frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 21 October 2022
DOI 10.3389/fenvs.2022.1041357

Incineration or pulverization? Evolutionary game model of management of nematode-infected pine wood in China in the carbon neutrality context

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 10 September 2022
ACCEPTED 07 October 2022
PUBLISHED 21 October 2022

CITATION
Wen X, Gu T, Qi H and Zhang F (2022), Incineration or pulverization? Evolutionary game model of management of nematode-infected pine wood in China in the carbon neutrality context.
Front. Environ. Sci. 10:1041357.
doi: 10.3389/fenvs.2022.1041357

The rapid spread of pine wilt disease has become a major crisis with regard to forest ecological security. Against the background of China's concerted effort to achieve carbon neutrality by 2060, balancing economic and environmental costs during the environmentally sound treatment of nematode-infected pine wood is an issue worthy of attention. In this study, we constructed an evolutionary game model of the central government, local governments, and infected wood management-related enterprises and analyzed the evolutionary process of the three parties with stable strategies based on a full consideration of actual circumstances. To verify the theoretical results, we conducted numerical simulations using MATLAB. The results of the study are as follows. 1) The central government plays a decisive role in how infected wood is handled. The greater the degree of regulation is, the greater the local government favors low carbon emissions and the more companies will choose the pulverization method. 2) Local governments bear the main responsibility in the processing of infected wood, and only when local governments are sufficiently penalized will enterprises choose to pulverize the wood and dispose of it. 3) Policy subsidies are an effective measure that will help the three parties in the model reach a balance more quickly. Overall, this study clarified the realization path of low-carbon treatment of nematode-infected pine wood from a policy perspective. The study results should help promote the low-carbon treatment of nematode-infected pine wood and provide a basis for the formulation of relevant forestry policies in the context of carbon neutrality.

KEYWORDS

carbon neutral, central and local government, infected wood, pine wilt disease, evolutionary game

1 Introduction

To implement the responsibilities and obligations of the Paris Agreement on Climate Change, the Chinese government has set the long-term goal of achieving "carbon neutrality" by 2060 (Mallapaty, 2020). Because forests provide ecological regulation functions such as CO_2 fixation and oxygen release (Augusto and Boča, 2022), they are considered important factors for achieving carbon neutrality. Because of the impact of rising temperatures and increased international trade (Grünig et al., 2020), the ecological security of forests is being severely challenged by alien organisms, attracting widespread attention from the government and the public (Seidl et al., 2018). In particular, against the current carbon neutrality background, protecting the role of forests as carbon sinks has become an important issue related to the level of national environmental governance and long-term stable economic development.

In China, an average of 20 million pine trees are infected with pine wood nematodes and die each year (Lu et al., 2020), representing the greatest cause of forest resource losses in China. Because active and effective control methods are lacking (Kong et al., 2021), cutting and disinfection have become the only realistic means to effectively prevent the spread of the disease in nearly 60 million ha of pine forests. Incineration and pulverization are currently the only two treatment methods available in China, and the economic and environmental benefits of these processes are very different. Whether to adopt low-carbon emissions but high-cost pulverization measures or high environmental pollution but low-cost wood incineration measures (Zhao et al., 2020) is a dilemma faced by forestry management departments under current conditions (Figure 1).

Appropriate policy interventions can help alleviate the frequent contradiction between economic development and environmental protection (Sjöberg, 2015; Li et al., 2021). However, the effectiveness of a policy depends largely on its implementation. From the perspective of the source, the high cost (Bachmann, 2020) of implementing environmental protection measures and the lack of awareness of the benefits of governance are the fundamental reasons for low environmental governance efficacy (Stranlund and Ben-Haim, 2008). The management policy for nematode-infested pine wood represents an extension of the Chinese-style decentralization model into the forestry field. The model's rules are formulated by the central government and implemented by local governments. However, in actual management, because of factors such as the level of economic development, management level (Babu and Mohan, 2018), and degree of attention (Ran et al., 2020), the management of infected wood often fails to meet the standards stipulated by policies, and in certain cases, it even evolves into a means for competing for liquidity resources. There are three difficulties at the policy level regarding how to effectively control the spread of pine wood nematodes while reducing the carbon emissions generated by the treatment of infected wood, as follows.

1) Will the central government's policy help solve the problems of the current incineration-based treatment method?
2) How can enterprises choose a more environmentally friendly pulverization method to deal with infected wood?
3) What is the best way to address nematode-infected pine wood in the future?

To resolve these three difficulties, in this study, a tripartite evolutionary game model is constructed based on evolutionary game theory to analyze the complex game interactions among the central government, local governments, and infected wood management-related enterprises.

