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How to promote the application of green pesticides by farmers? Evolutionary game analysis based on "government–farmer–consumer"

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Green pesticide use, as a key means to reduce pesticide use, plays a crucial role in promoting environmental and food safety. However, the effectiveness of green pesticide use policies in China falls short of expectations. Existing research mainly examines the policy promotion issues of green pesticide use from a static and single-agent perspective. However, green pesticide use behavior is a dynamic process influenced by multiple factors, including the government, farmers, and consumers. This paper builds an evolutionary tripartite game model of the government, farmers, and consumers from the perspective of dynamic strategy evolution and explores the evolutionary conditions that affect the stability of the tripartite game strategy during green pesticide application. The results show that 1) through different partnership models, the government, farmers, and consumers can evolve to a stable state. 2) Keeping the government's regulatory intensity in the market for green agricultural products within a reasonable range will help farmers apply green pesticides. 3) Users' preference for high-quality vegetables will increase the market selling price of green products. 4) Maintaining the government's ecological subsidies for green pesticides will help stimulate farmers' enthusiasm for using green pesticides. Therefore, the government should appropriately strengthen ecological subsidies and market supervision, guide consumers' green consumption behavior, and encourage farmers to use green pesticides.

KEYWORDS

green pesticides, evolutionary game theory, user preference, regulatory intensity, ecological subsidies

1 Introduction

As an integral part of agricultural production, pesticides play an important role in promoting environmental and food safety (Alavanja, 2009; Xiao-shan and Qi-ying, 2011; Anh et al., 2021; Lykogianni et al., 2021). The widespread use of pesticides in China has resulted in severe non-point-source pollution, which poses a significant threat to food safety. Statistics show that the amount of pesticides used in China reached 1.655 million tonnes in 2017, an increase of 125.8% compared to 1990, with consumption per unit area more than three times the global average (Guo and Hao, 2022).

Only 10%–20% of pesticides are applied to crops, and up to 80%–90% of pesticides applied to crops may directly affect non-target vegetation, drift, or volatilize off the treated

TABLE 1 Variables listed in the strategy game matrix.

Nomenclature	
G_{c1}	Government's training and publicity costs
G_{c2}	Government's ecological subsidies for green pesticides (through pesticide dealers)
G_{c3}	Government's price subsidies for green agricultural product merchants
G_{c4}	Increase in administrative costs caused by the loss of government credibility (when no strategy)
G_{c5}	Cost of environmental governance (caused by the use of polluting pesticides)
E_{g1}	Environmental governance benefits (farmers apply green pesticides)
E_{g2}	Social benefits such as social trust and social health (green consumption)
PC	Regulatory cost of the green agricultural product market (P is the regulatory intensity and C is the marginal regulatory cost)
PF	Punishment for farmers' violations of OEM
F_{c1}	Production cost due to the application of green pesticides
F_{c2}	Production cost due to the application of traditional pesticides
F_{c3}	Cost of green agricultural product certification
R	Increased risk of pests and diseases caused by green pesticides
W_1	Cost of green consumption by consumers (the green sales revenue by farmers)
W_2	Cost of traditional consumption by consumers (the traditional sales revenue by farmers)
α	Green consumption preferences
T	Consumer trust
E_{s1}	Health benefits because of consumers' green consumption
E_{s2}	Health benefits because of consumers' traditional consumption

area and contaminate air, soil, and non-target plants (Sun et al., 2018). Human exposure can occur through ingestion of pesticide-contaminated water and food, inhalation of pesticide-contaminated air, and direct use in occupational, agricultural, and domestic settings (Raffa and Chiampo, 2021). Pesticide residues in agricultural products have emerged as a significant hidden threat to food safety, with a major impact on consumer health concerns. According to data, in 2021, the Ministry of Agriculture randomly checked 2,857 batches of quality and safety samples of agricultural products; among them, 24 batches had problems, of which 10 batches exceeded the pesticide standard, accounting for 41.7% of the problems (Ministry of Agriculture and Rural Development of China, 2022).

The Chinese government attaches great importance to the advancement of pesticide reduction work and takes the use of green pesticides as its core focus to accelerate pesticide pollution control measures. The definition of "green pesticide" was proposed by Li Zhengming, an academician of the Chinese Academy of Engineering, at the Beijing Xiangshan Science Conference in September 2002 (Shao et al., 2021). It is believed that the characteristics of green pesticides include high activity, which can eliminate pests with low dosage; low risk, which does not affect beneficial species and growing crops; no residue, which can be degraded into non-toxic substances; and clean production with no waste generated in raw materials and production processes (Shao et al., 2021). As a high-quality substitute for traditional pesticides, green pesticides are unsatisfactory in terms of purchase volume and usage rate, which is rooted in two reasons. On one hand, the cost of green pesticides is significantly higher than that of traditional pesticides, which affects some farmers with a strong sense of cost control; on the other hand, based on the targeted pest control and low toxicity of green pesticides, farmers generally believe that their medicinal properties are weaker than those of traditional pesticides, which has caused farmers to worry about the increased risk of pests (Wang et al., 2020). In recent years, the government has paid great attention to the promotion of green pesticides. The State Council published "Guiding Opinions on Promoting the Revitalization of Rural Industries" in 2019, which proposed to promote fully standardized production on a county-by-county basis in the governance of agricultural products and strengthen the supervision of the entire industrial chain of pesticide quality and safety (The State Council PRC, 2019). The 20th National Congress of the Communist Party of China in 2022 proposed advancing the tackling of pollution prevention and control in depth, ensuring green development, and fully implementing food safety measures. This sets higher standards for the use of pesticides. In terms of specific measures, the Chinese government's green pesticide policy mainly uses transfer payment forms such as direct subsidies for the purchase of agricultural inputs and consumer price subsidies. Direct subsidies for the purchase of agricultural inputs have been a great attraction for farmers, but it is easy for farmers to stop using green pesticides when the subsidies stop. Consumer price subsidies have

TABLE 2 Players' payoff matrix.

	Government	Incentive (x)		Non-incentive $(1-x)$	
	Consumer	Green consumption (z)	Traditional consumption (1 – z)	Green consumption (z)	Traditional consumption (1 – z)
Farmer	Applying green pesticides (y)	$-G_{c1}-G_{c2}-G_{c3}+E_{g1}+E_{g2}-PC$,	$-G_{c1}-G_{c2}+E_{g1}-PC$,	$-G_{c4}+E_{g1}+E_{g2}$,	$-G_{c4}+E_{g1}$,
		$-F_{c1}-F_{c3}-R+\alpha W_1+T+G_{c2}$,	$-F_{c1}-F_{c3}-R+W_2+G_{c2}$,	$-F_{c1}-F_{c3}+\alpha W_1+T$,	$-F_{c1}-F_{c3}+W_2$,
		$-\alpha W_1+E_{s1}+G_{c3}$	$-W_2+E_{s2}$	$-\alpha W_1+E_{s1}$	$-W_2+E_{s2}$
	Applying traditional pesticides (1 – y)	$-G_{c1}-G_{c3}+E_{g2}-PC+PF-G_{c5}$,	$-G_{c1}-PC-G_{c5}$,	$-G_{c4}+E_{g2}-G_{c5}$,	$-G_{c1}-G_{c5}$,
		$-F_{c2}+W_2-T-PF$,	$-F_{c2}+W_2$,	$-F_{c2}+\alpha W_1-T$,	$-F_{c2}+W_2$,
		$-W_2+E_{s1}+G_{c3}$	$-W_2+E_{s2}$	$-\alpha W_1+E_{s1}$	$-W_2+E_{s2}$

better stimulated farmers' enthusiasm for green production and led farmers to use green pesticides in pursuit of high-quality agricultural products (Anh et al., 2021). Strict control by the government and quality control by the market have an important impact on vegetable farmers' motivation to use green pesticides and thus influence their green pesticide use behavior (Teng et al., 2022a).

Scholars have conducted rich and fruitful research on farmers' green pesticide application behavior. Existing studies generally believe that farmers' green pesticide application behavior is affected by many internal and external factors. Among the internal factors, farmers' insufficient understanding of green pesticides (Zhou, 2023), skepticism about the efficacy of green pesticides, education, farming experience, skills, and the high cost of green pesticide application have an important inhibitory effect on farmers' green pesticide application behavior (LIN et al., 2018; Ataei et al., 2021). These have led to serious discrepancies between farmers' willingness and behavior to apply green pesticides. Among the external factors are imperfect systems, lack of government publicity and training (Xiao-shan and Qi-ying, 2011), imperfect market monitoring systems and product traceability systems (Mitchell and Hurley, 2006), small planting size (Liu, 2020), lack of agricultural technology promotion (Jiang and He, 2022), and inadequate supply of rural credit (Li et al., 2023), which are also important factors that prevent farmers from using green pesticides. However, in the final analysis, the application of green pesticides has positive externalities and long-term benefit characteristics, which is inconsistent with farmers' pursuit of short-term individual interests, leaving farmers with no motivation to apply green pesticides (Zhi-gang et al., 2012). In addition, governmental attention (Teng et al., 2022a), farmers' risk attitude, and risk avoidance awareness (Zhou, 2023) are also important factors affecting farmers' green pesticide application behavior and technology promotion.

There have been extensive studies on factors affecting farmers' green pesticide application behavior (Mitchell and Hurley, 2006; Xiao-shan and Qi-ying, 2011; Zhi-gang et al., 2012; LIN et al., 2018; Liu, 2020; Ataei et al., 2021; Teng et al., 2022a; Guo and Hao, 2022; Jiang and He, 2022; Li et al., 2023; Zhou, 2023). However, through the literature review, it is not difficult to find that most of the existing studies set farmers as independent decision-making individuals, and the influencing factors explored are based on the premise of independent decision-making by farmers. However, subject to subjective and objective factors such as cognitive ability and information channels, any decision made by an individual farmer cannot be tested as optimal in one decision. Instead, the decision that is most beneficial to the farmer must be determined through multiple imitations and learnings (Tian and Zheng, 2022). In this process, both the government and consumers will have an impact on farmers' decisions. Therefore, farmers' green pesticide application behavior must be studied from a dynamic and systematic perspective. Evolutionary game theory is a theory that combines game theory analysis and dynamic evolution process analysis. In economics, it is often used to analyze the influencing factors in the formation of social habits, norms, systems, or institutions and explain their formation process (Zhang, 2013). In recent years, evolutionary game theory has been increasingly used in the study of population competition strategies, especially in the fields of energy and environmental governance (Luo et al., 2020). For example, Tian and Zheng (2022) discussed how to encourage farmers to reduce the use of chemical fertilizers by constructing a tripartite evolutionary game model among the government, farmers, and consumers (Tian M. et al., 2022). Xie and Jin (2019) constructed an evolutionary game model between different types of farmers and local governments to explore the key factors affecting the fallow behavior of different types of farmers. Therefore, based on the dynamic evolution perspective, this paper constructs a game model of farmers' adoption of green pesticides and analyzes the formation and evolution process of farmers' green pesticide application behavior. It is of great significance to promote the application of green pesticides by farmers and promote the green development of agriculture.

Compared with previous research (Zhang, 2013; Xie and Jin, 2019; Luo et al., 2020; Tian M. et al., 2022; Tian and Zheng, 2022), this paper mainly has the following marginal contributions: first, from the perspective of dynamic evolution, this paper revealed the influencing factors of farmers' green pesticide application behavior. Based on evolutionary game theory, this paper constructs an evolutionary game model of "bounded rationality" in farmers' green pesticide application, introduces replicated dynamic equations to solve the model, and examines the role of different factors in the dynamic evolution of farmers' green pesticide application decisions. Second, this paper proposes a new

TABLE 3 Stability of equilibrium points.

