-level governments on the grounds of poor supervision, and the punishment is P_G. The strong supervision strategy of local government entities should not only provide low-carbon subsidies A to enterprises but also incentive subsidies H to the public participating in supervision. At the same time, it has to pay the cost of supervision C_G, but in the case of low-carbon behavior of enterprises, political gains R_G are obtained.

Hypothesis 4. When the public does not participate in the supervision, there are mainly environmental gains and losses, namely environmental gains R_M and environmental losses P_M. When the public participates in the supervision, the low-carbon behavior of enterprises will bring additional environmental benefits ΔM to the public, and the public will also receive incentive subsidies H from local governments.

Hypothesis 5. Assuming R_G, R_E, R_M, C_G, C_E, C_M, P_G, P_E, P_M, A, H, ΔP, $\Delta M > 0$, $0 \leqslant \alpha, \beta, \lambda, \mu, \theta \leqslant 1$. Among them, α indicates the subsidy intensity of the local government for low-carbon behavior of enterprises, β indicates the public's influence intensity on the company's earnings, λ indicates the difficulty coefficient of enterprises in low-carbon behavior, μ indicates the punishment intensity imposed by the higher-level government on the local government, and θ indicates the fine intensity of the local government for non-low-carbon behavior of enterprises. The parameters are shown in Table 1.

3.2 Model building

For the local government, the strong supervision strategy is selected with the probability of x, and the weak supervision strategy is selected with the probability of $1-x$. For logistics enterprises, the low-carbon behavior strategy is selected with the probability of y, and the non-low-carbon behavior strategy is selected with the probability of $1-y$. For the public, the participation strategy is selected with the probability of z, and the non-participation strategy is selected with the probability

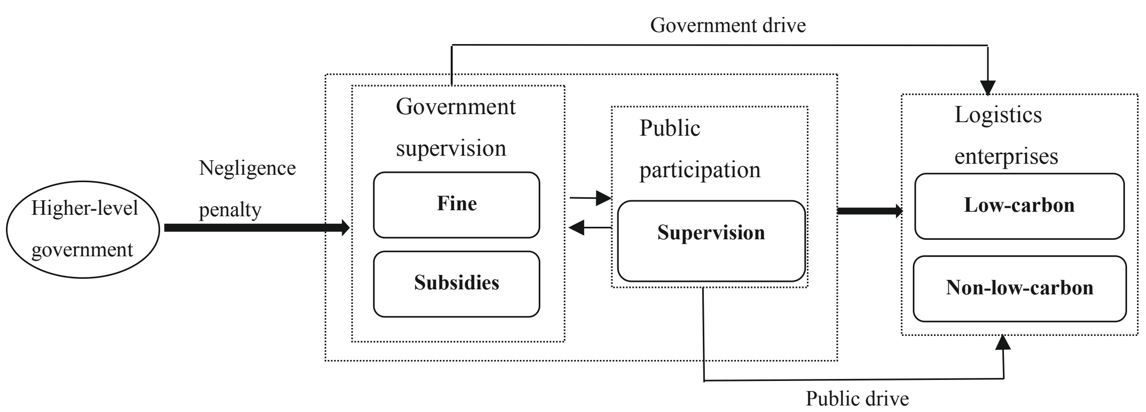

Fig. 1. Game interaction mechanism among the three parties.

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Table 1. Main parameters and definitions.

Parameter	Definition	Parameter	Definition
R_G	Government's political benefits	A	Government's subsidies for logistics enterprises
R_E	Logistics enterprise's own business income	H	Government's subsidies for public participation
R_M	Public environmental benefits	ΔP	The impact of public on logistics enterprises
C_G	Government regulatory cost	ΔM	Public extra low carbon benefits
C_E	Low-carbon behavior cost of logistics enterprises	α	The intensity of government's low-carbon subsides
C_M	Public supervision cost	β	The public's influence intensity on the enterprises
P_G	The higher-level government penalty for local governments	λ	The difficulty coefficient of enterprises in low-carbon behavior
P_E	Government fines on logistics enterprises	μ	The punishment intensity of the higher-level government
P_M	Public environmental loss	θ	The government's fine intensity of enterprises

Table 2. Three-party evolution game payment matrix.

Public non-participation						
Local government	Low-carbon behavior			Non-low-carbon behavior		
	Government	Enterprise	Public	Government	Enterprise	Public
Strong supervision	$R_G-C_G-\alpha A$	$R_E-\lambda C_E+\alpha A$	R_M	$-C_G+\theta P_E$	$R_E-\theta P_E$	$-P_M$
Weak supervision	$-\alpha A$	$R_E-\lambda C_E+\alpha A$	R_M	$-\mu P_G$	R_E	$-P_M$
Public participation						
Local government	Low-carbon behavior			Non-low-carbon behavior		
	Government	Enterprise	Public	Government	Enterprise	Public
Strong supervision	$R_G-C_G-\alpha A-H$	$R_E-\lambda C_E+\alpha A+\beta\Delta P$	$R_M-C_M+\Delta M+H$	$-C_G+\theta P_E-H$	$R_E-\theta P_E-\beta\Delta P$	$-C_M-P_M+H$
Weak supervision	$-\alpha A$	$R_E-\lambda C_E+\alpha A+\beta\Delta P$	$R_M-C_M+\Delta M$	$-\mu P_G$	$R_E-\beta\Delta P$	$-C_M-P_M$

of $1-z$. Here, x, y, and z are all functions of time t. Table 2 presents the game payment matrix of local governments, logistics enterprises and the public, according to the assumptions and parameters.

