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EDITED BY
Abhinav Upadhyay,
University of Connecticut, United States

REVIEWED BY
Vibhavari Sail,
Oklahoma Medical Research Foundation,
United States
Ngoc T. Phan,
University of Arkansas, United States

*CORRESPONDENCE
Yong Sun
✉ sunyong@gzhu.edu.cn
Maoan Yi
✉ yimaoan@sdu.edu.cn

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How to promote agricultural enterprises to reduce the use of pesticides and fertilizers? An evolutionary game approach

Qizheng He[1], Yong Sun[2,3]*, Maoan Yi[4]* and Huimin Huang[2]

[1]Department of Sociology, Wuhan University, Wuhan, Hubei, China, [2]School of Public Administration, Guangzhou University, Guangzhou, China, [3]Institute of Rural Revitalization, Guangzhou University, Guangzhou, China, [4]School of Management, Shandong University, Jinan, China

With increasing awareness of environmental protection, food safety has become an increasingly important concern for people. The excessive use of pesticides and fertilizers by agricultural enterprises poses a threat to food safety. However, effective promotion of their reduction faces many difficulties. To analyze how to promote the reduction of pesticide and fertilizer use and the path of decision-making evolution of different stakeholders under the changes of different influencing factors, this paper considers the interests of the government, agricultural enterprises and consumers, and constructs an evolutionary game model between the government and agricultural enterprises. The study found that: (1) the governance evolutionary game of reducing the use of pesticides and fertilizers can achieve four stable evolutionary strategies, among which the ideal stable state from a multi-centre governance perspective is the government choosing the regulatory strategy and agricultural enterprises choosing pesticide and fertilizer use reduction strategy. (2) The reward measures taken by the government have a more significant impact on both parties, and in the actual regulatory process, reward measures should be used cautiously, and regulatory mechanisms should be strengthened. (3) The green preferences of consumers are a key exogenous variable that significantly affects the decisions of agricultural enterprises and government. This study improves the policy analysis of pesticide and fertilizer use reduction in the Chinese context and provides innovative ideas for building a policy system to reduce the use of pesticides and fertilizers. The research conclusions provide guidance for promoting the reduction of pesticides and fertilizers use by agricultural enterprises.

KEYWORDS

agriculture, food safety, health risk, enterprises, pesticide, fertilizer, regulation, evolutionary game

1. Introduction

In recent decades, farmers have made extensive use of pesticides and fertilizers to maximize their agricultural yields (Zhang et al., 2011; Sharma and Singhvi, 2017; Zhang et al., 2019; Baweja et al., 2020; Zhan et al., 2021). According to data released by the Food and Agriculture Organization of the United Nations (FAO), global fertilizer consumption exceeded 53 million tonnes in 2020, while pesticide usage surpassed 4 million tonnes (Food and Agriculture Organization of the United Nations (FAO), 2023). Although this practice has resulted in higher crop yields, it is also harmful to the environment and human health (Xing and Zhu, 2000). Studies have indicated that irrational fertilizer application can lead to food and water contamination, resulting in various diseases (Ahmed et al., 2017; Sharma and Singhvi, 2017; Rahman and Zhang, 2018), while excessive use of pesticides can even cause cancer (Painuly and Dev, 1998; Kim et al., 2017). Thus, there is an increasing global concern for the safety of agricultural products (Uysal et al., 2013; Martin et al., 2018; Baweja et al., 2020; Srivastav, 2020; Tripathi et al., 2020; Sandoval-Insausti et al., 2021; Kim et al., 2022), especially studies have found that agricultural chemical residues do spread in the environment, causing serious pollution to terrestrial ecosystems and poisoning human food (Anju et al., 2010), including eggs and aquatic products are contaminated with pesticides and fertilizers (Van Overmeire et al., 2006; Carvalho, 2017; News, 2018), and the detection of excessive pesticide residues in the meals of a kindergarten in Licheng District, Jinan, Shandong Province, China, in 2016 (Xu and Sun, 2021). In response to such issues, European and American countries have intensified measures to ensure food safety, including the establishment of information databases, e.g., the Economically Motivated Adulteration (EMA) database at the US Center for Food Protection and Defence, the Food Fraud Database by Decernis (US), the Rapid Alert System for Food and Feed (RASFF) network among EU Member States, the EU Food Fraud Network (EU-FFN). Moreover, stringent penalties are enforced against individuals or entities found to be in violation of these regulations (Van der Meulen, 2015). Similarly, the Chinese government has implemented a series of initiatives aimed at reducing pesticide and fertilizer use while promoting sustainable agriculture (Zhang et al., 2019). At the end of 2020, China had achieved zero growth in fertilizer and pesticide consumption (Ministry of Agriculture, 2020) and is dedicated to establishing a new paradigm of sustainable agricultural development by 2030 (Ministry of Agriculture, 2023). In China, all agricultural products consumed by urban residents are subjected to rigorous pesticide residue tests, and the compliance rate with harmful substances has reached 80% (Xu and Sun, 2021).

As people's income, environmental awareness, and health consciousness increase (Han et al., 2010), green consumption is gradually gaining popularity (Rustam et al., 2020; Yue et al., 2020; Xie et al., 2022; Yang et al., 2022), leading people to pay more for healthy and eco-friendly food. According to the China Green Food Development Center, domestic green food sales reached 521.863 billion yuan in 2021, marking a rapid upsurge in market demand. As such, high-quality, pollution-free green agricultural products (Yi, 2017) are receiving increasing attention from consumers. Despite this, many consumers lack knowledge about green agricultural products (Rana and Paul, 2017), leading to green preferences that guide their purchasing behavior. Consequently, reducing the use of pesticides and fertilizers during agricultural production has become crucial in improving the quality and availability of green agricultural products. Only when consumers have access to high-quality green agricultural products and build a relationship of trust (Zhang et al., 2016), will they be more likely to make repeat purchases (Hellier et al., 2003). This will, in turn, increase sales of green agricultural products, improve farmers' incomes, and promote further reduction of pesticide and fertilizer use in agricultural production by farmers.