Equilibrium point	Jacobian matrix eigenvalue	Real part notation	Stability conclusion
	λ_1、 λ_2、 λ_3		
E1 (0,0,0)	$-G_{c1} - PC + G_{c4}$, $-F_{c1} - F_{c3} + F_{c2}$, $E_{s1} - E_{s2} + W_2 - \alpha W_1$	$(+, -, s)$	Saddle point
E2 (0,0,1)	$-G_{c1} - PC + G_{c4} - G_{c3} + PF$, $-F_{c1} - F_{c3} + F_{c2} + 2T$, $E_{s2} - E_{s1}$	$(+, s, -)$	Saddle point
E3 (0,1,0)	$-G_{c1} - PC + G_{c4} - G_{c2}$, $F_{c1} + F_{c3} - F_{c2}$, $E_{s1} - E_{s2} + W_2 - aW_1$	$(+, +, s)$	Saddle point or unstable point
E4 (0,1,1)	$-G_{c1} - PC + G_{c4} - G_{c2} - G_{c3}$, $F_{c1} + F_{c3} - F_{c2} - 2T$, $-E_{s1} + E_{s2} - W_2 + \alpha W_1$	$(-, s, s)$	Saddle point or stable point
E5 (1,0,0)	$G_{c1} + PC - G_{c4}$, $-F_{c1} - F_{c3} + F_{c2} + G_{c2} - R$, $E_{s1} - E_{s2} + G_{c3}$	$(-, s, +)$	Saddle point
E6 (1,0,1)	$G_{c1} + PC - G_{c4} + G_{c3} - PF$, $-F_{c1} - F_{c3} + F_{c2} + G_{c2} - R + PF - W_2 + aW_1 + 2T$, $-E_{s1} + E_{s2} - G_{c3}$	$(-, s, -)$	Saddle point or stable point
E7 (1,1,0)	$G_{c1} + PC - G_{c4} + G_{c2}$, $F_{c1} + F_{c3} - F_{c2} - G_{c2} + R$, $E_{s1} - E_{s2} + G_{c3} + W_2 - \alpha W_1$	$(-, s, s)$	Saddle point or stable point
E8 (1,1,1)	$G_{c1} + PC - G_{c4} + G_{c2} + G_{c3}$, $F_{c1} + F_{c3} - F_{c2} - G_{c2} + R - PF + W_2 - aW_1$ $-2T$, $-E_{s1} + E_{s2} - G_{c3} - W_2 + \alpha W_1$	$(-, s, s)$	Saddle point or stable point

The eigenvalues of the Jacobian matrix are used to determine whether the evolution is stable.

collaborative development framework that integrates the government, farmers, and consumers into a complex system. By observing the impact of the interaction mechanism between them on farmers' green pesticide application, this paper analyzes the conditions for achieving an ideal stable state. Third, existing research on farmers' use of green pesticides in agricultural markets often analyzes the willingness of farmers to use green pesticides based on factors such as the prices of green agricultural products and pesticides. However, this approach overlooks the psychological factors of consumers as market participants and farmers as pesticide users.

The remainder of this research is structured as follows. In Section 2, a three-party game model based on the application of green pesticides by the government, farmers, and consumers is constructed. Section 3 specifically analyzes the modeling process of this research and derives the evolutionary equilibrium and evolutionary stable point of the model. The model is simulated and analyzed using the 2017 agricultural data of Beijing as the initial value, and the influence of key variables is analyzed in depth. The views and literature of this paper are discussed in Section 4, and Section 5 summarizes the main conclusions of this paper, puts forward relevant policy recommendations, and points out the limitations of the paper.

2 Methods

2.1 Model construction

2.1.1 Theoretical basis

This paper uses the evolutionary game theory method to analyze farmers' green pesticide application behavior. Evolutionary game theory is a theory that combines game theory analysis with dynamic evolution process analysis, using systematic thinking from the biological discipline to study the entire economy and society (Taylor and Jonker, 1978). Compared with classical game theory, evolutionary games believe that participants are "bounded rational" rather than "completely rational" (Smith, 1982). Any participant's understanding of economic laws or certain successful behavioral rules and behavioral strategies is constantly revised and improved in the process of evolution. Successful strategies are imitated, resulting in some general "rules" and "systems" as standards of action for participants (Repnikova and Fang, 2018). Therefore, evolutionary game theory is often used to reveal the process and reasons for the formation of a certain rule, system, or behavior.

The green pesticide application strategy has been an important task led by the Chinese government in recent years. The slow evolution of strategies is not only due to farmers' consideration of cost and other factors but is also affected by consumers' green consumption preferences. The government, farmers, and consumers are in a dynamic evolution process in the application of green pesticides. The three parties cannot fully get the information in the environment and can only change their strategies over time to deal with the strategies of other parties and make the most favorable judgments in the process of continuous evolution. Therefore, this paper uses evolutionary game theory to accurately track and analyze the strategy dynamics of the game subject, which provides a theoretical basis for the iterative changes in strategies.

2.1.2 Problem description

This research involves a dynamic game among the government, farmers, and consumers, and its benefit distribution is set with reference to the actual research situation. The application of green pesticides is an important part of Chinese ecological security and food safety. It requires the government, farmers, and consumers to act together under the premise of their own interests to promote the social evolution of green pesticide application behavior.

In the process of the three functions, the government supervises and controls the application of highly polluting pesticides, encourages the promotion of green pesticide application, and

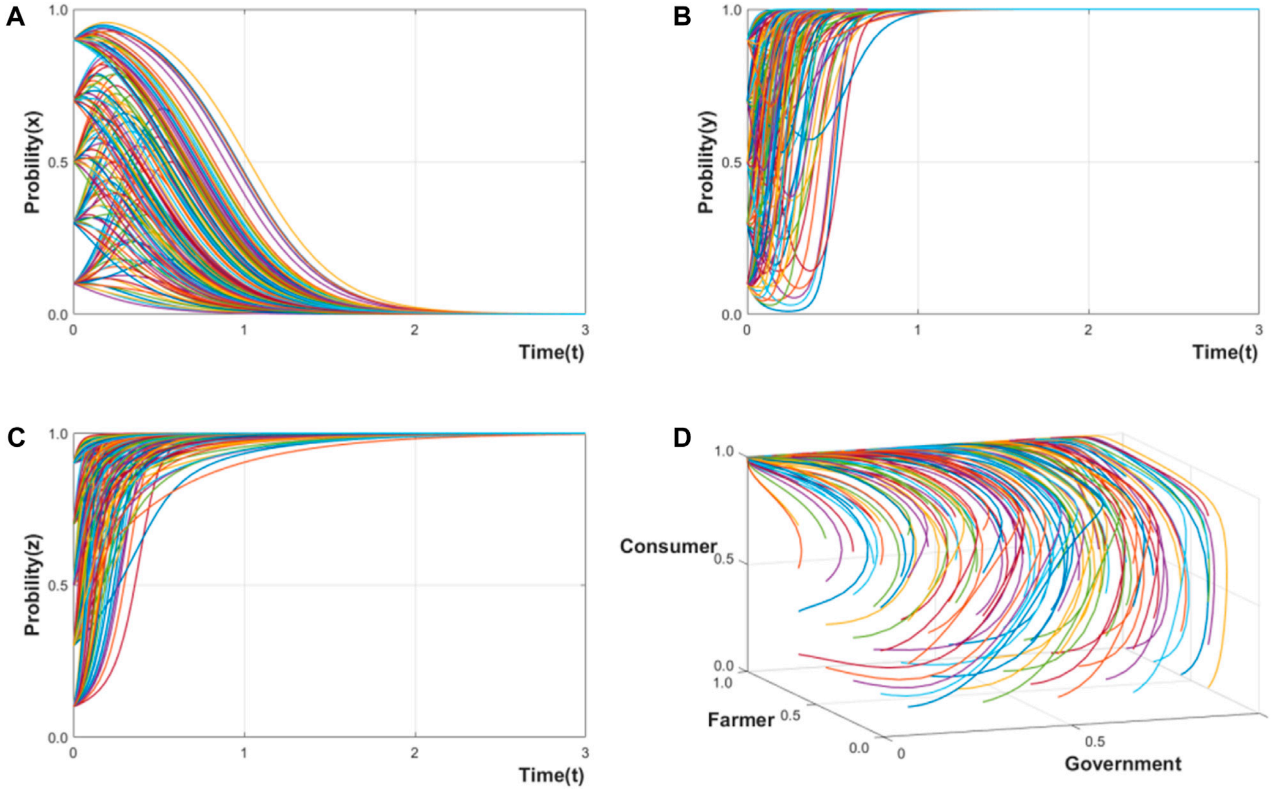

FIGURE 1
Evolution track of (0,1,1). **(A)**. The evolutionary trajectory of government. **(B)**. The evolutionary trajectory of farmers. **(C)**. The evolutionary trajectory of consumers. **(D)**. The evolutionary trajectory of government, farmers and consumers.

provides price subsidies to realize the functions of industry supervision and regulation. Its purpose is to reduce pesticide environmental pollution, improve food safety levels, and ultimately promote the construction of national health through the promotion of green pesticides (Su and Rui, 2022). For example, in February 2016, the "Ministry of Agriculture's Work on Strengthening the Law Enforcement and Supervision of Agricultural Product Quality and Safety" mentioned that it is necessary to strengthen the rectification of banned and restricted pesticides, promote the scientific use of pesticides, and effectively control the risks of pesticide use. In August 2021, the "Notice of Zhejiang Province on Vigorously Promoting Cost Reduction and Efficiency Increase in Grain Production" mentioned the continued implementation of the subsidy policy for the promotion of organic fertilizers and green pesticides. According to market research, government subsidies make the price of green pesticides close to that of traditional pesticides, which is conducive to their promotion. However, it is difficult for farmers to develop endogenous motivation for using subsidies to promote the application of green pesticides. The expansion of the green consumption market will help promote the use of green pesticides by farmers, but the high price of green agricultural products restricts their consumption level. Therefore, the government's publicity and price subsidies for green agricultural products promote green consumption, thus playing a better guiding role in the application of green pesticides.

Farmers are the main group involved in the application of green pesticides. However, farmers use green pesticides mainly based on their own economic benefits, and the selling price and cost are the core factors. Green agricultural products need to be certified, and this cost restricts the application of green pesticides by small-scale farmers. Farmers worry that green pesticides will not be effective in terms of pests and diseases, and this doubt restricts the purchase of green pesticides. Due to the high price of green products, farmers may carry out violations of original equipment manufacturer (OEM) labels, which will increase their profits but reduce consumers' trust in green consumption. This behavior would cause losses to the existing green pesticide application groups (Tian Mengling et al., 2022).

As the main group engaged in green consumption, consumers play a crucial role in providing final feedback on the application of green pesticides. On one hand, consumer trust plays a leading role in green consumption, and the pursuit of a high-quality life and an emphasis on health are the main reasons for green consumption. On the other hand, price is the main constraint factor for green consumption, but preferences may lead consumers to ignore price factors to a certain extent in pursuit of product quality (Guang et al., 2016; Nicolopoulou-Stamati et al., 2016; Geng et al., 2017; Xiang-yan et al., 2018; Zhao et al., 2018; Fu et al., 2020; Xi and Zhang, 2021; Xie et al., 2022). Farmers' violation of OEM labels has caused a setback to consumers' trust, which has a negative effect.

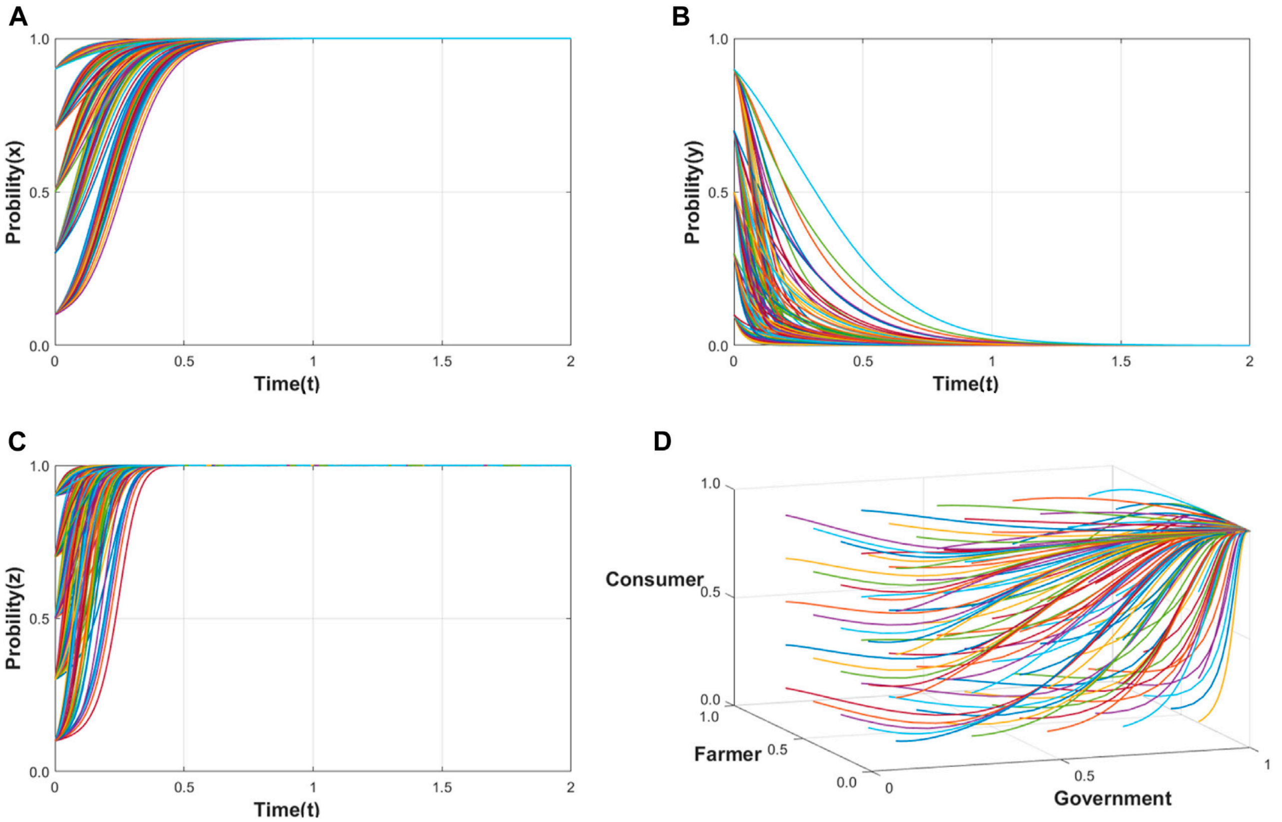

FIGURE 2
Evolution track of (1,0,1). **(A)**. The evolutionary trajectory of government. **(B)**. The evolutionary trajectory of farmers. **(C)**. The evolutionary trajectory of consumers. **(D)**. The evolutionary trajectory of government, farmers and consumers.