4 Solving and analyzing the model

4.1 Game equilibrium analysis of local government

The expected return of strong government supervision is U_{x1}, the expected return of weak supervision is U_{x2}, and the average return is $\overline{U}_x$:

$$U_{x1}=y[z(R_G-C_G-\alpha A-H)+(1-z)(R_G-C_G-\alpha A)]+(1-y)[z(-C_G+\theta P_E-H)+(1-z)(-C_G+\theta P_E)], \quad (1)$$

$$U_{x2}=y[z(-\alpha A)+(1-z)(-\alpha A)]+(1-y)[z(-\mu P_G)+(1-z)(-\mu P_G)], \quad (2)$$

$$\overline{U}_x=xU_{x1}+(1-x)U_{x2}. \quad (3)$$

The replication dynamic equation for constructing the government's "strong supervision" strategy $F(x)$ is as follows:

$$F(x)=\frac{\mathrm{d}x}{\mathrm{d}t}=x(U_{x1}-\overline{U}_x)=x(1-x)[-C_G-zH+yR_G+(1-y)(\theta P_E+\mu P_G)]. \quad (4)$$

Derive $F(x)$ to obtain:

$$\frac{\mathrm{d}F(x)}{\mathrm{d}x}=(1-2x)[-C_G-zH+yR_G+(1-y)(\theta P_E+\mu P_G)]. \quad (5)$$

Let $y_0=\dfrac{C_G+zH-\theta P_E-\mu P_G}{R_G-\theta P_E-\mu P_G}$. When $y=y_0$, $F(x)\equiv 0$, indicating that the government's strategic choice at this time does not change over time. When $y\neq y_0$, get $x=0$ and $x=1$ are two possible ESS (evolutionarily stable strategy); only when

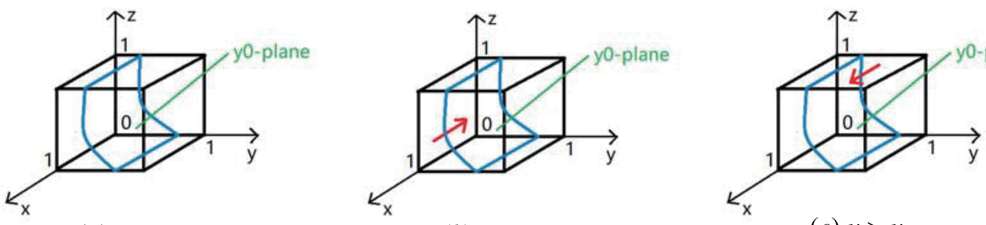

Fig. 2. Local government behavior dynamic evolution trend.

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$\frac{\mathrm{d}F(x)}{\mathrm{d}x}<0$, the point is the ESS of the game system. When $y<y_0$, $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=0}<0$ and $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=1}>0$, $x=0$ is the ESS. When $y>y_0$, $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=0}>0$ and $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=1}<0$, $x=1$ is the ESS. According to the above analysis, the three-dimensional dynamic evolution trend of the government can be obtained, as shown in Fig. 2.

The equilibrium analysis of the evolutionary game of the local government revealed that when C_G decreases and R_G increase, y_0 decreases. This indicates that the lower the costs the government pays in the process of strong supervision, the greater the performance benefits obtained, and the more the government is inclined to implement the strategy of strong supervision. The larger the z is, and the greater the y_0 is. This indicates that the government is more inclined to implement a strategy of weak supervision. It can be seen that public participation can share part of the government's supervision responsibility. When H increase, y_0 also increase. The government's subsidies to the public have a certain impact on the government's income. The increase in public subsidies will make the government more inclined to implement the weak supervision strategy with low cost.

4.2 Game equilibrium analysis of logistics enterprises

The expected benefit of low-carbon behavior of enterprises is U_{y1}, the expected benefit of non-low-carbon behavior is U_{y2}, and the average benefit is $\overline{U}_y$:

$$\begin{aligned}U_{y1}=&x[z(R_E-\lambda C_E+\alpha A+\beta\Delta P)+(1-z)(R_E-\lambda C_E+\alpha A)]+\\&(1-x)[z(R_E-\lambda C_E+\alpha A+\beta\Delta P)+(1-z)(R_E-C_E+\alpha A)],\end{aligned}\tag{6}$$

$$\begin{aligned}U_{y2}=&x[z(R_E-\theta P_E-\beta\Delta P)+(1-z)(R_E-\theta P_E)]+\\&(1-x)[z(R_E-\beta\Delta P)+(1-z)(R_E)],\end{aligned}\tag{7}$$

$$\overline{U}_y=yU_{y1}+(1-y)U_{y2}.\tag{8}$$

The replication dynamic equation for constructing the "low-carbon behavior" strategy of logistics enterprises $F(z)$ is as follows:

$$\begin{aligned}F(y)=&\frac{\mathrm{d}y}{\mathrm{d}t}=y(U_{y1}-\overline{U}_y)=\\&y(1-y)(-\lambda C_E+\alpha A+2z\beta\Delta P+x\theta P_E).\end{aligned}\tag{9}$$

Derive $F(z)$ to obtain:

$$\frac{\mathrm{d}F(y)}{\mathrm{d}y}=(1-2y)[-\lambda C_E+\alpha A+2z\beta\Delta P+x\theta P_E].\tag{10}$$

Let $z_0=\frac{\lambda C_E-\alpha A-x\theta P_E}{2\beta\Delta P}$. When $z=z_0$, $F(y)\equiv 0$, indicating that the strategic choice of logistics enterprises at this time does not change with time. When $z<z_0$, $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=0}<0$ and $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=1}>0$, $y=0$ is the ESS. When $z>z_0$, $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=1}<0$ and $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=0}>0$, $y=1$ is the ESS. According to the above analysis, the three-dimensional dynamic evolution trend of logistics enterprises can be obtained, as shown in Fig. 3.

The evolutionary game equilibrium analysis of logistics enterprises revealed that decreasing C_E, increasing A, increasing P_E, and increasing ΔP all cause z_0 to decrease. It can be seen that increasing the benefits of low-carbon behaviors of enterprises and increasing the losses of non-low-carbon behaviors of enterprises will increase the willingness of enterprises to engage in low-carbon and trustworthy behavior. When x increases, z_0 decreases. That is, logistics companies tend to implement low-carbon behavior strategies. This suggests that the government's supervision directly impacts the strategic choice of enterprises, and the government's increased supervision can urge enterprises to choose low-carbon behavior strategies.