There has been some research on green produce consumption behavior and the decision to reduce the use of pesticides and fertilizers. Among studies on the consumption behavior of green agricultural products, some scholars have examined the impact of consumers' behavior, self-control, and other psychological factors on the willingness of consumers to purchase agricultural products (Ajzen, 2002; Su et al., 2021; He et al., 2023). Factors that affect consumers' willingness and behavior to purchase green products are believed to be classified into internal and external categories (Liobikiene and Bernatoniene, 2017). Furthermore, it has been suggested that the quality, price, distribution channels, and degree of publicity of green agricultural products could affect consumers' purchasing behavior (Chang and Chen, 2014). In relation to decisions about reducing the use of pesticides and fertilizers, scholars have mainly focused on stakeholder aspects (Cui et al., 2019; Liu, 2022). Current research on reducing pesticide and fertilizer use has primarily centred on the external factors that influence consumers' green consumption behavior, with insufficient attention given to consumers' subjective willingness and the collaborative participation of multiple parties in governance, such as government regulation. So it is needed to examine the collaborative decision-making among stakeholders, taking into account the combined effects of consumer preferences and government regulations.

Evolutionary game theory offers a powerful tool for simulating complex biological and social systems (Roca et al., 2009; Wang et al., 2022), providing insight into their behavior and aiding in prediction. Based on the fundamental assumption of bounded rationality, it is more realistic and can offer valuable insights for analyzing and solving real-world issues that require collaborative governance among stakeholders (Sun et al., 2021). Its wide application in fields such as industrial policy (Ji et al., 2015; Liu et al., 2023), environmental management (Sun et al., 2022; Teng et al., 2022), and corporate strategic management (Wang et al., 2022; Zheng et al., 2023) has provided excellent inspiration for our study.

This paper aims to address the gaps in current research by exploring the evolutionary game paths of agricultural enterprises' production decisions and government regulation under different influencing factors while considering the impact of consumers' green preferences. Additionally, numerical simulations and experiments are conducted to determine the circumstances under which an ideal state can be attained. Specifically, this paper attempts to answer the following questions: how do consumers' green preferences affect agricultural enterprises' decisions to reduce pesticide and fertilizer use? What is the influence of government regulation on these decisions? And how to promote the reduction of pesticide and fertilizer use? Through examining policies and cases in China, this research contributes to the policy analysis of the reduction of pesticide and fertilizer use specific to the Chinese context and provides innovative solutions for the development of corresponding policy systems.

2. Review of the literature

Consumer preferences have important implications for the guide of product production. In recent years, scholars have developed several theories and models to explain green consumers' behavior and its impact on product production decisions (Sweeney and Soutar, 2001; Wang et al., 2014). First, income and price are key factors that influence consumer behavior. If green products are more expensive, consumers can switch to consuming cheaper generic products (D'Souza et al., 2006). Consumers' income also affects their tolerance for premium prices, and Eriksson (Eriksson, 2004) found that consumers with higher incomes are more likely to pay a higher premium for green products. With the promotion of government policies, the influence of consumers' environmental awareness on green consumption behavior is also increasing. Dunlap and Scarce (1991) argue that environmentally conscious consumers are more willing to pay higher prices for green products, while Maheshwari and Malhotra (2011) argue that when the price of green products is too high, the influence of environmental awareness on consumer decision-making behavior will have a negligible impact. Consumers' green preferences will also directly influence producer production decisions, who will produce various levels of green products to meet consumers' green demands and to make higher profits (Yu et al., 2016).

With the tightening of global ecological and environmental resource constraints, most countries have also put forward plans to control the chemicalization of agriculture, and thus research on the policy of reducing pesticide and fertilizer use in agricultural products has become a hot topic. On the one hand, scholars have explored the reasons for the excessive use of pesticides and fertilizers (He et al., 2021) and found that due to the imperfect knowledge system of farmers and the simple pursuit of economic benefits, they often believe that the amount of pesticides and fertilizers used is positively correlated with the yield of agricultural products, leading to their heavy use of pesticides and fertilizers. Jacquet et al. (2011) and Boecker and Finger (2016) argue that tax and subsidy policies are more effective in reducing pesticide and fertilizer use than technical training, while Rodriguez et al. (2009) finds that the conflict between limited extension capacity and diverse farmers' demand is the main factor preventing governments from promoting pesticide and fertilizer use. Gao et al. (2017), Petrescu-Mag et al. (2019) and others have explored the impact of different technologies on the reduction of pesticide and fertilizer use from a technological perspective. Many studies have already focused on the stakeholder relationships within governance to reduce pesticide and fertilizer use. It is widely recognized that exploring this issue from a stakeholder perspective is an important direction for research. For example, Cui et al. (2019) and Liu (2022) used an evolutionary game model to analyze the behavioral decisions of different agents in the reduction of pesticide and fertilizer use.

Current research on reducing pesticide and fertilizer use has primarily focused on the impact of external factors on consumers' purchasing behavior, with little attention paid to consumers' green preferences. Few comprehensive studies have been conducted that consider both consumer preferences and government regulation in relation to the reduction of pesticide and fertilizer use strategies of agricultural enterprises. This study addresses these gaps through the construction of an evolutionary game model that considers both consumer preferences and government regulation in agricultural enterprises' pesticide and fertilizer use reduction decisions. The study investigates the factors that influence the decision to reduce pesticide and fertilizer use, as well as the evolutionary characteristics of decision-making behavior. In general, this research provides valuable information for researchers and practitioners in the field.