2.1.3 Model assumption

In order to strategically promote the rational use of green pesticides, this paper constructed a game model involving the government, farmers, and consumers and assumed as follows:

Assumption 1. The three participants in the model, namely, the government, farmers, and consumers, can adopt two types of strategies in relation to the application of green pesticides. The government can implement various incentive or supervision policies to promote the use of green pesticides by farmers and promote green consumption among consumers.

It may also be due to various reasons, such as a good environment for the application of green pesticides, low implementation efficiency, or the unbearable cost of incentive policies, that some participants may find the payment of environmental pollution acceptable and choose not to adopt incentive policies. This paper considers both possibilities to exist and assumes that the probability of implementation is x, while the probability of non-implementation is 1-x. Similarly, depending on the economic benefits of agricultural products, farmers may also choose the strategy of applying green pesticides. This paper assumes that the probability of applying green pesticides is y and the probability of applying conventional pesticides is 1-y. Consumers may make different choices for green consumption due to issues such as health and thinking habits. This paper assumes that the probability of green consumption is z and the probability of traditional consumption is 1-z.

Assumption 2. From the perspective of the government, in order to ensure environmental security and food safety, the government mainly adopts encouraging and controlling strategies to promote the application of green pesticides by farmers. The payment of encouraging strategies includes training and publicity costs for farmers (denoted as G_{c1}), ecological subsidies for green pesticides through pesticide dealers (denoted as G_{c2}), and price subsidies for green agricultural products merchants (denoted as G_{c3}). The payment of controlling strategies includes the regulatory cost of the green agricultural product market (denoted as PC) (where P is the regulatory intensity and C is the marginal regulatory cost) and the punishment for farmers' violations of OEM (denoted as PF). Generally, encouraging strategies and controlling strategies are parallel. In addition, if the government does not adopt any strategy, the payment includes the increase in administrative costs caused by the loss of government credibility (denoted as G_{c4}) and the cost of environmental governance caused by the use of polluting pesticides (denoted as G_{c5}). If the strategy is successfully implemented, when farmers choose to apply green pesticides, the government will gain environmental governance benefits (E_{g1}). When consumers adopt green consumption, the government receives benefits (E_{g2}) such as social trust and social health.

Assumption 3. From the perspective of farmers, when choosing the strategy to apply green pesticides, the payment by farmers includes the production cost due to procurement (denoted as

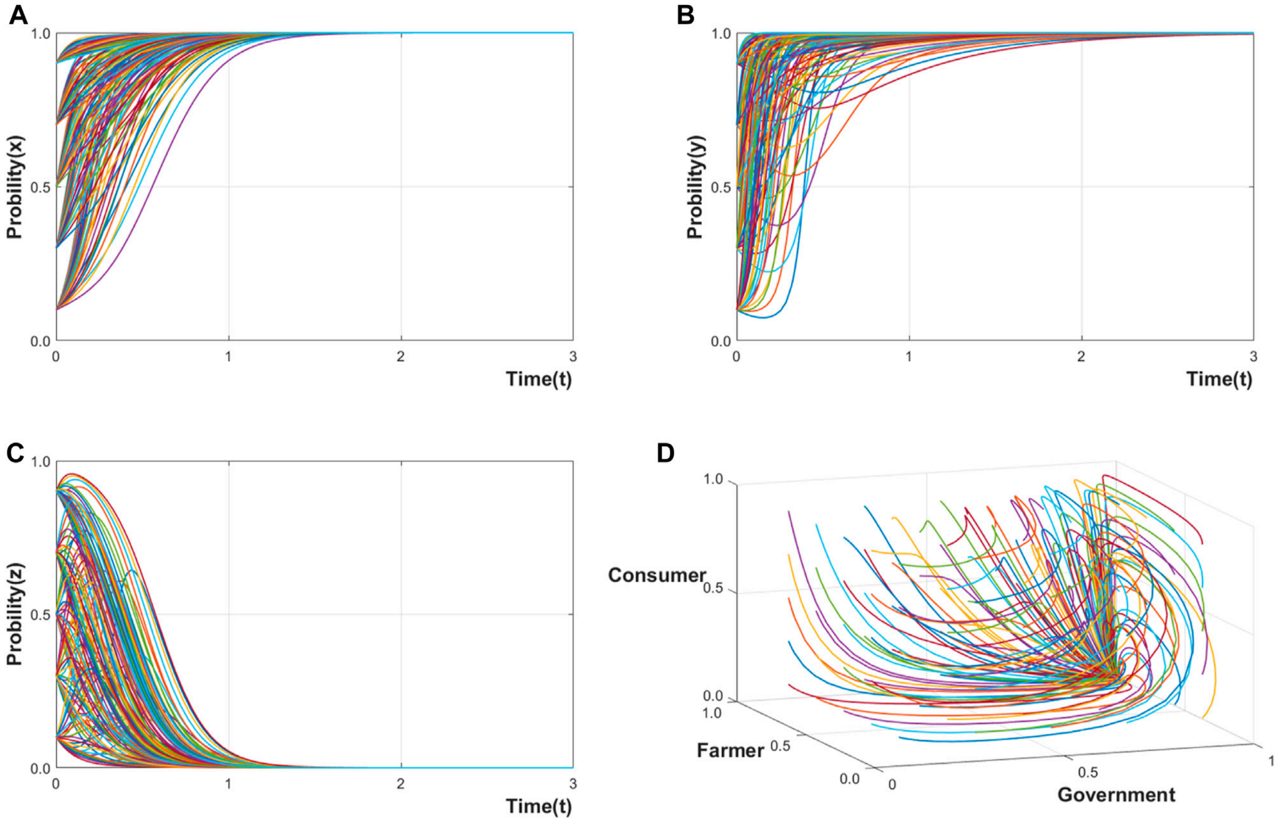

FIGURE 3
Evolution track of (1,1,0). **(A)**. The evolutionary trajectory of government. **(B)**. The evolutionary trajectory of farmers. **(C)**. The evolutionary trajectory of consumers. **(D)**. The evolutionary trajectory of government, farmers and consumers.

F_{c1}), the cost of green agricultural product certification (F_{c3}), and the increased risk of pests and diseases caused by green pesticides (denoted as R). This is because farmers believe that the toxicity of green pesticides is weaker than that of traditional pesticides and their drug effect would be lower. Farmers obtain sales revenue (W_1) and government subsidies (G_{c2}). If farmers choose traditional pesticides, they also need to pay traditional production costs (F_{c2}) and obtain traditional sales revenue (W_2). Regardless of the intermediate cost, this paper assumes that the farmers' sales revenue is equal to the consumer's cost and that $F_{c1} > F_{c2}$ and $W_1 > W_2$.

Assumption 4. From the perspective of consumers, this paper assumes that the cost of consumers' green consumption is W_1, the cost of consumers' traditional consumption is W_2 ($W_1 > W_2$), and the health benefits of consumers' green consumption are E_{s1} and E_{s2} ($E_{s1} > E_{s2}$). Different consumers have different green consumption preferences, denoted as α, with some willing to pay a higher price to buy their favorite green agricultural products. The driving force behind consumers' green consumption is trust. It will lose consumer trust T if consumers pay the cost of green consumption to buy traditional agricultural products (due to illegal OEM); otherwise, it will increase consumer trust.

Table 1 summarizes the actual meanings represented by the symbols of each variable. Based on the above assumptions, the income matrix of the government, farmers, and consumers is shown in Table 2.

2.2 Model analysis

2.2.1 Expected payoff and replicator dynamics equation of each participant

According to the matrix in Table 1, it is assumed that E_{11} is the expected payoff of the government's incentive strategy and E_{12} is the expected payoff of the government's non-incentive strategy.

The average expected payoff is $\overline{E_1} = xE_{11} + (1 - x)E_{12}$.

$$E_{11} = -G_{c1} - yG_{c2} - zG_{c3} - PC + yE_{g1} + zE_{g2} - (1 - y)G_{c5} + z(1 - y)PF, \quad (1)$$

$$E_{12} = -G_{c4} + yE_{g1} + zE_{g2} - (1 - y). \quad (2)$$

Then, according to the evolutionary game theory, the replication dynamic equation can be calculated according to the government's expected payoff, and the publicity is shown in formula (3).

$$F(x) = \frac{dx}{dt} = x(E_{11} - \overline{E_1}) = x(1 - x)(E_{11} - E_{12}) = x(1 - x)[-G_{c1} - PC + G_{c4} - yG_{c2} - zG_{c3} + z(1 - y)PF]. \quad (3)$$

It is assumed that E_{21} is the expected payoff of the farmers' strategy of applying green pesticides and E_{22} is the expected payoff of the farmers' strategy of applying traditional pesticides.

The average expected payoff is $\overline{E_2} = yE_{21} + (1 - y)E_{22}$.

TABLE 4 Initial values of all variable unit.

Initial parameter	Value (10^6Yuan)
Government's training and publicity costs G_{c1}	2.2
Government's ecological subsidies for green pesticides G_{c2}	6.3
Government's price subsidies for green agricultural products merchants G_{c3}	3.6
Increase in administrative costs caused by the loss of government credibility G_{c4}	18
Marginal regulatory cost C	12
Supervision of farmers' violations of OEM F	6.5
Regulatory intensity P	0.4
Production cost due to the application of green pesticides F_{c1}	42
Production cost due to the application of traditional pesticides F_{c2}	20
Cost of green agricultural product certification F_{c3}	7.2
Increased risk of pests and diseases caused by green pesticides R	12
Cost of green consumption by consumers W_1	44
Cost of traditional consumption by consumers W_2	22.5
Green consumption preferences α	1.2
Consumer trust T	4
Health benefits because of consumers' green consumption E_{s1}	60
Health benefits because of consumers' traditional consumption E_{s2}	30

$$E_{21} = -F_{c1} - F_{c3} - xR + z\alpha W_1 + (1-z)W_2 + xG_{c2} + zT, \quad (4)$$

$$E_{22} = -F_{c2} - zT - xzPF + (1 - z + xz)W_2 + z(1-x)\alpha W_{1.}. \quad (5)$$

The replicator dynamics equation can be calculated as

$$\begin{aligned} F(y) = \frac{dy}{dt} &= y(1-y)(E_{21} - E_{22}) \\ &= y(1-y)[-F_{c1} - F_{c3} + F_{c2} + x(G_{c2} - R) + xz(PF - W_2 + aW_1) + 2zT]. \end{aligned} \quad (6)$$

It is assumed that E_{31} is the expected payoff of the consumers' strategy of green consumption and E_{32} is the expected payoff of the consumers' strategy of traditional consumption.

The average expected payoff is $\overline{E_3} = zE_{31} + (1-z)E_{32}$.

$$E_{31} = -F_{c1} - F_{c3} - xR + z\alpha W_1 + (1-z)W_2 + xG_{c2} + zT, \quad (7)$$

$$E_{32} = -F_{c2} - zT - xzPF + (1 - z + xz)W_2 + z(1-x)\alpha W_{1.}. \quad (8)$$

The replicator dynamics equation can be calculated as

$$\begin{aligned} F(z) = \frac{dz}{dt} &= z(1-z)(E_{31} - E_{32}) \\ &= z(1-z)\left[E_{s1} - E_{s2} + xG_{c3} + \left(1 - x + xy\right)(W_2 - \alpha W_1)\right]. \end{aligned} \quad (9)$$

2.2.2 Local stability analysis of the evolutionary game

When $F(x, y, z) \to 0$, the point (x, y, z) tends to be stable over time, indicating that the model is in an optimized stable state. Specifically, when a = 0 and b < 0, the model is stable. According to the principle of the equation, the strategic stability analysis of the government, farmers, and consumers is as follows: when the replicator dynamics equation is 0 and its first derivative is less than 0, this strategy is the optimal solution that the government, farmers, and consumers can choose.