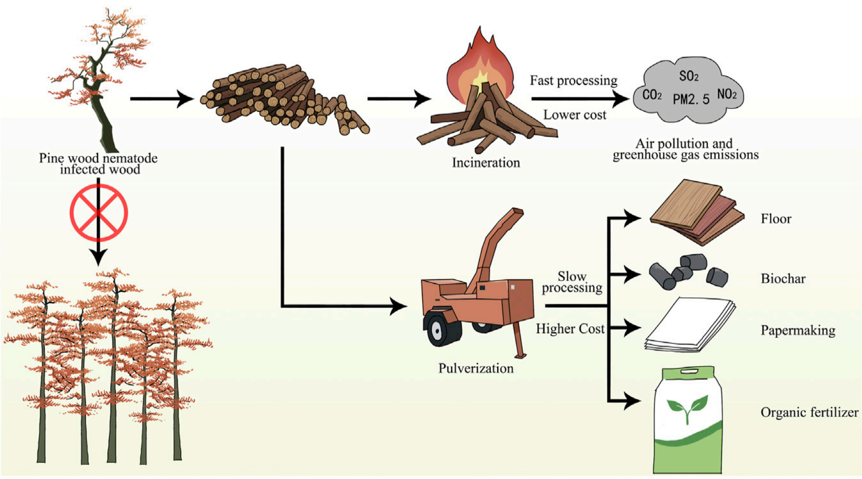

FIGURE 1
Main issues in nematode-infected pine wood management.

The main contribution of this research is its use of the evolutionary game approach to systematically analyze the behavioral choices of the central government, local governments, and wood-related enterprises in the low-carbon treatment of pine wood nematodes. This study would be of substantial practical significance and value in forming an idealized cooperative game guided by the central government, promoted by local governments, and implemented by enterprises.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of the literature. Section 3 presents the materials and methods, including the basic assumptions, construction of a payoff matrix, and replication dynamic equation. Section 4 presents the strategy change and stability analysis of the tripartite subject. Section 5 applies MATLAB for numerical simulation and parameter verification. Section 6 highlights the conclusions and provides policy recommendations.

2 Literature review

The unique management model of Chinese-style decentralization has been the focus of previous studies. Scholars have proposed that Chinese-style decentralization with its characteristics of principal-agent relationships generates central-local information asymmetry (Song, 2013). Limited by the pressure of economic growth (Pu and Fu, 2018), low-carbon development policies are often viewed unfavorably, leading to ineffective implementation (Ren et al., 2021). Studies have shown that decentralization promotes competition among local governments, devolution further reduces environmental quality, and centralization promotes good coordination between regional policies (Cole et al., 2006). However, several scholars have argued that local governments have advantages with regard to environmental protection information and preferences and can take full advantage of the flexibility of local government governance under fiscal decentralization and political centralization (Chinese-style decentralization system), which is conducive to local governments implementing policies in the context of local conditions (Garcia-Valiñas, 2007; Urban et al., 2016). Xu and Xu (2021) note that in the context of Chinese-style decentralization local governments actively respond to the central government not by lowering policy standards but by raising them. Because the government's low-carbon reform policies have both external economic and diseconomy effects, enterprises with profit-seeking characteristics typically lack the initiative to implement low-carbon reform and must be persuaded through taxation or subsidies (Sheng et al., 2020; Zhao and Bai, 2021).

Successful experiences from building operations provide important lessons for the implementation of low-carbon policies. Zhang et al. (2022) compared the decarbonization potential of China and the United States, currently the world's two largest carbon emitters, and found that technological innovation is significant for achieving carbon neutrality goals. Yan et al. (2022) compared the importance of different stages of regulatory regimes for achieving energy conservation and emission reduction based on the actual situation in China. Xiang et al. (2022a) found that higher levels of public participation will help achieve low-carbon goals. How to use policy to promote industrial restructuring has become a key factor for low carbon emissions in the future (Xiang et al., 2022b). Currently, the impact of specific regulatory policies for preventing the spread of forestry biological disasters on governance participants remains unclear, and there are few studies on forestry management policies in the context of carbon neutrality. In addition, previous studies mostly attribute strategic choices by the central government to regulation or nonregulation. However, in the context of China's current emphasis on carbon neutrality and forestry ecological security, the central government is rarely in a situation of absolute nonregulation (Ji et al., 2011); therefore, the conclusions of these studies regarding strategy selection remain limited.

To achieve low-carbon treatment of pine wilt disease-infected wood, two questions should be considered.

1) In the process of controlling pine wilt disease, do the central government, local government, and polluting enterprises engage in an environmental regulation game?
2) Does an increase in government rewards and penalties promote the low-carbon management of infected wood?

To answer these questions, a tripartite noncooperative evolutionary game model with bounded rationality is constructed for the central government, local governments and enterprises. The behavioral strategy choices of all parties are investigated through numerical simulation, and the evolutionary stabilization strategy of the implementation of environmental regulations for pine wilt disease management by the game participants is examined. The objective is to provide a theoretical basis and policy recommendations for promoting the low-emission management of forestry biological disasters.

3 Construction of the evolutionary game model

3.1 Basic assumptions

The low-carbon emission disposal of nematode-infected pine wood requires the establishment of an environmental governance system led by the central government, actively implemented by local governments, and strictly adhered to by enterprises. Given that the central government, local governments, and enterprises are all bounded rational parties, each of the three parties in the system has two strategy alternatives. Enterprises can choose simple and low-cost but high-carbon emission incineration or low-carbon emission pulverization; the strategy set is {incineration, pulverization}. The local government can choose to implement or not implement low-carbon emissions in the process of infected wood management; the strategy set is {implementation, nonimplementation}; given that the central government is paying increasing attention to carbon neutrality targets and the prevention and control of pine wilt disease, there is no possibility of nonregulation, and therefore, the central government's strategy set is {strict supervision, loose supervision}. To construct a more reasonable evolutionary game model, the following basic hypotheses are proposed.