3. Model design

3.1. Description of the problem

The increasing demand for quality, safety, nutrition, and environmental friendliness in agricultural products, resulting from economic and social advancements, as well as consumer improvement, prompts agricultural enterprises to improve production standards and reduce the use of pesticides and fertilizers. In response to the growing consumers' recognition and willingness to pay for green and organic agricultural products, a price premium has emerged, motivating agricultural enterprises to shift towards green production models, increase the use of environmentally friendly inputs such as organic pesticides and fertilizers, and decrease the use of pesticides and fertilizers. Consumers are increasingly aware of information related to the quality and safety of agricultural products, acquiring and disseminating relevant information through various channels, thereby establishing regulations and evaluating the production behavior of agricultural enterprises. This calls for enterprises to improve self-discipline and transparency, regulate the use of pesticides and fertilizers, and ensure product quality and safety. However, decisions made by enterprises regarding the reduction in pesticide and fertilizer use can decrease agricultural product yields. Therefore, they must consider the trade-off between increasing the amount and improving the quality of their products, with the green preferences of consumers being a significant influencing factor.

The Chinese government has developed a series of policies, regulations, and action plans to accelerate the reduction of pesticide and fertilizer use and enhance their efficiency (Jin and Zhou, 2018; Liu et al., 2021; Ji et al., 2023). This includes strengthening top-level design and institutional support for the reduction of pesticide and fertilizer use. Enterprises that actively participate in reducing pesticide and fertilizer use by promoting green prevention and control technologies, using green inputs, adopting intelligent agricultural equipment and improving product quality and efficiency are given incentive measures such as financial subsidies, tax concessions, credit support, and project funding preference. Conversely, enterprises that violate laws and regulations and standard norms by producing, operating, or utilizing unqualified or banned pesticides and fertilizers, thereby causing environmental pollution or issues with the quality and safety of agricultural products, are subjected to punitive measures such as fines, confiscation, revocation of licenses, orders to stop production and rectification, and public exposure by the law. In particular, the implementation of pesticide use file records focuses on agricultural enterprises, professional cooperatives, production bases, and large growers, recording the type of pesticide used, dosage, time, location, and other relevant information. Additionally, pesticide quality sampling and market inspections are intensified, and any irregularities in the production and use of pesticides are thoroughly investigated and dealt with by law enforcement agencies (Table 1).

Government regulation and consumer preferences are two important factors that influence the decision-making of agricultural enterprises. When government regulation is strong and effective, and consumer preferences are clear and stable, the likelihood of agricultural enterprises making decisions to reduce the use of pesticides and fertilizers is higher. Conversely, when government regulation is weak and ineffective, and consumer preferences are vague and constantly changing, the likelihood of agricultural enterprises making decisions to reduce the use of pesticides and fertilizers is lower. Consumer preferences for green, organic, and safe agricultural products can incentivize agricultural enterprises to improve product quality and brand image, thereby increasing their profits. When there is a conflict or mismatch between government regulation and consumer preferences, the likelihood of agricultural enterprises making decisions to reduce the use of pesticides and fertilizers depends on their balance and judgement of these different factors.

The governance of the reduction of pesticide and fertilizer use involves the government, enterprises, and consumers as the main community of interest, and their behavior inevitably influences the evolution of the pesticide and fertilizer use reduction system. Against this background, an analytical framework may be constructed to explore the reduction of pesticide and fertilizer use strategies and institutional optimization pathways for agricultural enterprises. Such a framework considers consumer preferences and government regulations in its design (see Figure 1).

TABLE 1 Pesticide and fertilizer use reduction policy in China.

Dimensionality	Contents
Policy areas	In agriculture, especially in the plantation sector, the aim is to promote the reduction of pesticide and fertilizer use, to improve the efficiency and quality of agricultural production and to safeguard food security and the ecological environment
Policy tools	Formulate action plans and implementation rules, strengthen scientific and technological innovation and promotion services, establish monitoring and evaluation, assessment, reward and punishment mechanisms, increase financial investment and policy support, and strengthen publicity and training, as well as regulation and management
Policy objects	Agricultural departments at all levels, various agricultural business entities (including family farms, co-operatives, leading enterprises, etc.), specialised prevention and control service organisations, agricultural research institutes, consumers, etc

3.2. Model assumption

In the analytical framework of this paper, the government, enterprises and consumers are the three stakeholders, among which consumers are not directly involved in the game, they have heterogeneous preferences and choose between green and non-green agricultural products, and their consumption behavior influences the reduction of pesticide and fertilizer use strategies of agricultural enterprises. When consumers consume green agricultural products and enterprises choose to reduce the use of pesticides and fertilizers, they can promote food safety and environmental protection, and the resulting green development effect is an important revenue objective for government participation in regulation. Based on the model context, the following assumptions can be made (Table 2).

> *Assumption 1*: Assume that the set of actions available to the agricultural enterprise is {reduction, non-reduction}. Agricultural products have a certain level of green health, denoted by q. Then the green agricultural products produced by reducing pesticide and fertilizer use and the non-green agricultural products produced without reduction have a green level of q_1 and q_2, respectively ($q_1 > q_2$), while the green agricultural products also have a certain reputation and can generate a brand premium. Green agricultural products and nongreen agricultural products have different price levels and cost inputs, respectively, and there are also differences in the final returns formed in the supply and