Therefore, from the perspective of the government, formula (3) can be deduced as follows:

(1) When $(G_{c1} + PC - G_{c4} + zG_{c3} - zPF)/(G_{c2} - zPF) < y < 1$, $\frac{d(f(x))}{dx}|_{x=1} > 0$, then $\frac{d(f(x))}{dx}|_{x=0} < 0$. It can be inferred that $x = 0$ is the evolutionary stable point of the government. It shows that the government forms a stable non-incentive strategy.

(2) When $y = (G_{c1} + PC - G_{c4} + zG_{c3} - zPF)/(G_{c2} - zPF)$ and $F(x) \equiv 0$, it can be inferred that the government has the same benefits under the two strategies of incentives and non-incentives, and all x are evolutionary stable.

(3) When $0 < y < (G_{c1} + PC - G_{c4} + zG_{c3} - zPF)/(G_{c2} - zPF)$, then $\frac{d(f(x))}{dx}|_{x=1} < 0, \frac{d(f(x))}{dx}|_{x=0} > 0$; it can be inferred that $x = 1$ is the evolutionary stable point of the government. It shows that the government's strategy changes from non-incentive to incentive and finally forms a stable state.

From the perspective of the farmers, formula (6) can be deduced as follows:

(4) When $0 < z < (F_{c1} + F_{c3} - F_{c2} - 2zT)/\ [G_{c2} - R + z(PF - W_2\ + aW_1)]$, then $\frac{d(f(y))}{dy}|_{y=1} > 0$ and $\frac{d(f(y))}{dy}|_{y=0} < 0$; it can be inferred that $y = 0$ is the evolutionary stable point of the farmers. It shows that farmers' strategies will shift from

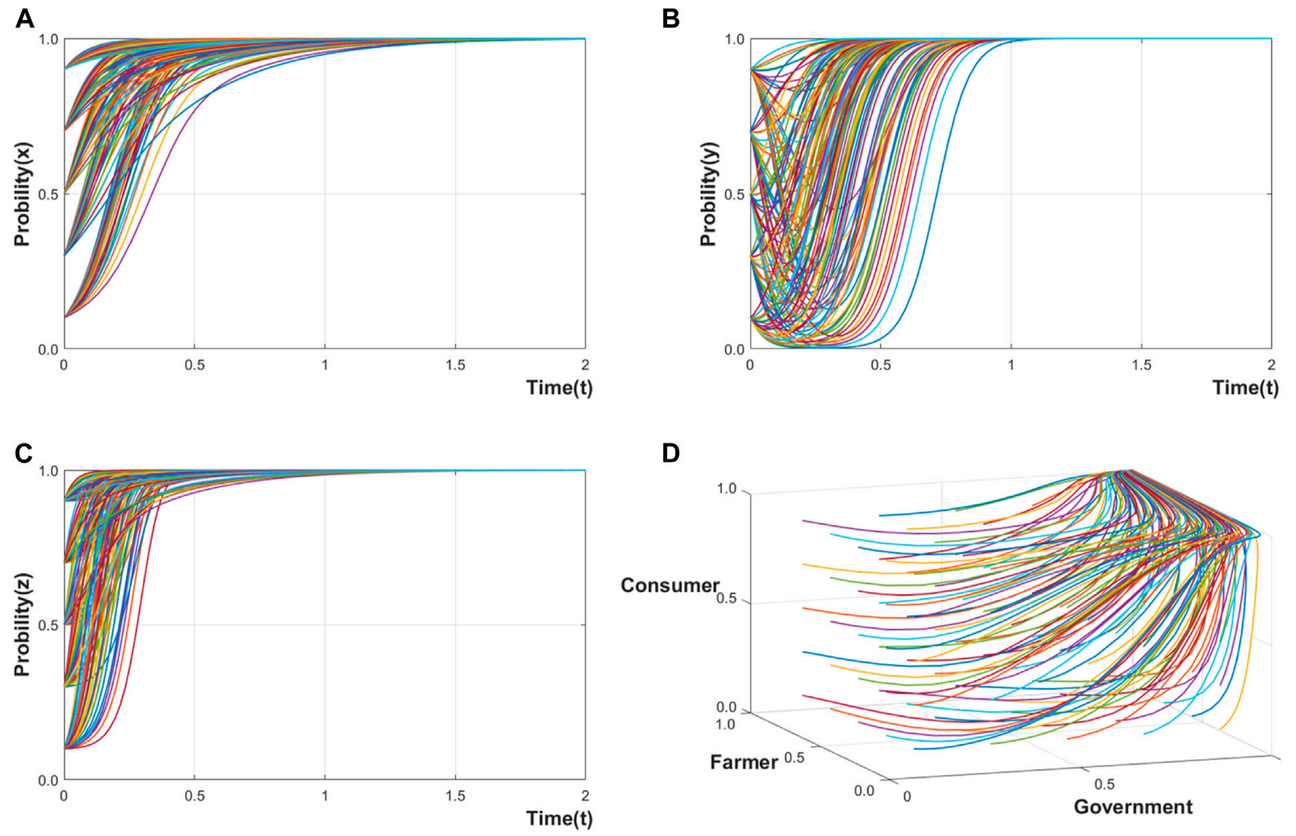

FIGURE 4
Evolution track of (1,1,1). **(A)**. The evolutionary trajectory of government. **(B)**. The evolutionary trajectory of farmers. **(C)**. The evolutionary trajectory of consumers. **(D)**. The evolutionary trajectory of government, farmers and consumers.

the application of green pesticides to traditional pesticides and form a steady state of choosing traditional pesticides.

(5) When $z = (F_{c1} + F_{c3} - F_{c2} - 2zT)/[G_{c2} - R + z(PF - W_2 + aW_1)]$, then $Fy \equiv 0$; it can be inferred that the farmers have the same benefits under the two strategies of application of green pesticides and traditional pesticides, and all y are evolutionary stable.

(6) When $(F_{c1} + F_{c3} - F_{c2} - 2zT)/[G_{c2} - R + z(PF - W_2 + aW_1)] < z < 1$, then $\frac{d(f(y))}{dy}|_{y=1} < 0$ and $\frac{d(f(y))}{dy}|_{y=0} > 0$; it can be inferred that $y = 1$ is the evolutionary stable point of the farmer. It shows that the farmers' strategy changes from the application of traditional pesticides to green pesticides and finally forms a stable state.

From the perspective of consumers, formula (9) can be deduced as follows:

(1) When $0 < x < (E_{s2} - E_{s1} + W_2 - \alpha W_1)/[(G_{c3} + y - 1)(W_2 - \alpha W_1)]$, then $\frac{d(f(z))}{dz}|_{z=0} < 0$ and $\frac{d(f(z))}{dz}|_{z=1} > 0$; it can be inferred that $z = 0$ is the evolutionary stable point of the consumers. It shows that consumers' strategies will shift from green consumption to traditional consumption and form a steady state of choosing traditional consumption.

(2) When $x = (E_{s2} - E_{s1} + W_2 - \alpha W_1)/[(G_{c3} + y - 1)(W_2 - \alpha W_1)]$, $Fz \equiv 0$; it can be inferred that the consumer share the same benefits under the two strategies of green consumption and traditional consumption, and all z are evolutionary stable.

When $(E_{s2} - E_{s1} + W_2 - \alpha W_1)/[(G_{c3} + y - 1)(W_2 - \alpha W_1)] < x < 1$, then $\frac{d(f(z))}{dz}|_{z=0} > 0$ and $\frac{d(f(z))}{dz}|_{z=1} < 0$; it can be inferred that $z = 1$ is the evolutionary stable point of the consumers. It shows that the consumers' strategy changes from traditional consumption to green consumption and finally forms a stable state.

2.2.3 Analysis of the trend of the evolutionary game

When replication dynamic equations $F(x)$、 $F(y)$、 and $F(z)$ are all equal to zero, eight equilibrium points can be obtained: E1 (0,0,0), E2 (0,0,1), E3 (0,1,0), E4 (0,1,1), E5 (1,0,0), E6 (1,0,1), E7 (1,1,0), and E8 (1,1,1). The theory holds that both the Nash equilibrium and the pure strategy Nash equilibrium are satisfied to achieve the evolutionarily stable strategy (ESS). Therefore, it is necessary to judge each equilibrium point. The asymptotic stability of the equilibrium points is judged using the Lyapunov discriminant method, so the design model needs to be solved using the Jacobian matrix.

In this paper, the Jacobian matrix of the government, farmers, and consumers is shown in formula (10); by taking the first-order partial derivatives of the replication dynamic $F(x)$、 $F(y)$、 and $F(z)$ with respect to x, y, and z, the eigenvalue of the Jacobian matrix can be obtained. The characteristic values of each point are shown in Table 3. The specific calculation process is as follows:

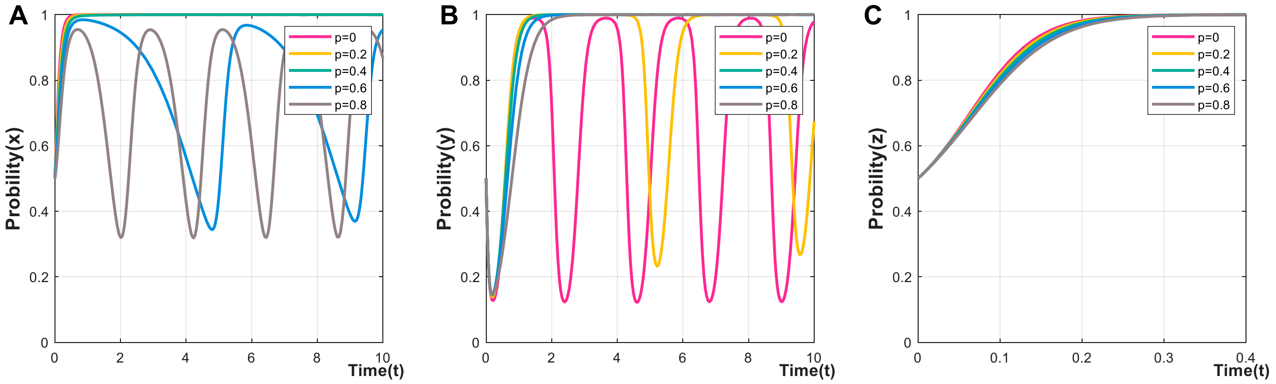

FIGURE 5
Impact of government supervision intensity. **(A)**. The impact of government. **(B)**. The impact of farmers. **(C)**. The impact of consumers.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}. \quad (10)$$

Therefore,

$$J_{11} = (1-2x)[-G_{c1} - PC + G_{c4} - yG_{c2} - zG_{c3} + z(1-y)PF], \quad (11)$$

$$J_{12} = x(1-x)(-G_{c2} - zPF), \quad (12)$$

$$J_{13} = x(1-x)(-G_{c2} + PF - yPF), \quad (13)$$

$$J_{21} = y(1-y)[G_{c2} - R + z(PF - W_2 + aW_1)], \quad (14)$$

$$J_{22} = (1-2y)[-F_{c1} - F_{c3} + F_{c2} + x(G_{c2} - R) + xz(PF - W_2 + aW_1) + 2zT], \quad (15)$$

$$J_{23} = y(1-y)[x(PF - W_2 + aW_1) + 2T], \quad (16)$$

$$J_{31} = z(1-z)[G_{c3} + (y-1)(W_2 - \alpha W_1)], \quad (17)$$

$$J_{32} = z(1-z)(xW_2 - x\alpha W_1), \quad (18)$$

$$J_{33} = (1-2z)[E_{s1} - E_{s2} + xG_{c3} + (1-x+xy)(W_2 - \alpha W_1)]. \quad (19)$$

If the eigenvalues of J are all less than 0, then the equilibrium point is considered to be an evolutionarily stable strategy. If one or two of the eigenvalues are less than 0, it is a saddle point; if all of them are greater than 0, it is an unstable point. According to previous assumptions, before the market stabilizes, the increase in administrative costs caused by the loss of government credibility G_{c4} would be higher than all other costs incurred by the government, that is, $G_{c4} > G_{c1} + G_{c2} + G_{c3}$. In addition, the cost-benefit comparison of green pesticide application, traditional pesticide application, and their agricultural product sales have certain rules like $F_{c1} > F_{c2}$, $E_{s1} > E_{s2}$, and $\alpha W_1 > W_2$. This paper considers that E1 (0,0,0), E2 (0,0,1), and E5 (1,0,0) can be defined as saddle points. In these cases, when one participant maximizes the benefits, the other two participants do not realize the optimal benefits, and it may also be that none of the three participants achieve the maximum benefits, which is not the subject of this research. In addition, neither participant in E3 (0,1,0) has maximized the benefits, and this option is also excluded. Therefore, this project discusses the saddle point or stable point E4 (0,1,1), E6 (1,0,1), E7 (1,1,0), and E8 (1,1,1). In this state, at least one participant has maximized benefits, or all three participants have maximized benefits.