H1. There are three important parties in the game process: the central government, local governments, and enterprises. The probability that the central government chooses the "strict supervision" strategy is x, the probability that the central government chooses the "relaxed supervision" strategy is $1-x$; the probability that local governments choose the "implementation of low-carbon management" strategy is y, the probability that local governments choose the "no low-carbon treatment" strategy is $1-y$, the probability that enterprises choose the "pulverization" strategy is z, and the probability that enterprises choose the "incineration" strategy is $1-z$.

H2. The central government's supervision intensity is γ, $0<\gamma\leq 1$. When the central government chooses strict supervision, the supervision cost is higher than that of the loose supervision strategy and is denoted as C_1. The central government represents the interests of the public. If enterprises choose to reduce carbon emissions, corresponding social benefits R will be generated.

H3. When local governments implement low-carbon treatment, the cost of governance is C_2, primarily the implementation cost and economic cost in the low-carbon management process. Under the strict supervision strategy of the central government, local governments choose to implement the low-carbon treatment strategy to obtain central government rewards E. When local governments fail to implement low-carbon management, they receive penalties (F_1) from the central government and lose their reputation (L_1).

H4. The additional cost of choosing pulverization rather than incineration is C_3. When enterprises choose incineration, Q trees can be incinerated; when they choose pulverization, N trees can be pulverized (because of the reduction in enterprise disposal capacity under the pulverization strategy, $Q>N$). P is the income obtained by enterprises for each tree disposal. Additionally, when the local government chooses to implement the carbon emission treatment strategy, enterprises that choose pulverization receive a corresponding local government subsidy (S) for profit losses. If enterprises choose the incineration strategy, they receive penalty (F_2) from the corresponding local government. Additionally, there is an adverse impact (L_2) on enterprises due to environmental pollution.

3.2 Construction of a payoff matrix and replication dynamic equation

Based on the preceding basic assumptions and parameter settings, the following payout matrix for the tripartite game is constructed (Table 1). In an evolutionary game, each party must continuously adjust the probability value (x, y and z) after multiple games to obtain a stable mixed strategy; the replication dynamic process involves each party in a game dynamically adjusting the strategy selection probability value. The differential equation adjusted with the probability values (x, y, z) is the replication dynamic equation.

Assume E_{11} and E_{12} are expected profits when the central government adopts the "strict supervision" and "loose supervision" strategies, respectively, and $\overline{E_1}$ is the average expected profit of the central government; then:

$$\begin{aligned}E_{11} = {} & yz\left[(1+\gamma)R - C_1 - (1+\gamma)E\right] + (1-y)z(-C_1+R-E) \\ & + yzR + (1-y)zR\end{aligned} \tag{1}$$

$$E_{12} = y(1-z)(-C_1+F_1) + (1-y)(1-z)\left[-C_1+(1+\gamma)F_1\right] \tag{2}$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \tag{3}$$

The evolutionary game replication dynamic equation for the central government strategy is as follows:

$$\begin{aligned}F(x) &= \frac{dx}{dt} \\ &= x(1-x)\left[yz\gamma(R-E+F_1) + (1-y-z)\gamma F_1 \right. \\ &\quad \left. + z(R-E-F_1) - yzR - C_1 + (1+\gamma)F_1\right]\end{aligned} \tag{4}$$

Assume E_{21} and E_{22} are the expected profits of local governments' "implementation of low-carbon management" and "nonimplementation of low-carbon management" strategies, respectively, and $\overline{E_2}$ is the average expected profit of local governments.

$$\begin{aligned}E_{21} = {} & xz\left[-C_2 - S + (1+\gamma)E\right] + x(1-z)(-C_2-F_1+F_2) \\ & + yz(-C_2-S) + y(1-z)(-C_2+F_2)\end{aligned} \tag{5}$$

$$E_{22} = xzE + x(1-z)\left[-(1+\gamma)F_1\right] \tag{6}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22} \tag{7}$$

The evolutionary game replication dynamic equation for the local government strategy is as follows:

$$F(y) = y(1-y)\left[xz\gamma E - z(S+F_2) + (z-1)x\gamma F_1 + F_2 - C_2\right] \tag{8}$$

TABLE 1 Payoff matrix for the tripartite decision.