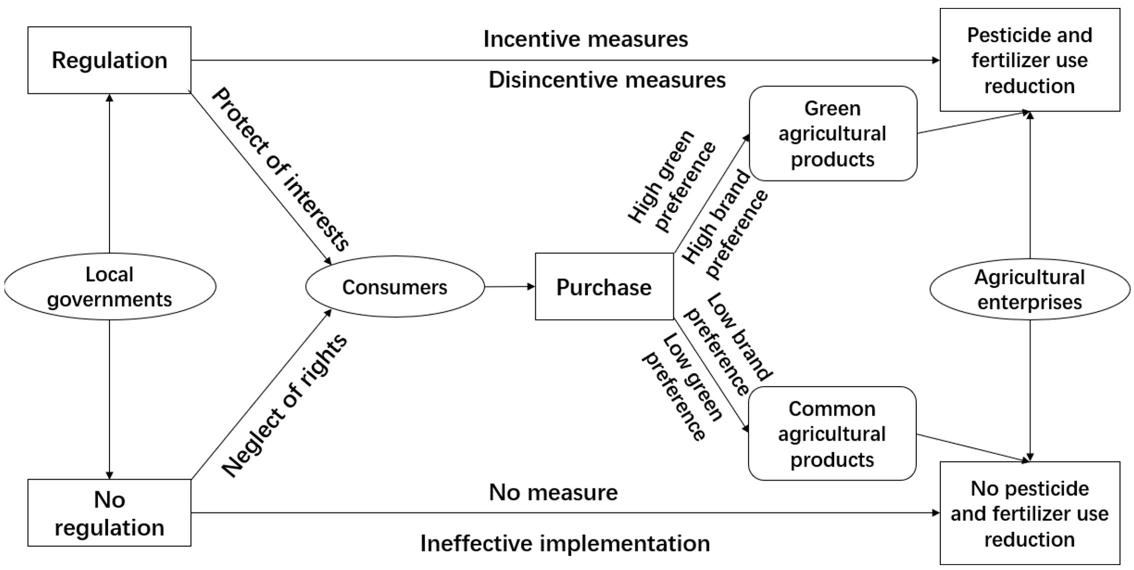

FIGURE 1
Theoretical framework.

TABLE 2 Parameters.

Parameters	Description
q_1	Green level of unit green produce
q_2	Green level of non-green produce in the unit
c_1	Supply cost per unit of green produce
c_2	Supply costs per unit of non-green produce
k	Payment factor for consumers' green preferences for agricultural products
l	Consumer brand preference coefficient for green produce
β	Probability of receiving incentives or subsidies when pesticides and fertilizers are reduced by agricultural enterprises
A	Agricultural enterprises receive incentives or subsidies when reducing pesticides and fertilizers
U_c	Green development benefits for agricultural enterprises when pesticides and fertilizers are reduced
C_g	Cost of the government when taking regulatory action
R	Reputational damage suffered when the government takes regulatory action
γ	Probability of being penalized by the government when agricultural enterprises do not reduce pesticides and fertilizers
T	Penalty for agricultural enterprises when pesticides and fertilizers are not reduced
C_w	Costs of the government environmental governance when pesticides and fertilizers are not reduced
x	Probability of agricultural enterprises choosing a pesticide and fertilizer use reduction strategy
y	Probability of the government choosing a regulatory strategy

demand process. Assume that their prices, costs and profits are p_1, p_2, c_1, c_2, Π_1, Π_2 ($p_1 > p_2$, $c_1 > c_2$).

Assumption 2: Suppose the set of optional actions for consumers is {consumption of green agricultural products, consumption of non-green agricultural products, non-consumption}. The utility of the consumer U, which differs for its three consumption strategies, is denoted by U_1, U_2, and U_3, respectively, and without loss of generality, U_3 can be standardized to 0. The consumer has a green preference α, which obeys a uniform distribution in [0, 1]. P is the willingness of the consumer to pay, which differs for its three consumption strategies, denoted by P_1, P_2, and P_3, respectively, and the willingness to pay is a function of its green preference payment coefficient k and their brand preference payment coefficient l. Therefore, we have $P_1 = q_1\ (k + l)$, $P_2 = q_2\ k$, and $P_3 = 0$. The total demand for green and nongreen produce is D_1 and $D2$, respectively.

Assumption 3: It is assumed that the set of actions available to the government is {regulation, non-regulation}. Without loss of generality, this paper assumes that the given standard of pesticide and fertilizer use is f_0. When the government takes regulatory measures, there will be relevant departments to carry out reward and punishment incentives, as well as through administrative management to monitor the possible excessive use of pesticides and fertilizers, so the government needs to pay a certain regulatory cost C_g, at this time, if the level of pesticide and fertilizer use is higher than the given use standard ($f > f_0$), it will be reported or monitored by the government with γ. If the level of pesticide and fertilizer use is higher than the given standard ($f > f$), it will be reported or monitored by the government will report or monitor it with a probability of γ. The local government regulatory department (hereinafter referred to as the government) will then impose a penalty, and the agricultural enterprise will be penalized with a unit product penalty T. When agricultural enterprises do not reduce the use of pesticides and fertilizers, the government needs to improve the environment, C_w represents the costs of the government environmental governance when pesticides and fertilizers are not reduced.

Assumption 4: To encourage agricultural enterprises to actively reduce pesticides and fertilizers use, the government will recognize green agricultural products, and the green agricultural product projects of agricultural enterprises may be recognized by the government with a probability of β. The government will give certain rewards or subsidies to the recognized green agricultural products projects or subsidies A. The government's active regulatory behavior is expected by some members of the public, and when it adopts non-regulatory measures, it may suffer certain reputational losses R. When agricultural enterprises choose a pesticide and fertilizer use reduction strategy, they will generate certain green development benefits U_c; when they choose a pesticide and fertilizer use nonreduction strategy, they will generate adverse impacts such as food safety risks and environmental pollution, and the government will need to spend certain costs C_g. The government needs to spend a certain amount of money to control the situation.