Scenario 1: (0,1,1) is the evolutionary stable point. In this scenario, the cost of government incentives is greater than the cost of non-incentives, and the government chooses no incentives. The cost of the application of green pesticides by farmers is smaller than that of traditional pesticides, and the farmers choose the application of green pesticides. The cost of green consumption by consumers is lower than traditional consumption, and consumers choose green consumption. Equalities (20)–(22) are established according to Table 3.

$$G_{c1} + PC + G_{c2} + G_{c3} > G_{c4}, \quad (20)$$

$$F_{c1} + F_{c3} < F_{c2} + 2T, \quad (21)$$

$$E_{s2} + \alpha W_1 < E_{s1} + W_2. \quad (22)$$

Scenario 1 shows that since farmers and customers form a stable internal cycle of green consumption, the loss of government credibility is reduced to below the incentive cost by the government, so the government chooses no incentive strategy. Farmers take consumer trust into consideration when considering the cost of agricultural products and think that the cost of applying green pesticides is smaller, so they choose the strategy of application of green pesticides. Consumers choose the green consumption strategy when their payment increment is greater than their cost increment through green consumption. Scenario 1 forms evolutionary stability, which happens to be the most favorable scenario that the government expects, and it is also a good internal cycle formed under the economic environment

In this scenario, consumer trust is the key factor affecting the balance between farmers and consumers. Therefore, cultivating and amplifying consumer trust will effectively promote the interaction between farmers and consumers, reducing the government's cost and workload. We include the corresponding parameters $G_{c1} = 2.2, G_{c2} = 6.3, \quad G_{c3} = 5.6, G_{c4} = 15, C = 12, F = 6.5, P = 0.4, F_{c1} = 39.6, \quad F_{c2} = 30, F_{c3} = 7.2, R = 12, W_1 = 44, W_2 = 22.5, a = 1.2, T = 12, E_{s1} = 62,$ and $E_{s2} = 30$, and simulate the evolution process. As shown in Figure 1, in any initial state, the model eventually conforms

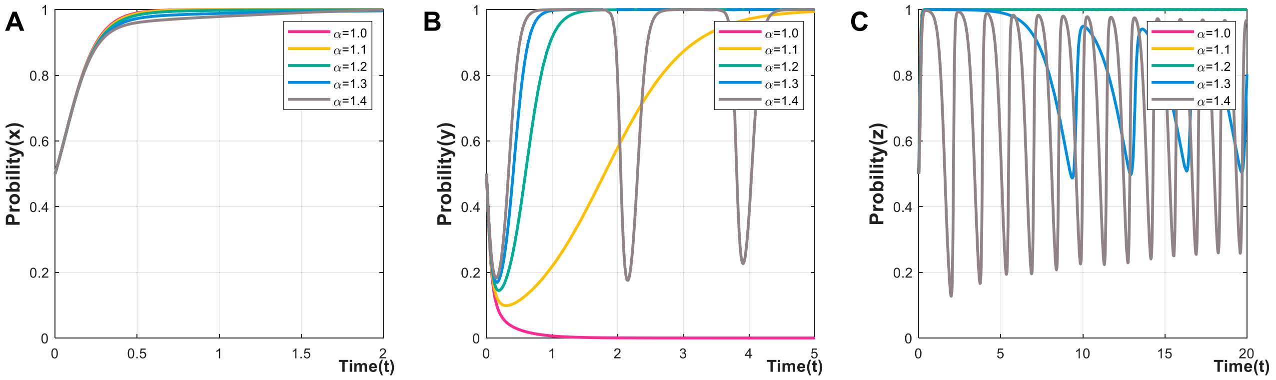

FIGURE 6
Impact of green consumption preferences. **(A)**. The impact of government. **(B)**. The impact of farmers. **(C)**. The impact of consumers.

to the characteristics of Scenario 1 and finally stabilizes at (0,1,1). This scenario is expected to be achievable in the future, but it is not in line with China's current economic situation.

Scenario 2: (1,0,1) is the evolutionary stable point. In this scenario, the cost of government incentives is smaller than the cost of non-incentives, and the government chooses incentives. The cost of the application of green pesticides by farmers is greater than that of traditional pesticides, and the farmers choose the application of traditional pesticides. The cost of green consumption by consumers is lower than traditional consumption, and consumers choose green consumption. Equalities (23)–(25) are established according to Table 3.

$$G_{c1} + PC + G_{c3} < G_{c4} + PF, \tag{23}$$

$$aW_1 + 2T + G_{c2} + PF + F_{c2} < W_2 + F_{c1} + F_{c3} + R, \tag{24}$$

$$E_{s2} < E_{s1} + G_{c3}. \tag{25}$$

Scenario 2 shows that all government incentive costs should be smaller than the sum of government credibility loss costs and governance costs, so the government opted for an incentive strategy. Farmers choose strategies of application of traditional pesticides by selling traditional agricultural products as green products through illegal OEM. When the health benefits brought by green consumption are greater than the costs, consumers choose strategies for green consumption. In this scenario, the information gap between consumers and farmers makes consumers think that green consumption is real. This scenario is unreasonable, but it exists objectively in China because of information asymmetry between farmers and consumers and relatively loose government supervision. The punishment for farmers' violations of OEM is the key factor affecting the strategies of the application of green pesticides. This paper includes the corresponding parameters $G_{c1} = 2.2, G_{c2} = 6.3, G_{c3} = 3.6, G_{c4} = 18, C = 12, F = 6.5, P = 0.2, F_{c1} = 39.6, F_{c2} = 20, F_{c3} = 7.2, R = 16, W_1 = 44, W_2 = 22.5, a = 1.2, T = 0, E_{s1} = 62$, and $E_{s2} = 30$, and simulates the evolution process. As shown in Figure 2, in any initial state, due to loose supervision and information asymmetry between consumers and farmers, farmers gradually choose the application of traditional pesticides. The model eventually conforms to the characteristics of Scenario 2 and eventually stabilizes at (1,0,1).

Scenario 3: (1,1,0) is the evolutionary stable point. In this scenario, the cost of government incentives is smaller than the cost of non-incentives, and the government chooses incentives. The cost of the application of green pesticides by farmers is smaller than that of traditional pesticides, and the farmers choose the application of green pesticides. The cost of green consumption by consumers is greater than traditional consumption, and the consumers choose traditional consumption. Equalities (26)–(28) are established according to Table 3.

$$G_{c1} + PC + G_{c2} < G_{c4}, \tag{26}$$

$$F_{c1} + F_{c3} + R < F_{c2} + G_{c2}, \tag{27}$$

$$\alpha W_1 + E_{s2} < E_{s1} + G_{c3} + W_2. \tag{28}$$

Scenario 3 shows that when the ecological subsidy for the application of green pesticides by the government is great and the efficacy of green pesticides is closer to that of traditional pesticides, farmers will choose strategies of application of green pesticides even if consumers choose traditional consumption. However, when the government's green consumption subsidies are smaller, consumers may carry out traditional consumption from the perspective of their own interests. The ecological subsidy for the application of green pesticides, appropriate agricultural subsidies, and the cost reduction and performance improvement caused by the innovation of green pesticide technology are the key reasons to promote the use of green pesticides by farmers, even if the market is small. This paper includes the corresponding parameters: $G_{c1} = 2.2, G_{c2} = 10, G_{c3} = 3.6, G_{c4} = 22, C = 12, F = 6.5, P = 0.4, F_{c1} = 20, F_{c2} = 20, F_{c3} = 5.2, R = 3, W_1 = 44, W_2 = 22.5, a = 1.2, T = 4, E_{s1} = 50, E_{s2} = 30$, and simulates the evolution process.

As shown in Figure 3, in any initial state, due to the government subsidy policy and the cost reduction and efficiency improvement of green pesticides, the model eventually conforms to the characteristics of Scenario 3 and eventually stabilizes at (1,1,0).

Scenario 4: (1,1,1) is the evolutionary stable point. In this scenario, the cost of government incentives is smaller than the cost of non-incentives, and the government chooses incentives. The cost of the application of green pesticides by farmers is smaller than that of traditional pesticides, and the farmers choose

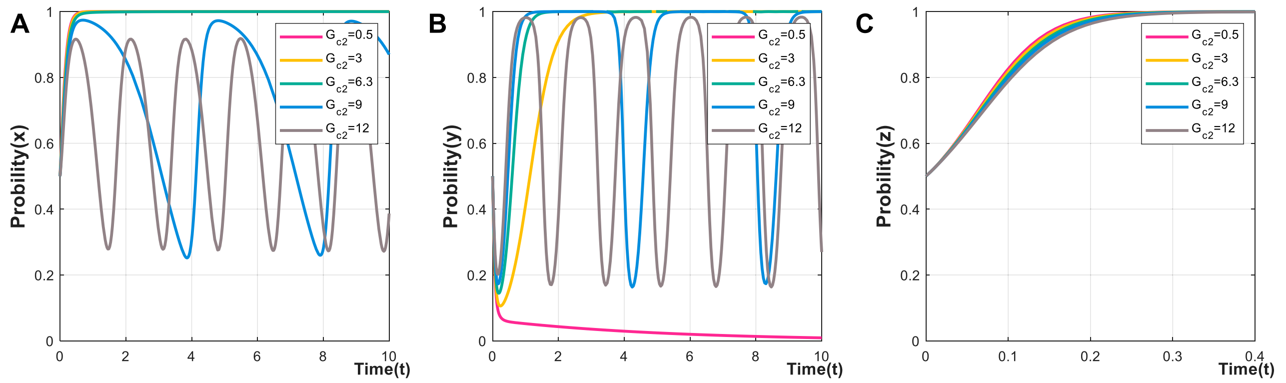

FIGURE 7
Impact of agricultural price subsidy. **(A)**. The impact of government. **(B)**. The impact of farmers. **(C)**. The impact of consumers.

the application of green pesticides. The cost of green consumption by consumers is smaller than traditional consumption, and the consumers choose green consumption. Equalities (29)–(31) are established according to Table 3.

$$G_{c1} + PC + G_{c2} + G_{c3} < G_{c4}, \tag{29}$$

$$F_{c1} + F_{c3} + R + W_2 < aW_1 + G_{c2} + 2T + F_{c2} + PF, \tag{30}$$

$$\alpha W_1 + E_{s2} < E_{s1} + G_{c3} + W_2. \tag{31}$$

Scenario 4 shows that, when the government encourages and regulates, farmers who choose traditional pesticides need to bear the cost of regulatory penalties and the risk of losing consumer trust. The choice of the application of green pesticides has to pay higher production costs but obtain more production subsidies and higher payment. Consumers receive subsidies for green consumption. When the incentive policy is within a good range, a steady state of win–win for all three participants will be achieved. This scenario is a form that is expected to be realized in China in the near future, and it is also a healthy form in which the government, farmers, and consumers jointly promote the application of green pesticides. This paper includes the corresponding parameters: $G_{c1} = 2.2, G_{c2} = 6.3, G_{c3} = 3.6, G_{c4} = 18, C = 12, F = 6.5,$ $P = 0.4, F_{c1} = 42, F_{c2} = 20, F_{c3} = 7.2, R = 12, W_1 = 44, W_2 = 22.5, a = 1.2, T = 4,$ $E_{s1} = 60,$ and $E_{s2} = 30.$ As shown in Figure 4, in any initial state, the model eventually conforms to the characteristics of Scenario 4. The three participants have achieved a win–win situation in the application of green pesticides and eventually stabilized at (1,1,1).

2.2.4 Relationship of the parameters

The normal occurrence of Scenario 2 (1,0,1) is based on the lack of government supervision and the information asymmetry between consumers and farmers. It is a typical, unreasonable, but real social phenomenon. When the regulation is reasonable and the information is gradually symmetrical, this stable state will disappear naturally and will be gradually promoted by the government to form a stable state of Scenario 4 (1,1,1). Scenario 4 is an ideal model in which the government, farmers, and customers participate together, and it is also the game model expected in this study. If a high level of information synchronization between farmers and consumers is achieved through means such as digital traceability, high-quality consumer groups are expected to promote the realization of Scenario 1 (0,1,1), where farmers and consumers have achieved a closed loop of green consumption without government participation. Furthermore, continuous technological improvements driving down the cost of green pesticides may prompt government subsidies to make up the difference. The closed-loop supervision of green pesticide application between the government and farmers will be normalized, that is, Scenario 1 (1,1,0). The above scenarios are part of an evolutionary process in social development.

3 Results

3.1 Initial parameters

According to research (Zhi-gang et al., 2012; Jian et al., 2015; Su and Rui, 2022), subsidies for the application of green pesticides are more common in northern China. As the most typical region, Beijing was focusing on exploring the new green product subsidy model of “substituting subsidies instead of issuing” oriented toward green ecology and granted limit subsidies for more than 120,000 mu of facility vegetables in 11 districts in 2017, effectively mobilizing the enthusiasm of farmers to apply green pesticides. This study selects the agricultural data of Beijing in 2017 as a case of setting the initial value of the variables in this paper, which has strong reference significance for promoting the application of green pesticides in other regions.