				Enterprise	
				Pulverization z	Incineration 1 − z
Central government	Strict regulation x	Local government	Low-carbon management y	$\begin{pmatrix}(1+\gamma)R-C_1-(1+\gamma)E\\-C_2-S+(1+\gamma)E\\-C_3+PN+S\end{pmatrix}$	$\begin{pmatrix}-C_1+F_1\\-C_2-F_1+F_2\\PQ-F_2-L_1\end{pmatrix}$
			Nonfulfillment of low-carbon management 1 − y	$\begin{pmatrix}-C_1+R-E\\E\\-C_3+PN\end{pmatrix}$	$\begin{pmatrix}-C_1+(1+\gamma)F_1\\-(1+\gamma)F_1\\PQ-L_1\end{pmatrix}$
	Lax regulation 1 − x	Local government	low-carbon management y	$\begin{pmatrix}R\\-C_2-S\\-C_3+PN+S\end{pmatrix}$	$\begin{pmatrix}0\\-C_2+F_2\\PQ-F_2-L_1\end{pmatrix}$
			Nonfulfillment of Low-carbon management 1 − y	$\begin{pmatrix}R\\0\\-C_3+PN\end{pmatrix}$	$\begin{pmatrix}0\\0\\PQ-L_1\end{pmatrix}$

Similarly, assume that E_{31} and E_{32} are expected profits when enterprises adopt the strategy of "pulverization" and "incineration", respectively, and $\overline{E_3}$ is the average expected profits of the enterprise; then:

$$E_{31} = xy(-C_3 + PN + S) + x(1-y)E + (1-x)y(-C_2 - S) + (1-x)(1-y)(-C_3 + PN) \tag{9}$$

$$E_{32} = xy(PQ - F_2 - L_1) + x(1-y)(PQ - L_1) + (1-x)y(PQ - F_2 - L_1) + (1-x)(1-y)(PQ - L_1) \tag{10}$$

$$\overline{E_3} = yE_{31} + (1-y)E_{32} \tag{11}$$

The evolutionary game replication dynamic equation for the enterprise strategy is as follows:

$$F(z) = z(1-z)[y(S+F_2) + L + PN - PQ - C_3] \tag{12}$$

4 Jacobian matrix partial stability analysis

4.1 Central government

According to the stability theorem of the replication dynamic equation, when the replication dynamic equation of the central government is $F(x) = 0$ and satisfies the derivative $F'(x) < 0$, the central government is in a stable state. When $y = y_0 = \frac{(z-1)\gamma F_1 - z(R-E-F_1)+C_1-(1+\gamma)F_1}{zy(R-E+F_1)-\gamma F_1 - zR}$, the replication dynamic equation is $F(x) \equiv 0$, and the strategy of the central government will not change with the evolution of the system. When $y > y_0$, $F'(x)|_{x=1} < 0$, and $x = 1$ (strict supervision) is the central government's stable regulation strategy. When $y < y_0$, $F'(x)|_{x=0} < 0$, and $x = 0$ (loose regulation) is the central government's stable regulation strategy (Figure 2A).

4.2 Local governments

When local governments' replication dynamic equation is $F(y) = 0$ and satisfies the derivative $F'(y) < 0$, local governments are in a stable state. When $x = x_0 = \frac{C_2 - F_2 + z(S+F_2)}{zy(E+F_1)-\gamma F_1}$, the replication dynamic equation is $F(y) \equiv 0$, and the strategy of local governments will not change with the evolution of the system. When $x > x_0$, $F'(y)|_{y=1} < 0$, and $y = 1$ (implementation of low-carbon management) is a stable regulatory strategy of local governments; when $x < x_0$, $F'(y)|_{y=0} < 0$, $y = 0$ (nonimplementation of low-carbon management) is a stable regulatory strategy of local governments (Figure 2B).

4.3 Enterprises

When enterprises' replication dynamic equation is $F(z) = 0$ and satisfies the derivative $F'(z) < 0$, the enterprise is in a stable state. When $y = y_0 = \frac{PQ - PN + C_3 - L}{S + F_2}$, the replication dynamic equation is $F(z) \equiv 0$, and the strategy of the enterprise will not change with the evolution of the system. When $y > y_0$, $F'(z)|_{z=1} < 0$, and $z = 1$ (pulverization) is the stable regulatory strategy of enterprises. When $y < y_0$, $F'(z)|_{z=0} < 0$, and $z = 0$ (Incineration) is a stable regulatory strategy of enterprises (Figure 2C).

4.4 Stability analysis

The evolution of the three parties, i.e., the central government, local governments, and enterprises, can be analyzed through a replication dynamic equation. However, it is impossible to directly determine the equilibrium point to which the system will eventually evolve. The Jacobian matrix (Friedman, 1998) is used to qualitatively analyze the local stability of the system at these equilibrium points. Combining

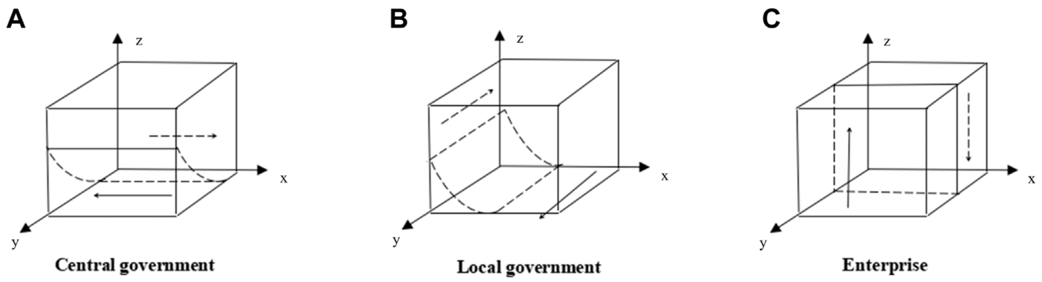

FIGURE 2
Phase diagram of the central government, local governments, and enterprises. Note: x denotes the central government chooses the "strict supervision" strategy, y denotes the local governments choose the "implementation of low-carbon management" strategy, and z denotes the enterprises choose the "pulverization" strategy.