4. Model building

4.1. Consumer utility functions

The utility of consumer consumption of green produce is

$$U_1 = \alpha P_1 - p_1 = \alpha q_1 \left(k + l\right) - p_1 \quad (1)$$

The utility of consumer consumption of nongreen produce is

$$U_2 = \alpha P_2 - p_2 = \alpha q_2 k - p_2 \quad (2)$$

The utility of consumer non-consumption is.

$$U_0 = 0 \quad (3)$$

When $U_1 > U_2$ and $U_1 > 0$, we have $\alpha > \frac{p_1 - p_2}{(k+1)q_1 - kq_2}$ and, such that, and when $\alpha_1 < \alpha < 1$, consumer demand for green products is $D_1 = \int_{\alpha_1}^{1} f(\alpha)d\alpha = 1 - \frac{p_1 - p_2}{(k+1)q_1 - kq_2}$. When $U_1 < U_2$ and $U_2 > 0$, there is $\frac{p_2}{kq_2} < \alpha < \frac{p_1 - p_2}{(k+1)q_1 - kq_2}$, such that $\alpha_2 = \frac{p_2}{kq_2}$, and when $\alpha_2 < \alpha < \alpha_1$, consumer demand for non-green produce is $D_2 = \int_{\alpha_2}^{\alpha_1} f(\alpha)d\alpha = \frac{p_1 - p_2}{(k+1)q_1 - kq_2} - \frac{p_2}{kq_2}$. When $U_2 < U_3$, there is $0 < \alpha < \frac{p_2}{kq_2}$, and when $0 < \alpha < \alpha_2$, the consumer chooses not to consume.

4.2. Profit functions for the supply of agricultural products by agricultural enterprises

Agricultural enterprises aim to maximise profits by supplying green and non-green agricultural products with the following profit functions:

$$\prod_1 = (p_1 - c_1)D_1 = (p_1 - c_1)\left(1 - \frac{p_1 - p_2}{(k+l)q_1 - kq_2}\right) \quad (4)$$

$$\prod_2 = (p_2 - c_2)D_2 = (p_2 - c_2)\left(\frac{p_1 - p_2}{(k+l)q_1 - kq_2} - \frac{p_2}{kq_2}\right) \quad (5)$$

Since, $\frac{\partial^2 \prod_2}{\partial p_2^2} = \frac{2(k+1)q_1}{kq_2(-(k+1)q_1 + kq_2)} < 0$ shows that the profit functions Π_1 and Π_2 are convex functions concerning $p1$ and $p2$ respectively, the optimal solution should satisfy a first-order partial derivative equal to 0. Therefore, we can make $\frac{\partial \prod_1}{\partial p_1} = 0$, $\frac{\partial \prod_2}{\partial p_2} = 0$, and associate to obtain p_1, p_2 as follows.

$$p_1 = \frac{(k+l)q_1(2c_1 + c_2 + 2kq_1 + 2lq_1 - 2kq_2)}{4(k+l)q_1 - kq_2} \quad (6)$$

$$p_2 = \frac{2(k+l)c_2q_1 + kq_2(c_1 + (k+l)q_1 - kq_2)}{4(k+l)q_1 - kq_2} \quad (7)$$

Substituting $p1$ and $p2$ into the demand function and profit function, respectively, we get

$$D_1 = \frac{(k+l)q_1(c_2 + 2(k+l)q_1 - 2kq_2) + c_1(-2(k+l)q_1 + kq_2)}{((k+l)q_1 - kq_2)(4(k+l)q_1 - kq_2)} \quad (8)$$

$$D_2 = \frac{(k+l)q_1(kq_2(c_1 + (k+l)q_1 - kq_2) + c_2(-2(k+l)q_1 + kq_2))}{kq_2(-4(k+l)q_1 + kq_2)(-(k+l)q_1 + kq_2)} \quad (9)$$

$$\prod_1 = \frac{((k+l)q_1(c_2 + 2(k+l)q_1 - 2kq_2) + c_1(-2(k+l)q_1 + kq_2))^2}{((k+l)q_1 - kq_2)(-4(k+l)q_1 + kq_2)^2} \quad (10)$$

$$\prod_2 = -\frac{(k+l)q_1(kq_2(c_1 + (k+l)q_1 - kq_2) + c_2(-2(k+l)q_1 + kq_2))^2}{kq_2(-4(k+l)q_1 + kq_2)^2(-(k+l)q_1 + kq_2)} \quad (11)$$

4.3. Payment matrix

In addition, considering the government's regulatory behavior, a game model can be constructed for both agricultural enterprises and the government that includes consumers' green preferences and government regulation. Assuming that both parties are finite rational participants who can choose their strategies according to their wishes, the payoff matrix of the government and agricultural enterprises can be obtained (Table 3).

TABLE 3 Payment matrix for both sides of the game.

		Government	
		Regulation (y)	Non-regulation $(1-y)$
agricultural enterprises	Pesticide and fertilizer use reduction (x)	$\Pi_1 + \beta A$, U_c -C_g -βA	Π_1, U_c -R
	Pesticide and fertilizer use non-reduction $(1-x)$	Π_2 -γT, -$C_g + \gamma T$-C_w	Π_2, -C_w -R

5. Model analysis

5.1. Analysis of replication dynamics

According to evolutionary game theory, the equilibrium strategy analysis is conducted separately for the government and agricultural enterprises. Let the expected return of agricultural enterprises choosing the pesticide and fertilizer use reduction strategy be E_{11}, the expected return of choosing the pesticide and fertilizer use non-reduction strategy be E_{12}, and the average expected return be $\bar{E}_1$, then

$$\begin{cases} E_{11} = y\left(\prod_1 + \beta A\right) + (1-y)\prod_1 \\ E_{12} = y\left(\prod_2 - \gamma T\right) + (1-y)\prod_2 \\ \bar{E}_1 = xE_{11} + (1-x)E_{12} \end{cases} \quad (12)$$

The replicated dynamic equation for the government's choice of incentive strategy is obtained from the Malthusian dynamic equation:

$$F(x) = \frac{dx}{dt} = x\left(E_{11} - \bar{E}_1\right) = -(-1+x)x\left(\prod_1 - \prod_2 + Ay\beta + Ty\gamma\right) \quad (13)$$