3.2 Variable assignment

The initial values of the variables in this study are mainly obtained through the following methods. The first way is to obtain information regarding the implementation of the green pesticide policy by querying the budget disclosure information on the official government website. According to the “2017 Project Expenditure Budget Statement of Beijing Municipal Bureau of Agriculture and Rural Affairs,” the Beijing Municipal Bureau of Agriculture and Rural Affairs invested 2.2 million yuan in agricultural publicity and education. In the work of pest control, the plant protection station issued a total of 6.305 million yuan of agricultural subsidies in the project of "substituting subsidies instead of issuing" for pesticide control and treated 120,000 mu of vegetables in facilities, with an average subsidy of approximately 52.5 yuan per mu. Agricultural product service stations spent 3.56 million yuan on agricultural product price subsidies, 4.79 million yuan on market quality supervision, and 2.6 million yuan on regulatory expenditure for farmer quality and safety. The second way is to obtain the input costs and output benefits of agricultural markets from statistical yearbooks and documents. According to the "Compilation of National Agricultural Product Cost and Benefit Data," in 2017, farmers invested 167 yuan in traditional pesticides per mu of vegetables, which is about 5% of the total cost of vegetables. According to the subsidy calculation, the cost of application of green pesticide per mu in vegetable plants is approximately 367 yuan, and we calculate that the cost of application of green pesticide in 120,000 mu of facilities is 42 million yuan and that of traditional pesticide is 20 million yuan.

It is approximately 7,500 yuan per mu of the average annual output value of traditional vegetables in Chinese cities in 2017, and the price of green agricultural products of vegetables and fruits is about 2–3 times that of traditional products (Academic Press, 2021; Tian Mengling et al., 2022; Xun et al., 2022; Yin et al., 2022). We believe that the average annual output value per mu of green vegetables can reach 15,000 yuan.

It can be obtained that the application of green pesticides contributed 44 million yuan (not the final price) and the application of traditional pesticides contributed 22.5 million yuan to the output value of vegetables in Beijing's 120,000 mu facility.

The third way is research and assumptions. The cost of China's green agricultural product certification is 18,000 yuan per item. Assuming that there are 6,000 cooperatives in Beijing participating in the planting of 120,000 mu of vegetables and that the green certification is depreciated according to the land circulation period of 15 years, we then analyze that the annual certification cost is 7.2 million yuan. The author collected 33 kinds of green vegetables (excluding delivery fees) from the agricultural product trading platform and compared them with the price monitoring data of the local farmers' market. The average price is about 20.3% larger. Therefore, it is assumed that the green consumption preference α is 1.2. According to 113 survey questionnaires from farmers in a certain area of Zhejiang Province, 84.9% of them believe that the intensity of government supervision is more general. The project team agrees that the intensity of government supervision P is 0.4. We calculate that when the government fully supervises, the regulatory cost of the green agricultural product market is 12 million yuan, and the supervision cost of punishment for farmers' violations of OEM is 6.5 million yuan. According to the practice of Xie, H., Wang, W., and Zhang, X. (2018), the increase in administrative costs caused by the loss of government credibility is estimated by the government's training and publicity costs, subsidy costs, and regulatory expenditure costs and tentatively set at 18 million yuan (Xie et al., 2018). The fourth way is to collect the opinions of agricultural experts. Some parameter data are difficult to collect, such as the increased risk of pests and diseases caused by green pesticides, consumer trust, the health benefits of consumers' green consumption, and traditional consumption. In order to improve the accuracy of parameter quantification, the project adopts Delphi technology and invites nine experts (six associate professors of agriculture and three professors of economics) divided into three groups to estimate the parameters. The entire valuation process consists of the following steps: the team provides the model, parameters, and collected basic information for expert reference; the experts provide estimates and reasons for their opinions and form written materials; summarize opinions and feedback to experts for correction; provide feedback for the third time and collect valuations again; use the averaging method to form the final valuation plan of the expert group. The increased risk of pests and diseases caused by green pesticides is mainly obtained by multiplying the amount of losses and the risk ratio of yield reduction caused by the application of green pesticides. Consumer trust is estimated by the user stickiness income formed by consumers buying high-quality products and the credit loss caused by consumers buying illegal OEM products. The health benefits are obtained through a comprehensive evaluation by experts in combination with consumer purchase costs and consumption status.

The parameter evaluation after the simplified calculation is shown in Table 4.

This paper considers that Scenario 4 (1,1,1) is the most practical scenario under the current situation, and it is an ideal model that we think is expected to be realized. That is, a win–win situation can be achieved for all three participants under the scenario where the government implements incentives, farmers choose the application of green pesticides, and consumers choose green consumption. In this study, the following parameters will be analyzed as key variables affecting the game of application of green pesticides: regulatory intensity on the green agricultural product market by the government (P), green consumption preferences (α), and government's ecological subsidies for green pesticides (G_{c2}). We will analyze this by making variable adjustments for these key parameters and keeping other parameters constant.

3.3 Impact of government supervision intensity

This paper sets the regulatory intensity on the green agricultural product market by the government (P) as 0, 0.2, 0.4, 0.6, and 0.8, which means that the government's regulatory intensity is 0, 50%, 100%, 150%, and 200% of the original parameter, respectively. The simulation results are shown in Figures 5A–C. The results show that government regulatory policies have a significant effect on promoting farmers and consumers to participate in cooperation. When the intensity of government supervision is lower than 50% of the current level, even if the government introduces a green pesticide subsidy policy and market consumers have strong green consumption demand, farmers will not choose to apply green pesticides. Facts have shown that when the government only focuses on incentives and ignores supervision, farmers may encounter moral hazards such as illegal labeling during the application of green pesticides (Aschemann-Witzel and Zielke, 2017; Geng et al., 2017). According to the simulation results, high incentives and low supervision will lead to a relative decrease in the cost of illegal labeling for farmers, and they will tend to choose illegal labeling to improve benefits, thereby reducing their willingness to apply green pesticides. When the intensity of government supervision is higher than 150% of the existing supervision level, farmers and consumers will reach cooperation; that is, farmers will choose to apply green pesticides and consumers will choose green consumption. However, high regulatory levels will lead to a decrease in the government's willingness to implement incentive policies. The main reason is that high regulatory expenditures will increase the government's financial burden, and the government needs to balance fiscal expenditures by reducing incentives. Therefore, the government's regulatory intensity is recommended to be kept within a reasonable range between 50% and 150%.

3.4 Impact of green consumption preferences

This paper sets the green consumption preferences (α) as 1, 1.1, 1.2, 1.3, and 1.4, which means that consumers are willing to choose green consumption of 83.3%, 91.7%, 100%, 108.3%, and 116.7% of the original price in different situations. The simulation results are shown in Figures 6A–C, which, respectively, represent the impact of the government, farmers, and consumers due to changes in green consumption preferences. The results show that consumers' green consumption preference is a key factor influencing farmers' choice to apply green pesticides and consumers' choice of green consumption. When the level of green consumption is reduced to 83.3% of the original parameter, farmers' decision-making will eventually evolve and stabilize to not apply green pesticides. The main reason is that the green agricultural product market under low green preference often exhibits oversupply, thus suppressing the market price of green agricultural products (Li and Niu, 2020). When farmers' net income from applying traditional pesticides is higher than the net income from using green pesticides, farmers' willingness to use green pesticides will gradually decrease, and eventually, they will choose to use traditional pesticides. When the level of green consumption reaches 108.3% of the original parameter, consumers' willingness to choose green consumption decreases, but this change will not affect farmers' strategies for applying green pesticides. When green consumption continues to rise above 116.7% of the original parameter, the decline in consumers' willingness to consume shows a cyclical fluctuation trend, and farmers' willingness to apply green pesticides also declines, showing a cyclical fluctuation trend. This shows that consumers' acceptance of green agricultural product prices cannot be higher than 110% of existing agricultural product prices. When it is higher than this value, consumers will not implement green consumption behaviors, even if they have high green consumption awareness. The decline in purchasing power affects the sales of green agricultural products and affects the application of green pesticides from the perspective of economic benefits. Therefore, gradually cultivating consumers' green consumption preferences and guiding the market price to stay within the range between 83.3% and 108.3% of the current price can maintain the stability of evolution.

3.5 Impact of agricultural price subsidy

This paper sets the government's ecological subsidy for green pesticides (G_{c2}) as 0.5, 3, 6.3, 9, and 12 based on the existing subsidy policy, which means that the level of the government's ecological subsidies for green pesticides is 8%, 47.6%, 100%, 142.8%, and 190.4% of the original level. The simulation results are shown in Figures 7A–C, which, respectively, represent the impact of the government, farmers, and consumers due to changes in the government's ecological subsidy for green pesticides. The results show that the government's ecological subsidy policy has a significant effect on farmers' application of green pesticides but has a smaller impact on consumers' consumption behavior.

When the level of the government's ecological subsidy for green pesticides is reduced to 47.6% of the original subsidy, farmers' willingness to apply green pesticides is always lower. This shows that the ecological subsidy given by the government to farmers is not enough to offset the expected risk costs caused by the application of green pesticides, so farmers tend to choose traditional pesticide applications. When the government's ecological subsidy for the application of green pesticides is increased to the original 47.6%–142.8%, farmers' willingness to apply green pesticides and consumers' willingness to consume green significantly increase. Farmers choose to apply green pesticides, and consumers also choose green consumption. When the level of the government's ecological subsidy for green pesticides is increased to 142.8% of the original level, the government's payment of subsidy increases the government's financial pressure, and the difficulty of implementation reduces the government's willingness to provide incentives. The decline in incentives makes it more difficult to apply for subsidies, which negatively affects farmers' enthusiasm for the application of green pesticides. Therefore, it is recommended that the government's price subsidy be kept within the range of 47.6% and 142.8% at the current stage to enable the three participants to reach a stable state.

4 Discussion

As the largest source of pollution, pesticides have seriously affected the country's ecological security and food safety (Li and Niu, 2020). Countries have also taken various measures to promote the reduction of pesticide applications. For example, the United States introduced the Conservation Reserve Program (CRP) to subsidize cleaner agricultural production; South Korea passed the "Environmental Agriculture Cultivation Law" to promote the reduction of pesticides using incentives, crop rotation, certification, and biological pesticides (JIN, 2005; Wang et al., 2018); and Japan promotes the pesticide reduction plan through the implementation of "environmental protection agriculture" with technological innovation, identification and labeling systems, financial support, and tax incentives (Jing and Xiujuan, 2013). In order to promote the development of green pesticides, China acted on the plans by formulating the 973 Plan (chaired by Academician Qian Xuhong of East China University of Science and Technology), the National Key Research and Development Program (chaired by Academician Song Bao'an of Guizhou University and Professor Li Zhong of East China University of Science and Technology), and the

"Action Plan for Zero Growth in Pesticide Use by 2020"(2015), committed to promoting the low toxicity of pesticides through technology research, policy subsidies, agricultural material supervision, and social publicity. According to the model established in this paper, it is an effective promotion strategy for the government to increase agricultural subsidy funds and strengthen the intensity of government supervision. On one hand, agricultural subsidies reduce the cost of application of green pesticides to achieve the purpose of incentives; on the other hand, the strengthening of government supervision increases the cost of non-compliance for farmers, making the application of green pesticides economically advantageous.

According to the simulation results of this paper, the government's green pesticide subsidy policy and regulatory policy are effective incentives to encourage farmers to apply green pesticides. However, high agricultural subsidies not only stimulate farmers' enthusiasm for green pesticide application but also put pressure on government fiscal expenditures. On one hand, agricultural subsidies can help farmers increase costs caused by the green application of pesticides and subsidize farmers' personal losses caused by improved environmental benefits, thus forming a significant positive impact on farmers' willingness to use green pesticides (Van Der Werf and Bianchi, 2022). On the other hand, agricultural subsidy incentives can only play a short-term role and cannot fundamentally stimulate farmers' pro-environmental behavior (Feng, 2006). This is also an important reason why the government is unwilling to provide high subsidies. Therefore, moderate regulation should be regarded as a long-term effective measure. In addition, using very strong regulatory measures will lead to excessive government regulatory costs and higher costs for farmers due to regulation, which will affect the overall stability of the model. If regulatory measures are not in place, it will cause farmers to illegally label their products and use traditional pesticides but sell green agricultural products. This research result is also consistent with the reality in China; for example, Fengtai District, Beijing, adheres to "green prevention and control, comprehensive prevention and control," strengthens various measures, and has achieved results in the control of agricultural non-point source pollution (He et al., 2023). Although many studies on agricultural environmental governance have pointed out the optimization path of environmental governance (Takeshima and Nkonya, 2014; Chu et al., 2022; Yuan et al., 2023), most of them are suggestions based on historical data. However, policy simulation is a virtual imitation of the effects of policy instrument implementation in the real world. Due to its future-oriented nature, its results cannot be verified with traditional out-of-sample fitting (Feng, 2006). The policy simulation results of this paper can make up for the shortcomings of existing research to a certain extent.