4.3 Public game equilibrium analysis

The expected benefit of public participation is U_{z1}, the expected benefit of non-participation is U_{z2}, and the average benefit is $\overline{U}_z$:

$$\begin{aligned}U_{z1}=&x[y(R_M-C_M+\Delta M+H)+(1-y)(-C_M-P_M+H)]+\\&(1-x)[y(R_M-C_M+\Delta M)+(1-y)(-C_M-P_M)],\end{aligned}\tag{11}$$

$$\begin{aligned}U_{z2}=&x[y(R_M)+(1-y)(-P_M)]+\\&(1-x)[y(R_M)+(1-y)(-P_M)],\end{aligned}\tag{12}$$

$$\overline{U}_z=zU_{z1}+(1-z)U_{z2}.\tag{13}$$

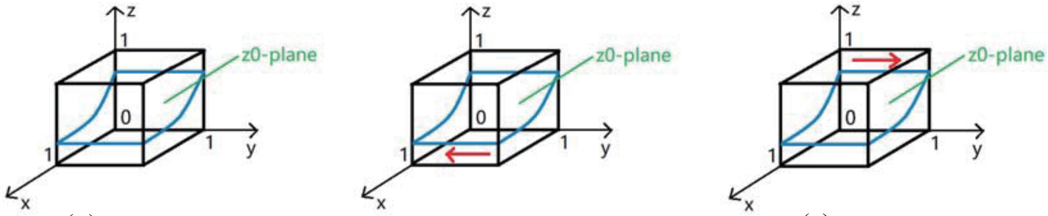
The replication dynamics equation for constructing the public "participation" strategy $F(z)$ is as follows:

$$F(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=z(U_{z1}-\overline{U}_z)=z(1-z)(-C_M+y\Delta M+xH).\tag{14}$$

Derive $F(z)$ to obtain:

$$\frac{\mathrm{d}F(z)}{\mathrm{d}z}=(1-2z)(-C_M+y\Delta M+xH).\tag{15}$$

Let $x_0=\frac{C_M-y\Delta M}{H}$. When $x=x_0$, $F(z)\equiv 0$, indicating that



(a) $z=z_0$ (b) $z<z_0$ (c) $z>z_0$

Fig. 3. Logistics enterprise behavior dynamic evolution trend.

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the public's strategy choice at this time does not change with time. When $x < x_0$, $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=0} < 0$ and $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=1} > 0$, $z = 0$ is the ESS. When $x > x_0$, $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=1} < 0$ and $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=0} > 0$, $z = 1$ is the ESS. According to the above analysis, the three-dimensional dynamic evolution trend of the public can be obtained, as shown in Fig. 4.

The equilibrium analysis of the evolutionary game of the public revealed that decreasing C_M, increasing H and increasing ΔM all cause x_0 to decrease. This indicates that the greater the subsidies and benefits obtained from public participation, the smaller the supervision cost, and the more the public is inclined to participate in the supervision of the carbon emissions behavior of logistics enterprises. When y increases, z_0 decreases. That is, the public is more inclined to participate in the supervision. This suggests that the choice of low-carbon behavior strategies by enterprises positively impacts the benefits of public participation. The more actively enterprises implement low-carbon behavior strategies, the more willing the public is to participate in the supervision.

4.4 Equilibrium analysis of the tripartite evolutionary system

The previous section mainly analyzes the respective critical conditions and stable equilibrium points of the evolution strategies of the three parties, and the following mainly analyzes the evolutionary stability strategies and equilibrium points under the joint action of the three parties. According to the previous analysis results, the dynamic system of the three-party evolutionary game can be obtained as follows:

$$\begin{cases} F(x)=\dfrac{\mathrm{d}x}{\mathrm{d}t}=x(1-x)[-C_G-zH+yR_G+(1-y)(\theta P_E+\mu P_G)], \\ F(y)=\dfrac{\mathrm{d}y}{\mathrm{d}t}=y(1-y)(-\lambda C_E+\alpha A+2z\beta\Delta P+x\theta P_E), \\ F(z)=\dfrac{\mathrm{d}z}{\mathrm{d}t}=z(1-z)(-C_M+y\Delta M+xH). \end{cases} \tag{16}$$

Simultaneously $F(x)=0$, $F(y)=0$, $F(z)=0$, the pure-strategy equilibrium solutions of the system are obtained as $E_1(0,0,0)$, $E_2(0,0,1)$, $E_3(0,1,0)$, $E_4(1,0,0)$, $E_5(0,1,1)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_8(1,1,1)$, respectively. According Ref. [23], analyzing the Jacobian matrix of each equilibrium point can judge the local stability of the system equilibrium point. Calculate the Jacobian matrix of the system, as shown in Eq. (17).

$$J=\begin{pmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial z} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{pmatrix}=$$

$$\begin{pmatrix} (1-2x)[-C_G-zH+yR_G+(1-y)(\theta P_E+\mu P_G)] & x(1-x)(R_G-\theta P_E+\mu P_G) & -x(1-x)H \\ y(1-y)\theta P_E & (1-2y)(-\lambda C_E+\alpha A+2z\beta\Delta P+x\theta P_E) & y(1-y)(2\beta\Delta P) \\ z(1-z)H & z(1-z)\Delta M & (1-2z)(-C_M+y\Delta M+xH) \end{pmatrix}. \tag{17}$$

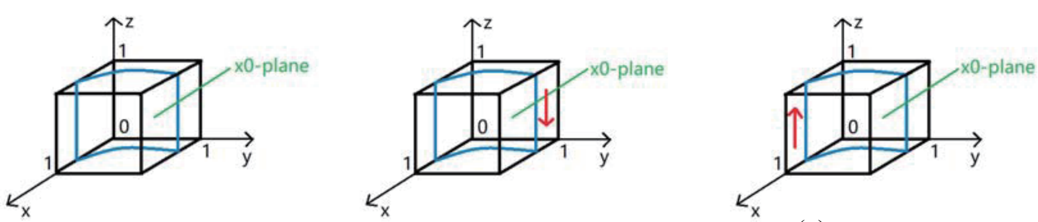
According to Lyapunov's first law, the criterion for judging the stability of an equilibrium point in an evolutionary game system is as follow: When the eigenvalues of the Jacobian matrix of the equilibrium point are all negative, the equilibrium point is the system's ESS, and the corresponding strategy is the evolutionary stability strategy of the system. According to this, eight equilibrium points are brought into the Jacobian matrix, and the eigenvalues and stability conditions of the eight equilibrium points are calculated, as shown in Table 3.

According to the different stability conditions, the evolution stability of the equilibrium point is analyzed as follows.

① When $C_G > \theta P_E + \mu P_G, \lambda C_E > \alpha A$, $E_1(0,0,0)$ is the ESS. It corresponds to the strategic combination of (weak supervision, non-low-carbon behavior, non-participation). This situation is extremely unfavorable to the low-carbon credit supervision of enterprises and should be avoided.