Similarly, the replication dynamic equation for government regulation can be obtained as

$$F(y) = \frac{dy}{dt} = y\left(E_{21} - \bar{E}_2\right) = -(-1+y)y\left(R - C_g - x\beta A + \gamma T - x\gamma T\right) \quad (14)$$

5.2. Analysis of evolutionary stabilisation strategies

Combining Eqs. (13), (14) yields a two-dimensional dynamical system (I), i.e.:

$$\begin{cases} F(x) = -(-1+x)x\left(\prod_1 - \prod_2 + Ay\beta + Ty\gamma\right) \\ F(y) = -(-1+y)y\left(R - C_g - x\beta A + \gamma T - x\gamma T\right) \end{cases} \quad (15)$$

Taking $F(x) = F(y) = 0$, respectively, five special equilibria can be solved for: $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, E_5 $(\frac{-C_g + R + \gamma T}{\beta A + \gamma T}, \frac{-\prod_1 + \prod_2}{A\beta + T\gamma})$. The asymptotic stability of the above five equilibria is further discerned by the local stability of the Jacobi matrix (Friedman, 1991; Sun et al., 2023).

First, the Jacobi matrix of the game equation is obtained by taking the first-order partial derivatives of $F(x)$ and $F(y)$ concerning x and y, respectively:

$$J = \begin{bmatrix} F_x(x) & F_y(x) \\ F_x(y) & F_y(y) \end{bmatrix} \quad (16)$$

Then, the determinant (*DetJ*) and trace (*TrJ*) of the Jacobi matrix are calculated, and the equilibrium can be considered as a homogeneous asymptotically stable equilibrium when $DetJ > 0$ and $TrJ < 0$, i.e., the evolutionary stability strategy (Friedman, 1991). The formulae for the determinant (*DetJ*) and trace (*trJ*) are as follows:

$$DetJ = F_x(x)F_y(y) - F_y(x)F_x(y) > 0 \quad (17)$$

$$TrJ = F_x(x) + F_y(y) < 0 \quad (18)$$

According to Eqs. (17), (18), the asymptotic stability of the five equilibria of the evolutionary game can be analyzed (Table 4). Asymptotic stability can be achieved at all four equilibria of E_1 (0,0), E_2 (0,1), E_3 (1,0), and E_4 (1,1) when certain conditions are satisfied, but at the equilibrium point E_5 (x^*, y^*), according to Taylor's study (Taylor and Jonker, 1978), the characteristic roots of the Jacobi matrix are a pair of purely imaginary roots, and the differential equation has only a stable limit ring but not asymptotic stability.

E_1 (0,0), E_2 (0,1), E_3 (1,0), and E_4 (1,1) are all asymptotically stable when certain conditions are satisfied. The conditions are as follows:

(1) If $\Pi_1 - \Pi_2 < 0$, $-C_g + \gamma T + R < 0$, the evolutionary stabilization strategy of the dynamical system (I) is {non-reduction, non-regulation}. The realistic situation of this strategy is mainly in the early stage of implementation of pesticide and fertilizer use reduction policy, when consumers' green consumption habits have not yet been developed, and their preference for green agricultural products is not high, when agricultural enterprises are not motivated to reduce the use of pesticides and fertilizers, and when the government lacks regulatory awareness.

(2) If $\Pi_1 - \Pi_2 + A\beta + T\gamma < 0$ and $C_g - \gamma T - R < 0$, the evolutionary stabilization strategy of the dynamical system (I) is {non-reduction, regulation}. The realistic situation of this strategy is mainly in the case that consumers have not formed green consumption habits, the excessive use of pesticides and fertilizers by agricultural enterprises can increase production but lead to many health problems and environmental problems, the government has the initiative to regulate but its reward and punishment mechanism is not enough to restrain the excessive use of pesticides and fertilizers by agricultural enterprises.

(3) If $-\Pi_1 + \Pi_2 < 0$ and $-C_g - \beta A + R < 0$, the evolutionary stabilization strategy of the dynamical system (I) is {reduction, non-regulation}. The realistic scenario for this strategy is that along with the upgrading of consumption, consumers' preferences for green agricultural products and brand preferences are increasing, they are willing to pay higher prices for green agricultural products, and agricultural enterprises are more motivated to produce green agricultural products, at which time an industry self-regulatory mechanism has been established, and at which time a benign reduction in the use of pesticides and fertilizers can be achieved without government regulation.

(4) If $-\Pi_1 + \Pi_2 - A\beta - T\gamma < 0$ and $C_g + \beta A - R < 0$, the evolutionary stabilization strategy of the dynamical system (I) is {reduction, regulation}. The realistic scenario of this strategy is mainly the distribution of consumer preferences between green and non-green agricultural products under heterogeneous consumer demand and the increasing green health of agricultural products through government regulation, which restrains the excessive use of pesticides and fertilizers by agricultural enterprises.

TABLE 4 Asymptotic stability analysis of equilibrium points.

Equilibrium points	DetJ	TrJ	Conditions	Results
(0,0)	$(\Pi_1 - \Pi_2) \times (-C_g + \gamma T + R)$	$(\Pi_1 - \Pi_2) + (-C_g + \gamma T + R)$	(1)	ESS
(0,1)	$(\Pi_1 - \Pi_2 + A\beta + T\gamma) \times (C_g - \gamma T - R)$	$(\Pi_1 - \Pi_2 + A\beta) + (C_g - R)$	(2)	ESS
(1,0)	$(-\Pi_1 + \Pi_2) \times (-C_g - \beta A + R)$	$(-\Pi_1 + \Pi_2) + (-C_g - \beta A + R)$	(3)	ESS
(1,1)	$(-\Pi_1 + \Pi_2 - A\beta - T\gamma) \times (C_g + \beta A - R)$	$(-\Pi_1 + \Pi_2 - T\gamma) + (C_g - R)$	(4)	ESS