the tripartite replication dynamic equations and making $F(x)=0$, $F(y)=0$, $F(z)=0$, the following equations are obtained:

$$\begin{cases} x(1-x)\left[yz\gamma(R-E+F_1)+(1-y-z)\gamma F_1+z(R-E-F_1)-yzR-C_1+(1+\gamma)F_1\right]=0 \\ y(1-y)\left[xz\gamma E-z(S+F_2)+(z-1)x\gamma F_1+F_2-C_2\right]=0 \\ z(1-z)\left[y(S+F_2)+L+PN-PQ-C_3\right]=0 \end{cases} \tag{13}$$

Thus, eight equilibrium points are obtained: $E_1(0,0,0)$, $E_2(0,1,0)$, $E_3(0,0,1)$, $E_4(1,0,0)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$. Additionally, the Jacobian matrix is obtained by the replication dynamic equation:

$$J=\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}=\begin{bmatrix} F_{11} & F_{12} & F_{13} \\ F_{21} & F_{22} & F_{23} \\ F_{31} & F_{32} & F_{33} \end{bmatrix} \tag{14}$$

$$F_{11}=(1-2x)\left[yz\gamma(R-E+F_1)+(1-y-z)\gamma F_1 + z(R-E-F_1)-yzR-C_1+(1+\gamma)F_1\right];$$

$$F_{12}=x(1-x)\left[z\gamma(R-E+F_1)-\gamma F_1-zR\right];$$

$$F_{13}=x(1-x)\left[y\gamma(R-E+F_1)-\gamma F_1+(R-E-F_1)-yR\right];$$

$$F_{21}=y(1-y)\left[z\gamma E+(z-1)\gamma F_1\right];$$

$$F_{22}=(1-2y)\left[xz\gamma E-z(S+F_2)+(z-1)x\gamma F_1+F_2-C_2\right];$$

$$F_{23}=y(1-y)\left[(z-1)xF_1\right];$$

$$F_{31}=0;$$

$$F_{32}=z(1-z)(S+F_2);$$

$$F_{33}=(1-2z)\left[y(S+F_2)+L+PN-PQ-C_3\right]$$

According to the Lyapunov method (Jitomirskaya and Schulz-Baldes, 2007), when all eigenvalues of the Jacobian matrix are $\lambda<0$, the equilibrium point gradually stabilizes; when all eigenvalues of the Jacobian matrix are $\lambda>0$, the equilibrium point is unstable; when the eigenvalue (λ) of the Jacobian matrix is either positive or negative, the equilibrium point is the saddle point. Taking the equilibrium point $E_1(0,0,0)$ as an example, the stability is analysed, and the Jacobian matrix is calculated as follows:

$$J_1=\begin{bmatrix} (2\gamma+1)F_1-C_1 & 0 & 0 \\ 0 & F_2-C_2 & 0 \\ 0 & 0 & L+PN-PQ-C_3 \end{bmatrix} \tag{15}$$

The three eigenvalues for the equilibrium point $E_1(0,0,0)$ are $\lambda_1=(2\gamma+1)F_1-C_1$, $\lambda_2=\mathrm{F}_2-\mathrm{C}_2$ and $\lambda_3=\mathrm{L}+\mathrm{PN}-\mathrm{PQ}-\mathrm{C}_3$. Because it is impossible to determine eigenvalues λ_1, λ_2, and λ_3, the discussion is divided into different situations. When λ_1, λ_2, and λ_3 are less than 0, the equilibrium point $E_1(0,0,0)$ is stable; otherwise, it is unstable or a saddle point. The results of the stability analysis of other equilibrium points are provided in Table 2.

There are a total of seven stable points in the game model. Considering that the intensity of environmental protection supervision in China has been increasing year by year in recent years (Jia and Chen, 2019; He and Geng, 2020), a large amount of greenhouse gases will be released by completely adopting the strategy of incinerating infected wood (Johnston and van Kooten, 2015), which is not conducive to achieving carbon neutrality. Therefore, we excluded four situations, i.e., $E_1(0,0,0)$, $E_2(0,1,0)$, $E_4(1,0,0)$ and $E_5(1,1,0)$, that cannot occur. $E_3(0,0,1)$, $E_6(1,0,1)$, and $E_8(1,1,1)$ are selected for stability analysis.

1) Scenario 1: When $R-C_1+\gamma F_1<E$, $PN-C_3>PQ-L$, that is, when the profits under the strict supervision strategy of the central government cannot make up for the subsidy paid to enterprises and when the profits when enterprises adopt a pulverization strategy are greater than the profits when enterprises adopt an incineration strategy, the central government tends to adopt the loose supervision strategy, and local governments tend to not implement low-carbon management, while enterprises tend to choose pulverization. Under this scenario, enterprises adopt the incineration strategy, causing adverse impacts (L) on themselves should the increase in carbon emissions be large enough, or

TABLE 2 Equilibrium point and stability condition of the system.