② When $C_G > R_G, \lambda C_E < \alpha A, C_M > \Delta M$, $E_3(0,1,0)$ is the ESS. It corresponds to the strategic combination of (weak supervision, low-carbon behavior, non-participation). This situation is a situation in which low-carbon behavior credit supervision is very mature and complete.

③ When $C_G < \theta P_E + \mu P_G, \lambda C_E > \alpha A + \theta P_E, C_M > H$, $E_4(1,0,0)$



(a) $x = x_0$ (b) $x < x_0$ (c) $x > x_0$

Fig. 4. Public behavior dynamic evolution trend.

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Table 3. Eigenvalues and stability conditions of each equilibrium point.

Equilibrium	Eigenvalues λ_1	Eigenvalues λ_2	Eigenvalues λ_3	Stability conditions
$E_1(0,0,0)$	$-C_G+\theta P_E+\mu P_G$	$-\lambda C_E+\alpha A$	$-C_M$	$C_G>\theta P_E+\mu P_G, \lambda C_E>\alpha A$
$E_2(0,0,1)$	$-C_G+\theta P_E+\mu P_G-H$	$-\lambda C_E+\alpha A+2\beta\Delta P$	C_M	Instability
$E_3(0,1,0)$	$-C_G+R_G$	$-(-\lambda C_E+\alpha A)$	$-C_M+\Delta M$	$C_G>R_G, \lambda C_E<\alpha A, C_M>\Delta M$
$E_4(1,0,0)$	$-(-C_G+\theta P_E+\mu P_G)$	$-\lambda C_E+\alpha A+\theta P_E$	$-C_M+H$	$C_G<\theta P_E+\mu P_G, \lambda C_E>\alpha A+\theta P_E, C_M>H$
$E_5(0,1,1)$	$-C_G+R_G-H$	$-(-\lambda C_E+\alpha A+2\beta\Delta P)$	$-(-C_M+\Delta M)$	$C_G>R_G-H, \lambda C_E<\alpha A+2\beta\Delta P, C_M<\Delta M$
$E_6(1,0,1)$	$-(-C_G+\theta P_E+\mu P_G-H)$	$-\lambda C_E+\alpha A+2\beta\Delta P+\theta P_E$	$-(-C_M+H)$	$C_G<\theta P_E+\mu P_G-H, \lambda C_E>\alpha A+2\beta\Delta P+\theta P_E, C_M<H$
$E_7(1,1,0)$	$-(-C_G+R_G)$	$-(-\lambda C_E+\alpha A+\theta P_E)$	$-C_M+\Delta M+H$	$C_G<R_G, \lambda C_E<\alpha A+\theta P_E, C_M>\Delta M+H$
$E_8(1,1,1)$	$-(-C_G+R_G-H)$	$-(-\lambda C_E+\alpha A+2\beta\Delta P+\theta P_E)$	$-(-C_M+\Delta M+H)$	$C_G<R_G-H, \lambda C_E<\alpha A+2\beta\Delta P+\theta P_E, C_M<\Delta M+H$

is ESS. It corresponds to the strategic combination of (strong supervision, non-low-carbon behavior, non-participation). This situation is also unfavorable to the low-carbon credit supervision of enterprises and should be avoided.

④ When $C_G>R_G-H, \lambda C_E<\alpha A+2\beta\Delta P, C_M<\Delta M$, $E_5(0,1,1)$ is the ESS. It corresponds to the strategic combination of (weak supervision, low-carbon behavior, participation). This is the case in which low-carbon behavior credit supervision is effective.

⑤ When $C_G<\theta P_E+\mu P_G-H, \lambda C_E>\alpha A+2\beta\Delta P+\theta P_E, C_M<H$, $E_6(1,0,1)$ is the ESS. It corresponds to the strategic combination of (strong supervision, non-low-carbon behavior, participation). This is a situation that should be extremely avoided in low-carbon behavior credit supervision.

⑥ When $C_G<R_G, \lambda C_E<\alpha A+\theta P_E, C_M>\Delta M+H$, $E_7(1,1,0)$ is the ESS. It corresponds to the strategic combination of (strong supervision, low-carbon behavior, non-participation). This is the case in which low-carbon behavior credit supervision is effective.

⑦ When $C_G<R_G-H, \lambda C_E<\alpha A+2\beta\Delta P+\theta P_E, C_M<\Delta M+H$, $E_8(1,1,1)$is the ESS. It corresponds to the strategic combination of (strong supervision, low-carbon behavior, participation). This is the case in which low-carbon behavior credit supervision is effective.

⑧ In addition to the aforementioned parameter conditions, which can form a stable situation, all other parameter situations are unstable situations. At this point at least one subject is in an unstable state during evolution. At this time, the agent's strategic willingness changes with time and cannot reach the evolutionary stability point of 0 or 1. This unstable situation often occurs in reality, which is a manifestation of the spiraling progress of the regulatory system in the process of formation.

4.5 The three stages of the regulatory system

Based on the evolution and stability of the three subjects analyzed above, the collaborative supervision of carbon trading credits can be divided into the following three stages: The initial stage of regulatory, the stage of regulatory development, and the stage of regulatory maturity.

① The initial stage of regulatory. This stage corresponds to the evolutionarily stable state $(0,0,0)$, $(1,0,0)$ and $(1,0,1)$. These three stable situations indicate that regardless of whether government entities and public entities conduct coordinated supervision, corporate entities will not fulfill their obligations to engage in low-carbon behavior, and further reforms of the regulatory system are needed to change the status quo.

② The stage of regulatory development. This stage corresponds to a state of evolutionary instability. The three game subjects repeatedly adjusted their strategies to find the most favorable state for themselves. At this time, the coordinated supervision of government subjects and public subjects is needed to make corporate subjects more inclined to adopt low-carbon behavior strategies. This is the construction stage of the carbon trading credit system, and the government and the public are in the process of exploring and reforming a regulatory system. The primary aim of the regulatory development stage is to make the low-carbon behavior of enterprises more trustworthy and more stable through coordinated supervision by the government and the public.

③ The stage of regulatory maturity. This stage corresponds to the evolutionarily stable states $(0,1,1)$, $(1,1,0)$, $(1,1,1)$ and $(0,1,0)$. In these stable situations, regardless of whether the government and the public conduct coordinated supervision, enterprises will spontaneously choose to conduct low-carbon behaviors. At this point, the enterprise has reached high low-carbon credit. This situation is an ideal situation for corporate low-carbon behavior credit supervision.