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6. Numerical simulation

In order to verify the accuracy of the model derivation and the validity of the discussion, we conducted dynamic simulations of the game system using MATLAB. Our simulations analyzed the impact of factors such as the initial willingness of agents to participate, government regulatory measures, and consumers' preferences for environmentally-friendly products on the strategies employed by both the government and agricultural enterprises. Based on the evolutionary game analysis above, it can be found that the adoption of pesticide and fertilizer use reduction strategy by agricultural enterprises and the government's choice of regulatory strategy is the ideal ESS. According to the assumption that the ideal ESS is the baseline scenario, the condition of $-\Pi_1+\Pi_2$ -$A\ \beta$-$T\ \gamma<0$ cut $C_g+\beta\ A$-$R<0$ needs to be satisfied at this point. Additionally, since 2019, we have been conducting research on environmental pollution in agriculture, specifically excessive use of pesticides and fertilizers. This research has accumulated a wealth of materials, including interview data, survey questionnaires, and policy documents. However, it should be noted that these materials are not entirely structured. Nevertheless, these resources provide crucial insights for setting up the model in this paper. We combine survey, research hypotheses, and the author's experience to determine parameter settings that can better reflect the real-world situation. so the parameters can be set as follows: $q_1=4$, $q_2=2$, $c_1=2$, $c_2=1$, $k=1$, $l=1$, $\beta=0.5$, $A=2$, $U_c=3$, $C_g=1$, $R=3$, $\gamma=0.2$, $T=1$, $C_w=1$, $x=0.5$, $y=0.5$ and set the simulation period at 10.

6.1. Impact of initial willingness of participants on the evolution of the system

As shown in Figure 2A, with a constant initial probability of a government regulatory decision, the higher the initial probability that agricultural enterprises choose a pesticide and fertilizer use reduction strategy, the less aggressive the government's choice to implement the regulation strategy, and the slower its behavior converges to a stable equilibrium. As shown in Figure 2B, with the initial probability that agricultural enterprises choose a pesticide and fertilizer use reduction strategy remaining unchanged, the higher the initial probability of the government's regulatory decision, the more active agricultural enterprises are in choosing a pesticide and fertilizer use reduction strategy, and the faster their behavior tends to a stable equilibrium. It can be seen that as long as the condition of $-\Pi_1+\Pi_2$ -$A\beta$-$T\gamma<0$ cut $C_g+\beta A$-$R<0$ is satisfied, effective government regulation can be achieved and agricultural enterprises are subject to the more obvious binding effect of government regulation, the government is very important for the reduction governance of pesticide and fertilizer use.

6.2. Impact of government incentives and disincentives on the evolution of the system

As shown in Figure 3, government regulatory measures have a significant impact on the choice of agricultural enterprises strategy, especially the impact of incentive-based measures is more pronounced. As shown in Figures 3A,B, when the government increases green incentives for agricultural enterprises, they are more motivated to choose pesticide and fertilizer use reduction strategies; however, such incentives constitute costs for government departments, so excessive incentives can lead to lower returns or even outlive government departments, and eventually withdraw from the incentive mechanism. When $A=2$, it has not exceeded the threshold of subsidies that the government can afford. But when $A=3$, it has exceeded the threshold, and the government may choose not to regulate. As a result, its political performance is compromised, leading to a decrease in average returns for the government. Based on our investigation, there are notable disparities in the implementation of pesticide environmental governance between developed and underdeveloped regions. One key factor contributing to this disparity is the insufficient emphasis on environmental governance due to fiscal constraints and the inadequate consideration of environmental governance in the political

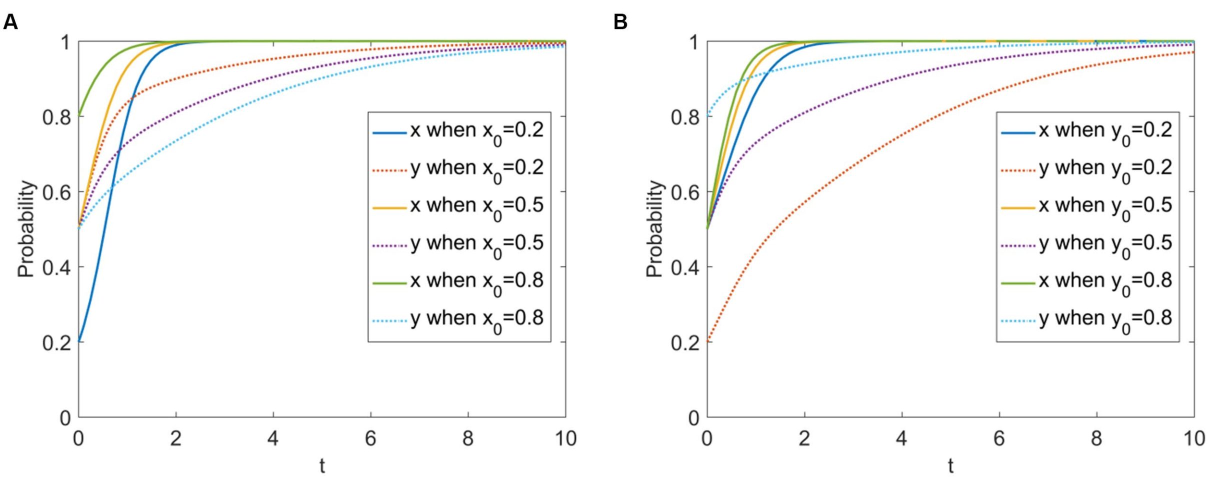

FIGURE 2
Impact of initial willingness of participants on the evolution of the system. **(A)** Impact of x_0 on the evolutionary of the system. **(B)** Impact of y_0 on the evolutionary of the system.