Compared with government incentives, encouraging farmers to form an incentive and self-execution mechanism is the key to truly promoting farmers' application of green pesticides. Some scholars believe that agricultural marketization can help guide farmers to engage in green production behaviors (Chandler et al., 2008; Boussemart et al., 2016; Wen et al., 2018; Buchholz and Musshoff, 2021). Realizing the normalization of green consumption through market transactions is a better solution to give full play to the subjective initiative of farmers in the application of green pesticides. It has the advantages of low management costs, small side effects, and high effectiveness by regulating the price of green agricultural products in a market-oriented way to improve the quality of the industrial chain (Jouzi et al., 2017). Appropriate green consumption preferences will improve the sales price of high-quality agricultural products, attract farmers to cultivate intensively, and produce better green agricultural products, thereby forming a benign market atmosphere. However, in real life, there is serious pricing chaos in the green agricultural product market, which is a dilemma where producers "cannot sell" and consumers "cannot afford" (TUYLS and NOWÉ, 2005; Tuyls and Parsons, 2007; Eddleston et al., 2008; Junge et al., 2011; Xuerong et al., 2016; Luo et al., 2017; Shuqin and Fang, 2018; Delgado et al., 2019; Mengfei et al., 2019; Chi et al., 2021; Pan et al., 2021; Ren et al., 2021; Smith et al., 2021; Teng et al., 2021; Teng et al., 2022b; Teng et al., 2022c; Li et al., 2022; Liu et al., 2022; Permana and Sanjaya, 2022; Su et al., 2022). The simulation results of this article show that increasing consumers' preference for green consumption is an effective incentive method driven by the market, but the price of green agricultural products higher than consumers' expectations will not only reduce consumers' willingness to consume green but also reduce farmers' willingness to apply green pesticides. Therefore, to improve farmers' willingness to apply green pesticides, we must not only improve farmers' ecological compensation and appropriate supervision for green production at the policy level but also build a green agricultural product price mechanism at the market level.

5 Conclusion and policy implications

Based on the evolutionary game theory, this paper constructs an evolutionary game model of the application of green pesticides, which reveals the dynamic game mechanism in which the government, farmers, and consumers participate in the balance of interests. By combining case data from Beijing, this paper explores the impact of parameter changes on the evolution trajectory of the three strategy choices. Its main conclusions are as follows:

First, the scenario where the government implements incentive policies, farmers use green pesticides, and consumers choose green consumption is an ideal stable state. Key factors influencing the evolution of the system to stabilize in this ideal state include government subsidy costs, regulatory costs, farmers' non-compliance costs, and consumers' green consumption preferences. Among them, government subsidy and supervision are the direct factors affecting the application of green pesticides, and the consumer's green consumption preference is the indirect factor.

Second, the government recommends keeping the regulatory intensity within a reasonable range, between 50% and 150% of the original regulatory intensity, which will help farmers apply green pesticides. Insufficient supervision can easily lead to moral hazards among farmers who illegally label their products. Although high regulatory intensity can avoid this problem, it will lead to rising government regulatory costs and workload, thus affecting the government's willingness to regulate. At the same time, keeping the government's ecological subsidies for green pesticides within the range of 47.6% and 142.8% will help stimulate farmers' enthusiasm for the application of green pesticides. Insufficient subsidies may cause farmers to choose the application of traditional pesticides again, while excessive subsidies will reduce the willingness of the government to subsidize.

Third, for consumers and farmers, the appropriate price range for green agricultural products is 80%–110% of the existing price level. When the price of green agricultural products is lower than 80% of the existing price, it will inhibit farmers' willingness to apply green pesticides, but when the price of green agricultural products is higher than 110% of the existing price level, it is not conducive to consumers' implementation of green consumption behavior.

Based on the above research conclusions, this study puts forward the following suggestions:

First, the government should moderately strengthen ecological subsidies and market supervision. The application of green pesticides should be promoted from a dual perspective to ensure that supervision and subsidies are within their own tolerance and will not cause excessive pressure on their own workload and financial situation. The subsidy strategies should fully combine the regional economic development level and the government's financial situation. The workload of market supervision should also be moderately controlled, and it is recommended to actively adopt the digital management methods that are vigorously promoted in Jiangsu, Zhejiang, and Shanghai to reduce the government's burden and improve work efficiency. Second, according to the regional characteristics of consumers' green consumption preferences, the sales price of popular high-quality fruits and vegetables should be appropriately guided to increase to encourage farmers to apply green pesticides. Third, digital agriculture should be vigorously promoted. The government should make good use of agricultural monitoring technology and blockchain traceability technology, as well as the in-depth application in agriculture of platforms such as Global Migration to 2D, thus tracking the application of pesticides in the production process of green agricultural products from the source, improving the product testing and digital management system, and eliminating information asymmetry with real-time display of the full link of information so as to establish a trust consensus mechanism between consumers and farmers to reduce the pressure of government supervision.

An explanation is needed for the fact that the decision spaces of all participants in the game model in this paper are simplified to some extent without considering the influence of other stakeholders, such as pesticide manufacturers and vegetable and fruit merchants, on the model. Future research may consider incorporating more stakeholders into the scope of the study. In addition, this paper only uses data from Beijing in 2017 as a project case, which has certain limitations. Future research could combine quantitative methods or other large-sample research approaches to enhance the authenticity and universality of this model.

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: data curation, investigation, project administration, resources, software, validation, visualization, writing–original draft, and writing–review and editing. XC: conceptualization, formal analysis, methodology, and writing–review and editing. XS: funding acquisition, supervision, and writing–review and editing.

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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.

Publisher's note

References

Academic Press (2021). *Recent highlights in the discovery and optimization of crop protection products*. Academic Press, 39–64.

Alavanja, M. C. (2009). Introduction: pesticides use and exposure, extensive worldwide. *Rev. Environ. health* 24 (4), 303–309. doi:10.1515/reveh.2009.24.4.303

Anh, H. Q., Le, T. P. Q., Da Le, N., Lu, X. X., Duong, T. T., Garnier, J., et al. (2021). Antibiotics in surface water of East and Southeast Asian countries: a focused review on contamination status, pollution sources, potential risks, and future perspectives. *Sci. Total Environ.* 764, 142865. doi:10.1016/j.scitotenv.2020.142865

Aschemann-Witzel, J., and Zielke, S. (2017). Can't buy me green? A review of consumer perceptions of and behavior toward the price of organic food. *J. Consumer Aff.* 51 (1), 211–251. doi:10.1111/joca.12092

Ataei, P., Gholamrezai, S., Movahedi, R., and Aliabadi, V. (2021). An analysis of farmers' intention to use green pesticides: the application of the extended theory of planned behavior and health belief model. *J. Rural Stud.* 81, 374–384. doi:10.1016/j.jrurstud.2020.11.003

Boussemart, J. P., Leleu, H., and Ojo, O. (2016). Exploring cost dominance in crop farming systems between high and low pesticide use. *J. Prod. Analysis* 45, 197–214. doi:10.1007/s11123-015-0443-1

Buchholz, M., and Musshoff, O. (2021). Tax or green nudge? An experimental analysis of pesticide policies in Germany. *Eur. Rev. Agric. Econ.* 48 (4), 940–982. doi:10.1093/erae/jbab019

Chandler, D., Davidson, G., Grant, W. P., Greaves, J., and Tatchell, G. M. (2008). Microbial biopesticides for integrated crop management: an assessment of environmental and regulatory sustainability. *Trends Food Sci. Technol.* 19 (5), 275–283. doi:10.1016/j.tifs.2007.12.009

Chi, Y., Zhou, W., Wang, Z., Hu, Y., and Han, X. (2021). The influence paths of agricultural mechanization on green agricultural development. *Sustainability* 13 (23), 12984. doi:10.3390/su132312984

Chu, Z., Bian, C., and Yang, J. (2022). How can public participation improve environmental governance in China? A policy simulation approach with multi-player evolutionary game. *Environ. Impact Assess. Rev.* 95, 106782. doi:10.1016/j.eiar.2022.106782

Delgado, J. A., Short Jr, N. M., Roberts, D. P., and Vandenberg, B. (2019). Big data analysis for sustainable agriculture on a geospatial cloud framework. *Front. Sustain. Food Syst.* 3, 54. doi:10.3389/fsufs.2019.00054

Eddleston, M., Buckley, N. A., Eyer, P., and Dawson, A. H. (2008). Management of acute organophosphorus pesticide poisoning. *Lancet* 371 (9612), 597–607. doi:10.1016/S0140-6736(07)61202-1

Feng, X. (2006). *Theory and method of rural marketization*. Beijing: China Economic Press.

Fu, S., Chen, W., Ding, J., and Wang, D. (2020). Multi-party game and simulation of government impact on the development of agricultural supermarket docking. *Complex Syst. Complex. Sci.* 17 (3), 10. doi:10.13306/j.1672-3813.2020.03.005

Geng, Y. N., Zheng, S. F., and Lu, Q. (2017). Impact of economic incentives and social networks on farmers' adoption of integrated pest management technology—evidence from the kiwifruit main production areas of Shaanxi Province. *J. Huazhong Agric. Univ. Soc. Sci. Ed.* 6, 59–69. doi:10.13300/j.cnki.hnwkxb.2017.06.008

Guang, J., Hong-Li, C., and Bao-Qing, S. (2016). Study on food security, farmers' behavior and developing strategy—based on a survey data from farmers in hubei. *J. Anhui Agric. Sci.* doi:10.13989/j.cnki.0517-6611.2016.01.093

Guo, Q., and Hao, Li (2022). Green pesticide application behavior of farmers from the perspective of land ownership heterogeneity. *J. Zhejiang Agric. Sci.* (09), 2068–2072. doi:10.16178/j.issn.0528-9017.20213202

He, W., Zhang, K., Kong, Y., Yuan, L., Peng, Q., Mulugeta Degefu, D., et al. (2023). Reduction pathways identification of agricultural water pollution in Hubei Province, China. *Ecol. Indic.* 153, 110464. doi:10.1016/j.ecolind.2023.110464

Jian, Yu, Yu-e, C., Bian, Z.-qiang, Xiang-hong, T., Zhang, J., and He-hui, Z. (2015). Investigation on pesticides residues in rural drinking water in typical provinces of north and south China. *J. Environ. Health* 32 (No.8), 721–723. doi:10.16241/j.cnki.1001-5914.2015.08.018

Jiang, H., and He, Y. (2022). Evaluation of optimal policy on environmental change through green consumption. *Sustainability* 14 (9), 4869. doi:10.3390/su14094869

Jing, H., and Xiujuan, J. (2013). Enlightments of environmental safety agriculture in Japan to agriculture sustainable development in China. *J. Northwest A&F Univ. Soc. Sci. Ed.* 13 (4), 93–97. doi:10.13968/j.cnki.1009-9107.2013.04.004

Jin, Z. (2005). Environment-Friendly agricultural development policy in S.Korea. *Issues Agric. Econ.* (3), 73–78. doi:10.13246/j.cnki.iae.2005.03.017

Jouzi, Z., Azadi, H., Taheri, F., Zarafshani, K., Gebrehiwot, K., Van Passel, S., et al. (2017). Organic farming and small-scale farmers: main opportunities and challenges. *Ecol. Econ.* 132, 144–154. doi:10.1016/j.ecolecon.2016.10.016

Junge, X., Lindemann-Matthies, P., Hunziker, M., and Schüpbach, B. (2011). Aesthetic preferences of non-farmers and farmers for different land-use types and proportions of ecological compensation areas in the Swiss lowlands. *Biol. Conserv.* 144 (5), 1430–1440. doi:10.1016/j.biocon.2011.01.012

Li, C., and Niu, B. (2020). Design of smart agriculture based on big data and internet of things. *Int. J. Distributed Sens. Netw.* 16, 155014772091706. doi:10.1177/1550147720917065

Li, H., Wang, C., Chang, W. Y., and Liu, H. (2023). Factors affecting Chinese farmers' environment-friendly pesticide application behavior: a meta-analysis. *J. Clean. Prod.* 409, 137277. doi:10.1016/j.jclepro.2023.137277

Li, H., Yuan, K., Cao, A., Zhao, X., and Guo, L. (2022). The role of crop insurance in reducing pesticide use: evidence from rice farmers in China. *J. Environ. Manag.* 306, 114456. doi:10.1016/j.jenvman.2022.114456

Lin, R., Zhou, L., and Zhou, S. D. (2018). Effect of nearby farms and operation scale on farmer's pesticide application—a case study on peanut growers. *Fujian J. Agric. Sci.* 33 (11), 1224–1230. doi:10.19303/j.issn.1008-0384.2018.11.018