The above was primarily a theoretical evolutionary game analysis of the low-carbon logistics credit supervision of logistics enterprises. In real life, the low-carbon logistics credit supervision system will inevitably move from the initial stage of supervision to the stage of supervision development and then to the mature stage of supervision. In this process, how the regulatory development stage moves to the regulatory maturity stage is generally the focus of everyone's attention.

5 Multi-agent simulation experiment

The following is a simulation of key policy parameters through a visual multi-agent simulation method, observing the impact of parameter changes on the tripartite evolution system and comparing the strategy improvements that the government, enterprises, and the public should make in the regulatory development stage.

The evolution path and stable state of each subject can be displayed more intuitively through the simulated graphics. In this paper, Netlogo is used as a tool for multi-agent simulation modeling, referring to the interaction logic designed by Cui[24] to design rules and logic, establish the CA algorithm of the credit supervision system, and quantitatively study the

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main body of local government in the way of multi-agent interaction. The result of the tripartite game between the main body of logistics enterprises and the main body of the public.

5.1 Rules and logic design

(i) The local government entities are represented by Gov, the logistics enterprise entities are represented by Ent, and the public entities are represented by Man. Assume that the total number of two types of local government agents, two types of logistics enterprises, and two types of public agents is 500, and six agents are distinguished by six different colors, as shown in Fig. 5.

(ii) The agent randomly moves one unit in any direction in an interaction. When the two agents randomly move to the same position, the strategy game is performed and the strategy is improved. By comparing the expected benefits of different strategies in period t and the actual benefits in period$t$, the agent decides whether to keep the strategy of period t or change the strategy in period $t+1$.

(iii) The actual benefits of local government agents, logistics enterprise agents, and public agents in period t are Gov(t), Ent(t), and Man(t), respectively, which are the benefits in the payment matrix. The two expected benefits of the government subject are $U_{x1}(t)$ and $U_{x2}(t)$; see Eqs. (1) and (2) . The two expected benefits of the main body of the enterprise are $U_{y1}(t)$ and $U_{y2}(t)$; see Eqs. (6) and (7). The two expected benefits of the public subject are $U_{z1}(t)$ and $U_{z2}(t)$; see Eqs. (11) and (12).

(iv) Policy learning rules: For a government agent with a "weak supervision" strategy, if the expected benefit ($U_{x1}(t)$) of the strong supervision strategy in period t is greater than the expected benefit ($U_{x2}(t)$) of the weak supervision strategy, and the expected benefit of the weak supervision strategy is greater than the actual value (Gov(t)) of the government agent choosing the "weak supervision" strategy, the government agent changes its strategy to a "strong supervision" strategy during period $t+1$. At the same time, the agent color changes from purple to red. Otherwise, the government agent is still in the "weak supervision" strategy during period $t+1$, and the color of the agent is still red. Similarly, the strategies and color changes of government agents with "strong supervision" in period $t+1$ can be obtained. StrG(t) represents the strategy of the government agent in period t, M represents the strategy of "strong supervision", and Z represents the strategy of "weak supervision". The formula of the policy learning rule is as follows:

$$\mathrm{StrG}(t+1)=\begin{cases}\mathrm{StrG}(t)=M,\ \mathrm{StrG}(t)=Z \text{ and } U_{x1}(t)>U_{x2}(t)\geqslant \mathrm{Gov}(t);\\ \mathrm{StrG}(t)=Z,\ \mathrm{StrG}(t)=M \text{ and } U_{x2}(t)>U_{x1}(t)\geqslant \mathrm{Gov}(t);\\ \mathrm{StrG}(t),\ \text{other situations.}\end{cases} \tag{18}$$

The strategy and color changes of logistics enterprise agents in period $t+1$ occur in a similar manner. StrE(t) represents the strategy of the enterprise agent in period t, Y represents the strategy of "low-carbon behavior", N represents the strategy of "non-low-carbon behavior", and the formula of the policy learning rule is as follows:

$$\mathrm{StrE}(t+1)=\begin{cases}\mathrm{StrE}(t)=Y,\ \mathrm{StrE}(t)=N \text{ and } U_{y1}(t)>U_{y2}(t)\geqslant \mathrm{Ent}(t);\\ \mathrm{StrE}(t)=N,\ \mathrm{StrE}(t)=Y \text{ and } U_{y2}(t)>U_{y1}(t)\geqslant \mathrm{Ent}(t);\\ \mathrm{StrE}(t),\ \text{other situations.}\end{cases} \tag{19}$$

The strategy and color changes of the public agent in period $t+1$ also occur in a similar manner. StrM(t) represents the strategy of the enterprise agent in period t, F represents the "participation" strategy, and C represents the "non-participation" strategy. The formula of the policy learning rule is as follows:

$$\mathrm{StrM}(t+1)=\begin{cases}\mathrm{StrM}(t)=F,\ \mathrm{StrM}(t)=C \text{ and } U_{z1}(t)>U_{z2}(t)\geqslant \mathrm{Man}(t);\\ \mathrm{StrM}(t)=C,\ \mathrm{StrM}(t)=F \text{ and } U_{z2}(t)>U_{z1}(t)\geqslant \mathrm{Man}(t);\\ \mathrm{StrM}(t),\ \text{other situations.}\end{cases} \tag{20}$$

5.2 Initial simulation parameter settings

First, the evolution trajectory of each subject in the three stages is simulated. The initial willingness is set as (0.5, 0.5, 0.5), only the cost parameters of the three subjects are changed, and other parameters remain unchanged, as shown in Table 4. The trajectories of the willingness of three representative subjects in the regulatory development stage are drawn in Fig. 6. The vertical axis of the graph represents probability, and the horizontal axis represents time. The red curve represents the change of the local government's will-

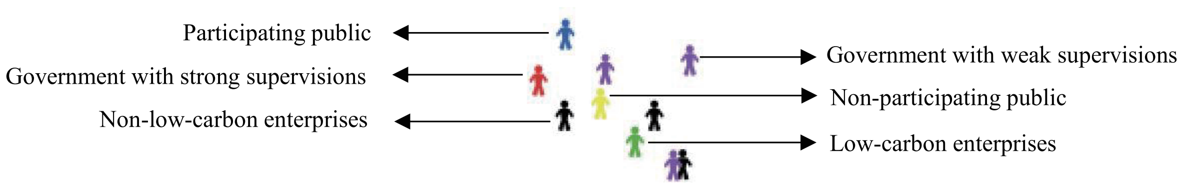

Fig. 5. Color distinction of six agents.