Equilibrium points	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	Stability condition
$E_1\,(0,0,0)$	$(2\gamma+1)F_1-C_1$	F_2-C_2	$L+PN-PQ-C_3$	$(2\gamma+1)F_1<C_1$; $F_2<C_2$; $PN-C_3<PQ-L$
$E_2\,(0,1,0)$	$(1+\gamma)F_1-C_1$	C_2-F_2	$S+F_2+L+PN-PQ-C_3$	$(1+\gamma)F_1<C_1$; $F_2>C_2$; $PN-C_3+S<PQ-L-F_2$
$E_3\,(0,0,1)$	$R-E-C_1+\gamma F_1$	$-S-C_2<0$	$PQ-PN-L+C_3$	$R-C_1+\gamma F_1<E$; $PN-C_3>PQ-L$
$E_4\,(1,0,0)$	$C_1-(2\gamma+1)F_1$	$-\gamma F_1+F_2-C_2$	$L+PN-PQ-C_3$	$(1+2\gamma)F_1>C_1$; $F_2-C_2<\gamma F_1$; $PN-C_3<PQ-L$
$E_5\,(1,1,0)$	$C_1-(1+\gamma)F_1$	$C_2+\gamma F_1-F_2$	$S+F_2+L+PN-PQ-C_3$	$(1+\gamma)F_1>C_1$; $F_2-C_2>\gamma F_1$; $PN-C_3+S<PQ-L-F_2$
$E_6\,(1,0,1)$	$C_1+E-R-\gamma F_1$	$\gamma E-S-C_2$	$PQ-PN-L+C_3$	$E<R-C_1+\gamma F_1$; $\gamma E-S<C_2$; $PN-C_3>PQ-L$
$E_7\,(0,1,1)$	$\gamma(R+F_1)-(1+\gamma)E-C_1$	$S+C_2>0$	$PQ-PN-S-L-F_2-C_3$	Unstable
$E_8\,(1,1,1)$	$(1+\gamma)E-\gamma(R+F_1)+C_1$	$S+C_2-\gamma E$	$PQ-PN-S-L-F_2+C_3$	$(1+\gamma)E<\gamma(R+F_1)-C_1$; $\gamma E-S>C_2$; $PN+S-C_3>PQ-F_2-L$

enterprises can control the relevant costs under the pulverization strategy as much as possible.

2) Scenario 2: When $E<R-C_1+\gamma F_1$, the profits of the central government's strict supervision strategy completely compensate for its subsidies to local governments. Therefore, the central government tends to evolve in the direction of the strict supervision strategy, and the profits of enterprises under different strategies are similar to those in Scenario 1. For local governments, $\gamma E-S<C_2$. That is, when the central government's subsidies cannot make up for the cost after deducting the subsidies to enterprises, local governments tend not to implement the low-carbon management strategy.
3) Scenario 3: When $(1+\gamma)E<\gamma(R+F_1)-C_1$, $\gamma E-S>C_2$ and $PN+S-C_3>PQ-F_2-L$, all parties tend to the evolutionary game direction of {strict supervision, implementation of low-carbon management, pulverization}. Compared to Scenario 2, the difference between the subsidies received by local governments from the central government and the subsidies for enterprises is still greater than the cost of implementing low-carbon management. The profits obtained by enterprises when they choose the pulverization strategy are higher than the profits obtained by enterprises when they choose the incineration strategy. The profits are higher mainly because the local government has higher subsidies for the enterprise pulverization strategy or higher penalties for the incineration strategy, while the central government's profits are similar to those of Scenario 2. Therefore, after a period of evolution, the main party in the game eventually tends in the direction of {strict supervision, implementation of low-carbon management, pulverization}, which is also the ideal situation in this study.

5 System simulation analysis

To more intuitively display the dynamic evolution path and stable state of the system under different constraints and intensities of influencing factors by the central government, local governments, and enterprises, MATLAB is used to perform numerical simulation and verify the parameter values that meet the conditions in the optimal state, i.e., Scenario 3 (Figure 3).

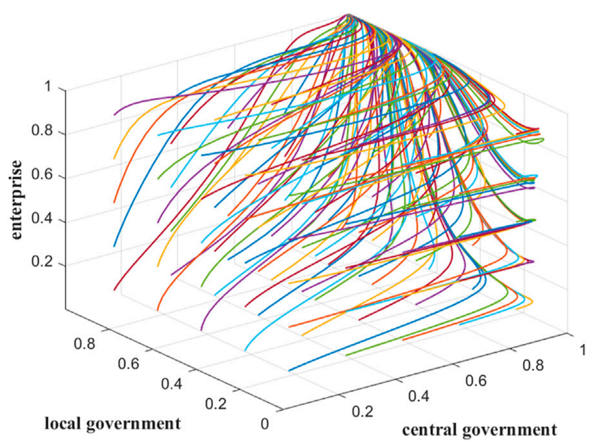

FIGURE 3
Ideal state simulation diagram. Note: The initial values of the various parameters are $C_1=4$, $C_2=3$,$C_3=2$, $E=20$, $F_1=15$, $F_2=15$, $L=8$, $\gamma=0.5$, $p=2$, $N=10$, $Q=15$, $S=5$, and $R=55$.