Liu, gang (2020). The institutional logic and practice path for green development of agriculture. *Contemp. Econ. Manag.* 42 (05), 35–40. doi:10.13253/j.cnki.ddjjgl.2020.05.005

Liu, Y., Shi, R., Peng, Y., Wang, W., and Fu, X. (2022). Impacts of technology training provided by agricultural cooperatives on farmers' adoption of biopesticides in China. *Agriculture* 12 (3), 316. doi:10.3390/agriculture12030316

Luo, J., Qiu, C., Zheng, Y., and Zhang, H. (2017). Game model analysis and comparison of three patterns of agro-technical popularization. *Journ al Yunnan Agric. Univ. Soc. Sci.* 11 (1), 8. doi:10.3969/j.issn.1004-390X(s).2017.01.004

Luo, M., Fan, R., Zhang, Y., and Zhu, C. (2020). Environmental governance cooperative behavior among enterprises with reputation effect based on complex networks evolutionary game model. *Int. J. Environ. Res. Public Health* 17 (5), 1535. doi:10.3390/ijerph17051535

Lykogianni, M., Bempelou, E., Karamaouna, F., and Aliferis, K. A. (2021). Do pesticides promote or hinder sustainability in agriculture? The challenge of sustainable use of pesticides in modern agriculture. *Sci. Total Environ.* 795, 148625. doi:10.1016/j.scitotenv.2021.148625

Mengfei, G., Yuxin, W., and Jing, Z. (2019). Research on the stakeholder evolution game of ecological compensation for commercial forests in key ecological locations. *Issues For. Econ.* doi:10.16832/j.cnki.1005-9709.2019.05.006

Ministry of Agriculture and Rural Development of China (2022). Notice on 24 batches of agricultural products found to be problematic in supervision and sampling tests. *Ministry Agric. Rural Aff. Circular*. Available at: http://www.jgs.moa.gov.cn/gzdt/202201/t20220110_6386595.htm.

Mitchell, P. D., and Hurley, T. M. (2006). Adverse selection, moral hazard, and grower compliance with Bt corn refuge. *Regul. Agric. Biotechnol. Econ. policy*, 599–623. doi:10.1007/978-0-387-36953-2_27

Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P., and Hens, L. (2016). Chemical pesticides and human health: the urgent need for a new concept in agriculture. *Front. public health* 4, 148. doi:10.3389/fpubh.2016.00148

Pan, Y., Ren, Y., and Luning, P. A. (2021). Factors influencing Chinese farmers' proper pesticide application in agricultural products–A review. *Food control.* 122, 107788. doi:10.1016/j.foodcont.2020.107788

Permana, Y. H., and Sanjaya, M. R. (2022). Nudging green preferences: evidence from a laboratory experiment. *J. Int. Commer. Econ. Policy* 13 (02), 2250011. doi:10.1142/S1793993322500119

Raffa, C. M., and Chiampo, F. (2021). Bioremediation of agricultural soils polluted with pesticides: a review. *Bioengineering* 8 (7), 92. doi:10.3390/bioengineering8070092

Ren, C., Jin, S., Wu, Y., Zhang, B., Kanter, D., Wu, B., et al. (2021). Fertilizer overuse in Chinese smallholders due to lack of fixed inputs. *J. Environ. Manag.* 293, 112913. doi:10.1016/j.jenvman.2021.112913

Repnikova, M., and Fang, K. (2018). Authoritarian participatory persuasion 2.0: netizens as thought work collaborators in China. *J. Contemp. China* 27 (113), 763–779. doi:10.1080/10670564.2018.1458063

Shao, X., Du, S., Zhong, Li, and Qian, X. (2021). "Research and development of green pesticides in China," in *Recent highlights in the discovery and optimization of crop protection products* (Academic Press), 29–36.

Shuqin, J. I. N., and Fang, Z. H. O. U. (2018). Zero growth of chemical fertilizer and pesticide use: China's objectives, progress and challenges. *J. Resour. Ecol.* 9 (1), 50–58. doi:10.5814/j.issn.1674-764x.2018.01.006

Smith, H. H., Idris, O. A., and Maboeta, M. S. (2021). Global trends of green pesticide research from 1994 to 2019: a bibliometric analysis. *J. Toxicol.* 2021, 1–11. doi:10.1155/2021/6637516

Smith, J. M. (1982). *Evolution and the theory of games* (Cambridge, England: Cambridge University Press).

Su, X., and Rui, Li (2022). Practice on promoting the use of pesticides in Kongtong District. *Gansu Agric.* (01), 113–115. doi:10.15979/j.cnki.cn62-1104/f.2022.01.030

Su, X., Shi, J., Wang, T., Shen, Q., Niu, W., and Xu, Z. (2022). More income, less pollution? How income expectation affects pesticide application. *Int. J. Environ. Res. Public Health* 19, 5136. doi:10.3390/ijerph19095136

Sun, S., Sidhu, V., Rong, Y., and Zheng, Y. (2018). Pesticide pollution in agricultural soils and sustainable remediation methods: a review. *Curr. Pollut. Rep.* 4, 240–250. doi:10.1007/s40726-018-0092-x

Takeshima, H., and Nkonya, E. (2014). Government fertilizer subsidy and commercial sector fertilizer demand: evidence from the Federal Market Stabilization Program (FMSP) in Nigeria. *Food policy* 47, 1–12. doi:10.1016/j.foodpol.2014.04.009

Taylor, P. D., and Jonker, L. B. (1978). Evolutionary stable strategies and game dynamics. *Math. Biosci.* 40 (1-2), 145–156. doi:10.1016/0025-5564(78)90077-9

Teng, Y., Chen, X., Jin, Y., Yu, Z., and Guo, X. (2022a). Influencing factors of and driving strategies for vegetable farmers' green pesticide application behavior. *Front. Public Health* 10, 907788. doi:10.3389/fpubh.2022.907788

Teng, Y., Chen, X., Yu, Z., and Wei, J. (2021). Research on the evolutionary decision-making behavior among the government, farmers, and consumers: based on the quality and safety of agricultural products. *IEEE Access* 9, 73747–73756. doi:10.1109/ACCESS.2021.3078561

Teng, Y., Lin, P. W., Chen, X. L., and Wang, J. L. (2022c). An analysis of the behavioral decisions of governments, village collectives, and farmers under rural waste sorting. *Environ. Impact Assess. Rev.* 95, 106780. doi:10.1016/j.eiar.2022.106780

Teng, Y., Pang, B., Wei, J., Ma, L., Yang, H., and Tian, Z. (2022b). Behavioral decision-making of the government, farmer-specialized cooperatives, and farmers regarding the quality and safety of agricultural products. *Front. Public Health* 10, 920936. doi:10.3389/fpubh.2022.920936

The State Council (PRC) (2019) *Guiding opinions on promoting the revitalization of rural Industries*. National Development [2019] No. 12.

Tian, M., and Zheng, Y. (2022). How to promote the withdrawal of rural land contract rights? An evolutionary game analysis based on prospect theory. *Land* 11 (8), 1185. doi:10.3390/land11081185

Tian, M., Zheng, Y., Sun, X., and Zheng, H. (2022a). A research on promoting chemical fertiliser reduction for sustainable agriculture purposes: evolutionary game analyses involving government, farmers, and consumers. *Ecol. Indic.* 144, 109433. doi:10.1016/j.ecolind.2022.109433

Tian, M., Zheng, Y., Sun, X., and Zheng, H. (2022b). A research on promoting chemical fertiliser reduction for sustainable agriculture purposes: evolutionary game analyses involving 'government, farmers, and consumers'. *Ecol. Indic.* 144, 109433. doi:10.1016/j.ecolind.2022.109433

Tuyls, K., and Parsons, S. (2007). What evolutionary game theory tells us about multiagent learning. *Artif. Intell.* 171 (7), 406–416. doi:10.1016/j.artint.2007.01.004

Tuyls, K., and Nowé, A. (2005). Evolutionary game theory and multi-agent reinforcement learning. *Knowl. Eng. Rev.* 20 (1), 63–90. doi:10.1017/S026988890500041X

Van Der Werf, W., and Bianchi, F. (2022). Options for diversifying agricultural systems to reduce pesticide use: can we learn from nature? *Outlook Agric.* 51 (1), 105–113. doi:10.1177/00307270221077442

Wang, Y., Zhu, Y., Zhang, S., and Wang, Y. (2018). What could promote farmers to replace chemical fertilizers with organic fertilizers? *J. Clean. Prod.* 199, 882–890. doi:10.1016/j.jclepro.2018.07.222

Wang, Z., Geng, Y., and Liang, T. (2020). Optimization of reduced chemical fertilizer use in tea gardens based on the assessment of related environmental and economic benefits. *Sci. total Environ.* 713, 136439. doi:10.1016/j.scitotenv.2019.136439

Wen, L., Junfang, S. I., and Liyun, X. U. (2018). Analysis of the game among the government,businesses,and consumers at the backdrop of the sharing economy-the operation of shared bicycles as an example. *J. Jianghan Univ. Soc. Sci. Ed.* doi:10.16387/j.cnki.42-1867/c.2018.04.009

Xi, X., and Zhang, Y. (2021). Complexity analysis of production, fertilizer-saving level, and emission reduction efforts decisions in a two-parallel agricultural product supply chain. *Chaos, Solit. Fractals* 152, 111358. doi:10.1016/j.chaos.2021.111358

Xiang-yan, G., Yan-xiang, Ge, and Hua-nan, Z. (2018). Study on ecological compensation standard of watershed based on reset cost: a case study of xiaoqing River Basin. China Population. *Resounrce Environ.* 28 (1), 140–147. doi:10.12062/cpre.20170720

Xiao-shan, Y., and Qi-ying, L. (2011). On factors influencing peasant households' willingness to use bio-rational pesticide and green pesticides under the economic incentives-A study based on the questionnaire survey of peasant households in fujian province. *J. Jiangxi Agric. Univ.* 10 (1), 5. doi:10.16195/j.cnki.cn36-1328/f2011.01.020

Xie, H., and Jin, S. (2019). Evolutionary game analysis of fallow farmland behaviors of different types of farmers and local governments. *Land Use Policy* 88, 104122. doi:10.1016/j.landusepol.2019.104122

Xie, H., Wang, W., and Zhang, X. (2018). Evolutionary game and simulation of management strategies of fallow cultivated land: a case study in Hunan province, China. *Land Use Policy* 71, 86–97. doi:10.1016/j.landusepol.2017.11.050

Xie, Y., Su, Y., and Li, F. (2022). The evolutionary game analysis of low carbon production behaviour of farmers, government and consumers in food safety source governance. *Int. J. Environ. Res. Public Health* 19 (19), 12211. doi:10.3390/ijerph191912211

Xuerong, Li, Wang, H., and Zhang, L. (2016). The policy practice of foreign pesticide application reduction and its enlightenment to China. *World Agric.* 2016 (11), 6. doi:10.13856/j.cn11-1097/s.2016.11.013

Xun, L., Garcia-Ruiz, F., Fabregas, F. X., and Gil, E. (2022). Pesticide dose based on canopy characteristics in apple trees: reducing environmental risk by reducing the amount of pesticide while maintaining pest and disease control efficacy. *Sci. Total Environ.* 826, 154204. doi:10.1016/j.scitotenv.2022.154204

Yin, Z., Li, B., Li, S., Ding, J., and Zhang, L. (2022). Key influencing factors of green vegetable consumption in Beijing, China. *J. Retail. Consumer Serv.* 66, 102907. doi:10.1016/j.jretconser.2021.102907

Yuan, L., Wu, X., He, W., Degefu, D. M., Kong, Y., Yang, Y., et al. (2023). Utilizing the strategic concession behavior in a bargaining game for optimal allocation of water in a transboundary river basin during water bankruptcy. *Environ. Impact Assess. Rev.* 102, 107162. doi:10.1016/j.eiar.2023.107162

Zhang, W. (2013). *Game and society* (Beijing, China: Peking University Press).

Zhao, L., Wang, C., Gu, H., and Yue, C. (2018). Market incentive, government regulation and the behavior of pesticide application of vegetable farmers in China. *Food control.* 85, 308–317. doi:10.1016/j.foodcont.2017.09.016

Zhi-gang, WANG, Sheng-nan, HUANG, and Zh-peng, H. E. (2012). On farmers cognition and adoption of green pesticide in different agricultural production mode-based on investigations in haidian beijing. *Shouguang Shandong Qingan Heilongjiang* 11 (05), 454–459. doi:10.13842/j.cnki.issn1671-816x.2012.05.003

Zhou, J. (2023). Study on the effect of farmers' cooperatives in promoting the reduction of fertilizer use by farmers. *J. Northwest A&F Univ. Soc. Sci. Ed.* 23 (05), 116–128. doi:10.13968/j.cnki.1009-9107.2023.05.12