Table 4. Simulation parameter settings.

Parameter	R_G	R_E	R_M	C_G	C_E	C_M	P_G	P_E	P_M	A	H	ΔP	ΔM	α	β	λ	μ	θ
Instability 1	6	8	3	5.5	3	3	5	5	3	5	3	3	2	0.5	0.5	0.5	0.5	0.5
Instability 2	6	8	3	4	11	2.5	5	5	3	5	3	3	2	0.5	0.5	0.5	0.5	0.5
Instability 3	6	8	3	2.5	18	2	5	5	3	5	3	3	2	0.5	0.5	0.5	0.5	0.5

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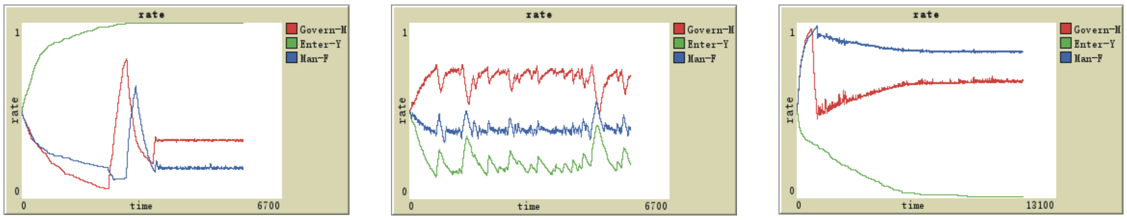


(a) Evolutionary trajectory of instability 1 (b) Evolutionary trajectory of instability 2 (c) Evolutionary trajectory of instability 3

Fig. 6. Simulation diagram of regulatory development stages.

ingness to strengthen supervision, the green curve represents the change of the low-carbon behavior willingness of logistics enterprises, and the blue curve represents the change of the public's willingness to participate in the supervision.

The running trajectories of each subject in the regulatory development stage are shown in Fig. 6. Three representative instability scenarios are selected. In the case of instability 1, the enterprise must be willing to carry out low-carbon behavior, which is equivalent to the stable situation $(0,1,0)$. In the situation of instability 3, the enterprise must be unwilling to carry out low-carbon behavior, which is equivalent to the stable situation $(1,0,1)$.

In the case of instability 2, the low-carbon behavior willingness of enterprises is low, and the three game subjects are in an unstable state. This corresponds to the normalization stage of the repeated game of credit supervision of low-carbon behavior of logistics enterprises in real life. Therefore, the parameters of instability 2 in the regulatory development stage are used as the initial simulation parameters.

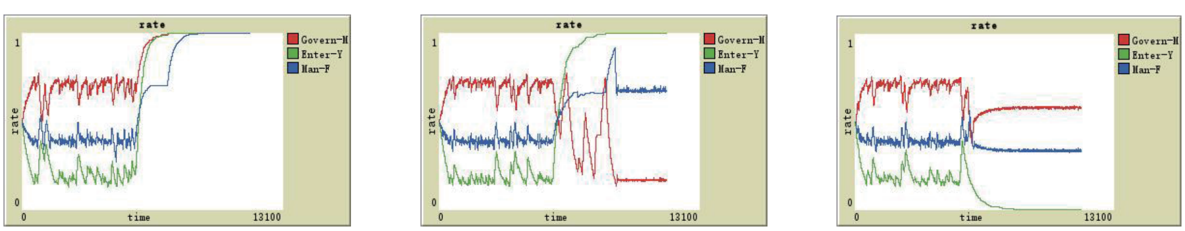
In this study, the reduction in the degree of weak government supervision, the degree of public non-participation, and the degree of enterprises not engaging in low-carbon behaviors were considered as the improvement in the degree of collaborative governance between the government and the public. Therefore, the results of the system simulation are mainly reflected by the strategy curves and the collaborative governance degree curves of the three agents.

5.3 Simulation analysis of cost variables

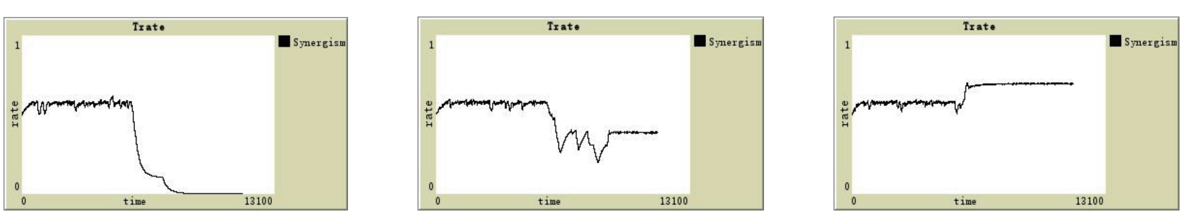
From the previous analysis, it can be seen that reducing the cost of each subject can improve the effect of supervision. Therefore, the impact of reducing government regulatory costs C_G, corporate low carbon behavior costs C_E and public participation costs C_M on system evolution is compared and analyzed. In the case of initial willingness to be $(0.5, 0.5, 0.5)$, after the system runs 6000 times, reduce C_G, C_E, and C_M by 30% respectively and run 6000 times again. The evolution trajectory graphs are shown in Fig. 7a–c. The evolution diagram of the collaborative governance degree are shown in Fig. 7d–f.

As shown in Fig. 7a–c, reducing C_G and C_E can effectively promote the low-carbon behavior of enterprises, and reducing C_M will reduce the willingness of low-carbon behavior of enterprises, but reducing the three costs can improve the stability of the system. As shown in Fig. 7d–f, reducing the three costs can increase the stability of the collaborative governance degree. We are more able to improve the collaborative governance degree of the government and the public by reducing C_G than by reducing C_E, while reducing C_M will reduce the governance of the government and the public.