5.1 Central government's supervision of local governments

In the initial state, the main party in the game eventually evolves in the direction of {strict supervision, implementation of low-carbon management, and pulverization}, which verifies the above stability analysis. With other parameters kept unchanged and only the supervision intensity of the central government over local governments changed and set to $\gamma=0.2$, $\gamma=0.5$ and $\gamma=0.8$, the evolutionary trend for each subject is observed (Figure 4). When the central government's supervision of

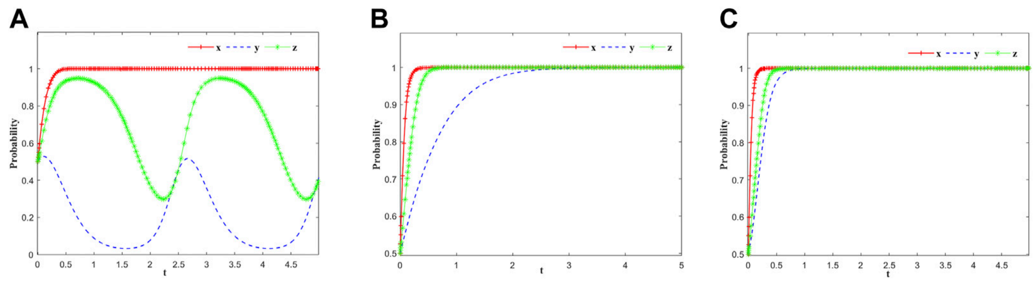

FIGURE 4
Simulation of the evolutionary strategy of the three parties under different levels of supervision by the central government. Note: t denotes the time, i.e., the speed of achieving low carbon treatment, and γ = 0.2, 0.5, 0.8 in Panel 4 **(A–C)**, respectively, denote that the central government's regulation of local governments ranges from small to large.

local governments is relatively low, i.e., $\gamma = 0.2$, the system tends to be unstable. When the supervision (γ) of local governments by the central government gradually increases, the local government shifts from the initial nonimplementation of low-carbon management to implementation, and the greater the intensity of supervision is, the faster the local government will choose to implement low-carbon management. In addition, because local governments choose low-carbon management faster, enterprises are more inclined to choose a pulverization strategy.

5.2 Penalties imposed by local governments on enterprises

When local governments impose penalties on enterprises $F_2 = 3$, the equilibrium and stability point of the three parties is (1, 0, 0), that is, the equilibrium and stable state of {strict central government supervision, local governments do not implement low-carbon management, and enterprises adopt incineration}. When $F_2 = 8$, $F_2 = 15$, the equilibrium point of the three parties is (1, 1, 1), that is, the equilibrium and stable state of {strict central government supervision, local governments implement low-carbon management, and enterprises adopt pulverization}. Additionally, when local governments' penalties for enterprises are higher, the time for the subject of the tripartite game to evolve toward (1, 1, 1) is shorter (Figure 5).

5.3 Central government's supervision of local governments

With the values of other parameters fixed, subsidies provided by local governments to enterprises are simulated in the situation of $S = 2$, $S = 5$, and $S = 10$. The effect of the changes in F_2 from low to high on the evolutionary trend of the strategy choice of the tripartite subjects is shown in Figure 6. The simulation results indicate that when $S = 2$ the equilibrium stability point of the three parties is (1, 1, 1), that is, the equilibrium and stable state of {strict central government supervision, local governments do not implement low-carbon management, and enterprises adopt incineration}. With the gradual increase in local government subsidies to enterprises to $S = 5$, the evolutionary time local governments choose to implement low-carbon management gradually increases. When local government subsidies increase to $S = 10$, the system tends to be unstable, mainly because when the subsidies provided by local government are too high, their own interests cannot be satisfied, thus greatly reducing their enthusiasm for implementing low-carbon management. Speculative behavior will occur to maximize own interests, and enterprises tend to choose the incineration strategy.

6 Summary

6.1 Conclusion and policy implications

In this study, we constructed a tripartite evolutionary game model, i.e., "central government-local government-enterprise", in the context of carbon neutrality and pine wilt disease in China. MATLAB was used for the numerical simulation. The main findings of this study are as follows.

1) The ideal strategy for the three parties is achieved when the central government implements strict supervision, local governments implement low-carbon management, and enterprises choose pulverization. Therefore, the central government should encourage local governments to actively implement low-carbon management strategies by increasing the intensity of their supervision of local governments, and local governments should prompt enterprises to choose the pulverization strategy by imposing penalties on enterprises that choose incineration strategies and appropriately increasing subsidies for enterprises when they adopt pulverization strategies.