In sum, in terms of improving the effect of the supervision system, reducing the cost of strong government supervision is greater than reducing the cost of low-carbon behavior of enterprises, and the effect of reducing the cost of public participation does not increase but decreases. Therefore, when formulating long-term regulatory policies, when it is difficult to reduce the low-carbon cost of enterprises, the first considera-



(a) Evolutionary trajectory, $C_G: 4 \rightarrow 2.8$ (b) Evolutionary trajectory, $C_E: 11 \rightarrow 7.7$ (c) Evolutionary trajectory, $C_M: 2.5 \rightarrow 1.75$



(d) Degree of collaborative governance, $C_G: 4 \rightarrow 2.8$ (e) Degree of collaborative governance, $C_E: 11 \rightarrow 7.7$ (f) Degree of collaborative governance, $C_M: 2.5 \rightarrow 1.75$

Fig. 7. Simulation diagram of decreasing C_G, C_E, C_M.

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tion is to reduce the regulatory cost of the government. However, it should be noted that when introducing the supervision force of the public, it is necessary to set a certain supervision threshold for the public to prevent the public opinion from causing excessive damage to the enterprise, which could cause the logistics enterprises to group to resists the low-carbon reform.

5.4 Simulation analysis of government variables

The government's reward and punishment variables have a great influence on the supervision effect. Compare and analyze the effects of increasing the strength of government low-carbon subsidies α, the strength of government fines θ, and the strength of higher-level government penalties μ on the evolution of the system. In the case of initial willingness to be $(0.5, 0.5, 0.5)$, after the system runs 6000 times, increase α, θ, and μ by 30% respectively and run 6000 times again. The evolution trajectory graphs are shown in Fig. 8a–c. The evolution diagrams of the collaborative governance degree are shown in Fig. 8d–f.

As shown in Fig. 8a–c, increasing α, θ, and μ can effectively promote the low-carbon behavior among enterprises. Increasing α has the strongest promotion effect, and increasing μ has the worst effect on the stability of the system. As shown in Fig. 8d–f, increasing α, θ, and μ can all significantly improve the degree of collaborative governance between the government and the public, and the improvement effect is equivalent. In terms of the stability of collaborative governance, increasing α and θ both improve stability, while increasing μ reduces stability.

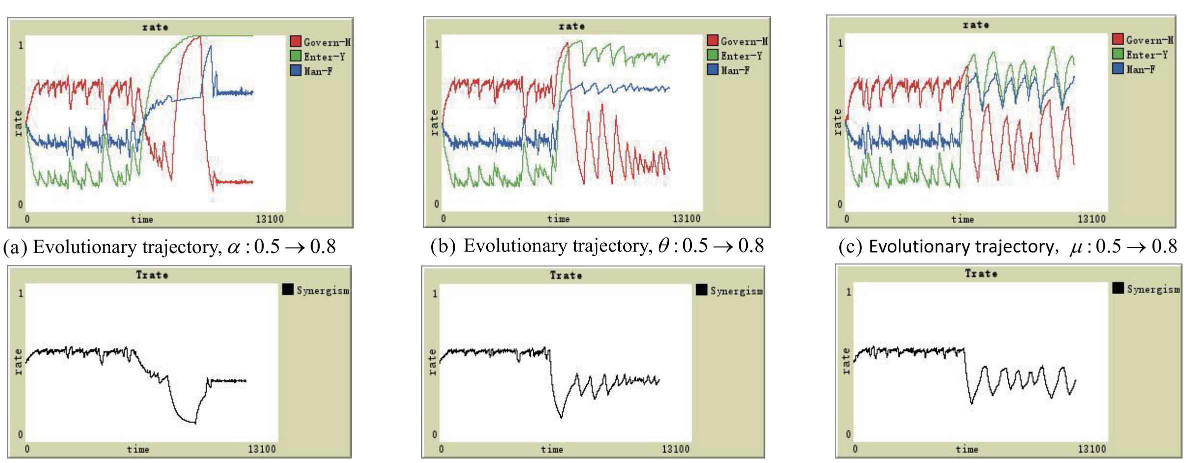
In sum, in terms of improving the effect of the supervision system, increasing the government's low-carbon subsidies is greater than increasing the government's fines than the higher-level government's penalties. Therefore, when considering external rewards and punishments for logistics companies to improve the low-carbon compliance level of enterprises, it is possible to increase the government's low-carbon subsidies, government fines and higher-level government penalties at the same time. However, efforts should be focused on increasing the government's low-carbon subsidies, along with increasing the government's fines, and avoiding the increase in penalties of higher-level governments to avoid confusion in the low-carbon market.

5.5 Simulation analysis of public variables

The concomitant variables of the public also have a large impact on regulatory effectiveness. Therefore, the effects of increasing the public's impact on the enterprise's income ΔP, increasing the government's subsidies to the public H, and increasing the additional low-carbon benefits of public participation ΔM are compared and analyzed. In the case of initial willingness to be $(0.5, 0.5, 0.5)$, after the system runs 6000 times, increase ΔP, H, and ΔM by 30% respectively and run 6000 times again. The evolution trajectory graphs are shown in Fig. 9a–c. The evolution diagrams of the collaborative governance degree are shown in Fig. 9d–f.

As shown in Fig. 9a–c, only increasing ΔP can effectively promote the low-carbon behavior of enterprises, while increasing H can seriously reduce the low-carbon behavior of enterprises, and increasing ΔM only increases the stability of the system. As shown in Fig. 9d–f, increasing ΔP can significantly improve the degree of collaborative governance of the government public, increasing H can significantly reduce the degree of collaborative governance of the government public, and increasing ΔM can only enhance the stability of the degree of collaborative governance of the government public.

In sum, in terms of improving the effect of the supervision system, only increasing the public's influence on the company's income can improve the effect, and increasing the additional low-carbon income of public participation can only enhance the stability of the system. Increasing government subsidies to the public would be counterproductive. Therefore, to strengthen the supervisory role of the public, it is most important to strengthen the public's influence on the profits of enterprises. It is also important to increase the additional benefits obtained from public participation. It is worth noting that increasing government subsidies to the public would actually reduce the low-carbon behavior of enterprises. Therefore, the amount of subsidies to the public should be



(a) Evolutionary trajectory, $\alpha: 0.5 \to 0.8$ (b) Evolutionary trajectory, $\theta: 0.5 \to 0.8$ (c) Evolutionary trajectory, $\mu: 0.5 \to 0.8$

(d) Degree of collaborative governance, $\alpha: 0.5 \to 0.8$ (e) Degree of collaborative governance, $\theta: 0.5 \to 0.8$ (f) Degree of collaborative governance, $\mu: 0.5 \to 0.8$

Fig. 8. Simulation diagram of increasing α, θ, μ.