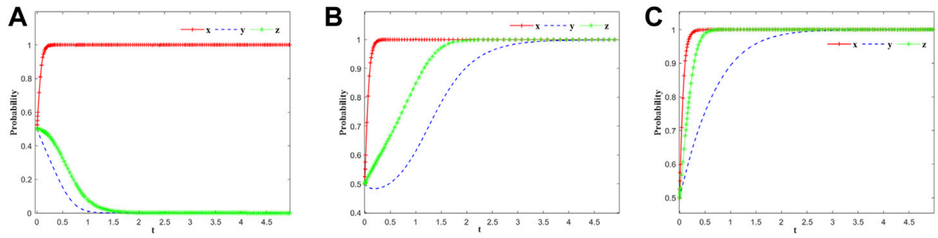

FIGURE 5
Simulation of the evolutionary strategy of the three parties under different penalties imposed by local governments on enterprises. Note: t denotes the time, i.e., the speed of achieving low-carbon treatment, and F_2 = 3, 8, 15 in Panel 5 **(A–C)**, respectively, denote the penalties imposed by the local government on the enterprises from small to large.

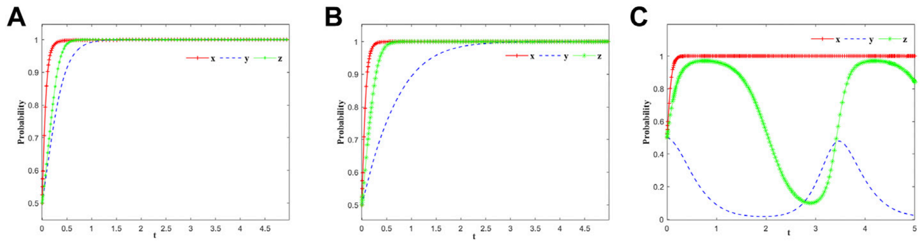

FIGURE 6
Simulation of the evolutionary strategy of the three parties under different local government subsidies to enterprises. Note: t denotes the time, i.e., the speed of achieving low-carbon treatment, and S = 2, 5, 10 in Panel 6 **(A–C)**, respectively, denote the subsidies from the local government to the enterprise from small to large.

2) When the parameters are set, the strategy evolution among the central government, local governments, and enterprises is affected by the central government's own and the other two parties' strategy choices. However, regardless how the selection ratio for each party changes, it will not change the final behavioral strategy choice of the parties in the game and will eventually reach a stable point under different stability conditions.

Based on these conclusion, this paper proposes the following policy recommendations.

First, the central government should strengthen its supervision of local government behaviors in the process of infected wood management and effectively encourage local governments to actively implement low-carbon strategies. If local governments do not implement the low-carbon strategy, they should be subject to higher penalties from the central government. When the penalty received by local governments far exceeds the cost of implementing low-carbon management, local governments will naturally tend to actively implement the low-carbon strategy. Conversely, when local governments choose to implement low-carbon management, if the central government can provide a certain degree of subsidies or corresponding incentives, it can also effectively encourage local governments to adopt low-carbon strategies.

Second, local governments should assume the main responsibility in the implementation of infected wood treatment. The evolution of enterprises' strategies is affected by the intensity of penalties and subsidies by local governments. Local governments should increase the penalties for enterprises that choose incineration, making it impossible for such enterprises to obtain speculative gains when they choose this strategy to compensate for the higher administrative penalties, thus effectively constraining enterprises' speculative behavior. Furthermore, local governments should increase the subsidies for enterprises that choose pulverization to support environmental technology innovation. In addition to providing direct financial support, financial support for technological upgrading projects can also be achieved through equity financing, industrial funds, and debt financing.

Third, public participation should be introduced into the reputation mechanism. Through the media or the public evaluation of enterprises, rewards and penalties for enterprises can be adjusted. That is, a good reputation would increase the rewards for enterprises, and a poor reputation would increase the penalties for an enterprise. In addition, to achieve a win-win situation, the government can also assess the service level of enterprises, introduce third-party supervision and other means to conduct infected wood management bidding, and improve the operation of the entire management process to promote pest management and low-carbon environmental protection.

6.2 Study limitations and future research directions

Our study suggests several avenues for future research. Here, the low-carbon treatment strategy for nematode-infected pine wood was emphasized, and a three-way evolutionary game model was constructed. This study applies a mathematical model approach, which takes into account the behavioral choices between subjects with different strategies and provides policy recommendations based on the current realities of infected wood management.

In terms of this study's limitations, on the one hand, a questionnaire could be adopted in future studies to determine why wood-related enterprises choose high-carbon emissions treatment, which would strengthen the connection between the study and actual circumstances. On the other hand, the model presented here could be extended, including by constructing a dynamic game model under information asymmetry, considering the game sequence, and analyzing the strategic choices of the parties in a long-term repeated game.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XW: conceptualization, methodology, software, data curation, supervision, and writing (original draft). TG: visualization, investigation, software. HQ: software, validation. FZ: writing (reviewing and editing).

Funding

This study was supported by the National Key R&D Program of China (2021YFD1400900), the National Forestry and Grassland Bureau major emergency science and technology projects (ZD202001), and the Fujian Forestry Science and Technology Project (MLW-2021-35).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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