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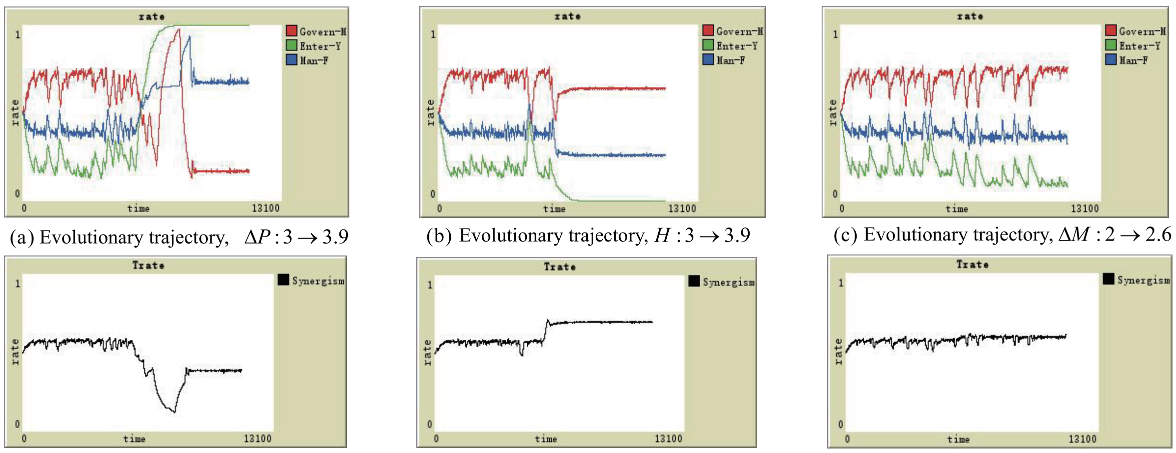

(a) Evolutionary trajectory, $\Delta P: 3 \to 3.9$ (b) Evolutionary trajectory, $H: 3 \to 3.9$ (c) Evolutionary trajectory, $\Delta M: 2 \to 2.6$

(d) Degree of collaborative governance, $\Delta P: 3 \to 3.9$ (e) Degree of collaborative governance, $H: 3 \to 3.9$ (f) Degree of collaborative governance, $\Delta M: 2 \to 2.6$

Fig. 9. Simulation diagram of increasing $\Delta P, H, \Delta M$.

limited to prevent unethical practices in which negative effects are caused by those acting only in their own interests.

6 Conclusions

This study aimed to establish a reasonable and effective supervision mechanism to promote low-carbon behavior among logistics enterprises. By establishing a tripartite evolutionary game model of the local government, logistics enterprises, and the public, it explored the different regulatory decisions and effects of the government and the public. In addition, a simulation analysis of the promotion effect of different parameters was carried out, which provided certain policy references and suggestions for promoting the low-carbon behavior of logistics enterprises. The conclusions were as follows:

(Ⅰ) Both local government supervision and public participation can promote the low-carbon behavior of enterprises. The combined impact of the two can effectively change the strategic choice of enterprises and promote the low-carbon behavior among them.

(Ⅱ) Reducing the cost of low-carbon behavior of logistics enterprises is the best method for improving the level of low-carbon behavior of enterprises. When it is impossible to reduce the low-carbon cost of enterprises, reducing the cost of government supervision can also significantly improve the level of low-carbon behavior of enterprises. Therefore, in the process of supervision, the government can reduce the steps of supervision and verification, reduce the level of supervision agencies, and coordinate supervision by multiple ministries, thereby reducing the cost of supervision and improving the level of supervision.

(Ⅲ) Keeping the public at a certain cost of participation and supervision, and excessively reducing the cost of the public would be counterproductive. The cost of public speech on the Internet is too low, resulting in a two-sided effect of public supervision. Therefore, a special network platform can be established to supervise the low-carbon behavior of logistics enterprises, set certain access thresholds, and advocate that the public speak with data and facts, so as to maintain the effectiveness of public supervision.

(Ⅳ) Increasing government low-carbon subsidies and increasing government fines can effectively improve the level of low-carbon behavior of enterprises, and the effect of increasing the former is better than that of increasing the latter. In terms of low-carbon subsidies, we can subsidize the low-carbon research and development of logistics companies, such as providing technical subsidies for the research and development of green packaging. We can also subsidize the low-carbon infrastructure of logistics companies by, for example, helping to build charging piles for new energy vehicles. In terms of fines, carbon taxes can be imposed on logistics companies with excess carbon emissions or the government's policy support can be reduced. It is suggested to mainly provide low-carbon and trustworthy subsidies to enterprises, supplemented by the government's low-carbon untrustworthy fines for enterprises, which can better promote the enthusiasm of enterprises for low-carbon behavior.

(Ⅴ) Increasing punishment by the higher-level government can effectively improve the level of low-carbon behavior of enterprises and the degree of collaborative governance of the government and the public but can also reduce the stability of the supervision system. It is necessary for the higher-level government to impose certain dereliction of duty penalties on the local government; however, the excessive influence of the higher-level government on the supervision of the local government will reduce the stability of the market.

(Ⅵ) Increasing the public's impact on the company's earnings can promote low-carbon enterprises than can increasing government subsidies to the public. To increase the public's influence on enterprises, the public must establish sufficient low-carbon preferences, and the public's market influence must be increased. The two actions together can influence the low-carbon strategy of enterprises.

There are still some limitations to this study. As it cannot obtain the support of real data, an empirical analysis was not conducted, and the adequacy of the actual situation needs to be verified. The benefits and costs of the three game subjects involve various aspects. For the sake of research convenience, the parameters are not subdivided. For example, the setting of government subsidies in the future can be subdivided into re-

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search and development subsidies and infrastructure subsidies, the effects of the two subsidies can be compared and analyzed, and suggestions can be provided. Finally, the strategy in three-party games in this paper has two elements. While in reality, each subject has more than two choices, it is more reasonable to consider the evolutionary game with three or more strategy factors in the subject's strategy and conduct a more practical analysis.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biographies

Yu Dong is an Associate Professor with the University of Science and Technology of China (USTC) and a Vice President of Anhui University of Science & Technology. He received his Ph.D. degree in Management from the USTC. His main research directions are decision science and operations management, and he is interested in studing game theory in management science issues.

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