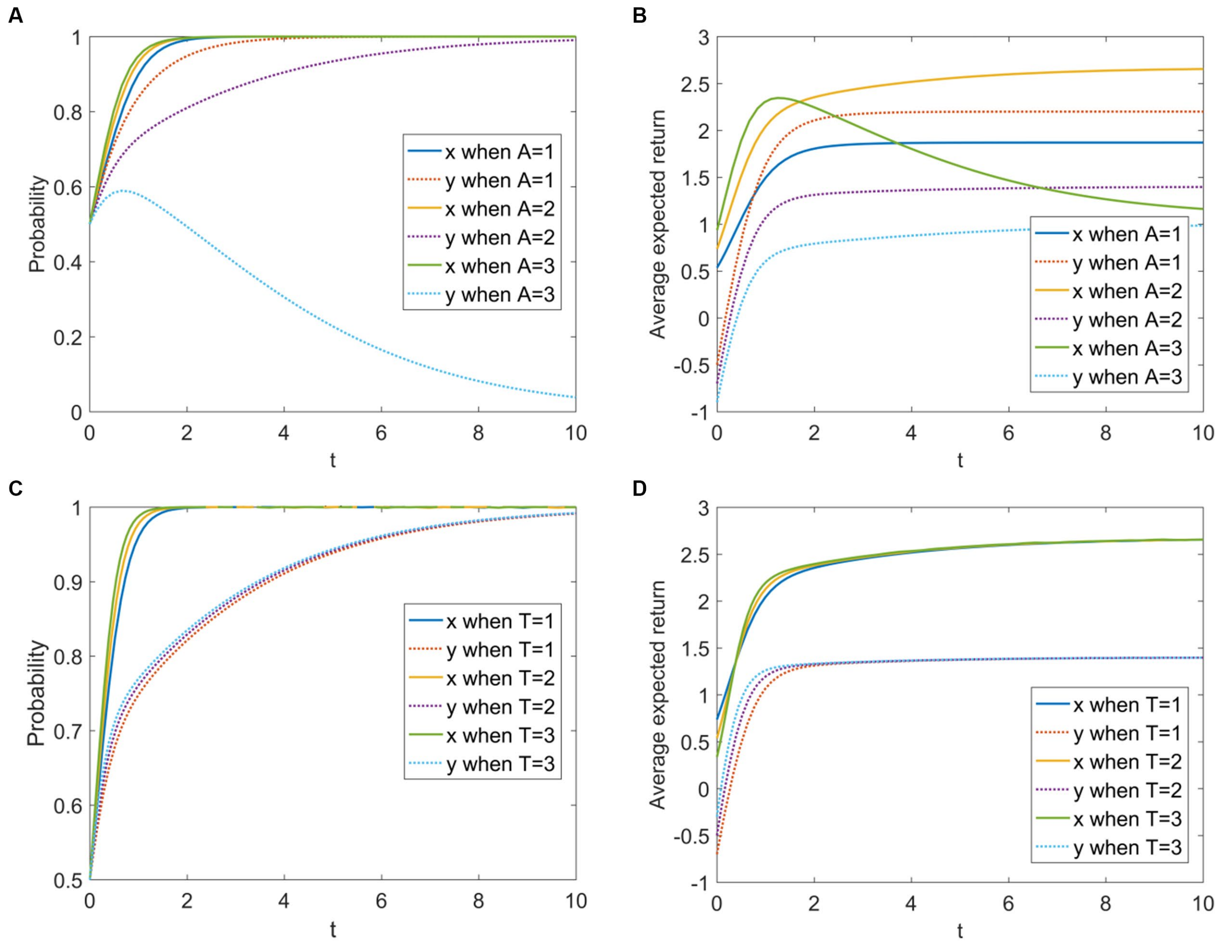

FIGURE 3
Impact of government incentives and disincentives on the evolution of the system. **(A)** Impact of *A* on the player behavior. **(B)** Impact of *A* on the player average expected returns. **(C)** Impact of *T* on the player behavior. **(D)** Impact of *T* on the player average expected returns.

performance assessment of officials. Excessive subsidies can strain the government's financial resources, and the benefits of effective governance do not outweigh the incurred costs, inevitably dampening the enthusiasm of local governments to engage in regulation. These findings align with previous research on environmental governance under the central-local power structure in China (Kostka and Nahm, 2017).

As shown in Figures 3C,D, when the government increases the administrative penalty for excessive use of pesticides and fertilizers by agricultural enterprises, they become more motivated to choose reduction strategies of pesticide and fertilizer use. The sensitivity of changes in agricultural enterprises strategy choice is comparable to that of incentives, reflecting little difference in the effect of incentives and penalties on agricultural enterprises strategy choice, but it is clear that the difference in the effect of incentives and penalties on government strategy choice is significant. In addition, incentive measures change the expected returns to stable equilibrium for both agricultural enterprises and government, but penalty measures do not fundamentally change their expected returns. This mechanism suggests that incentives have a more pronounced effect on both subjects and that, in the actual regulation process, incentives should be used judiciously, and the construction of a binding regulation mechanism should be strengthened.

6.3. Impact of consumer green preferences on the evolution of the system

As shown in Figure 4, in the evolutionary game system of pesticide and fertilizer use reduction governance, the green preferences of consumers are the key exogenous variables, which significantly influence the decisions of agricultural enterprises and the government. As shown in Figures 4A,B, the higher the green preference of consumers, the higher the incentive of agricultural enterprises to choose products with reduction strategies for pesticide and fertilizer use, the lower the incentive of government regulation, and the faster the evolutionary game system converges to a stable equilibrium. At the same time, the higher the green preference of consumers, the higher the initial expected return of agricultural enterprises and the higher their expected return when they reach the stable equilibrium; it does not affect the initial return of the government and the expected return when they reach the stable equilibrium, but it can promote the convergence of the government's return to the maximum faster.

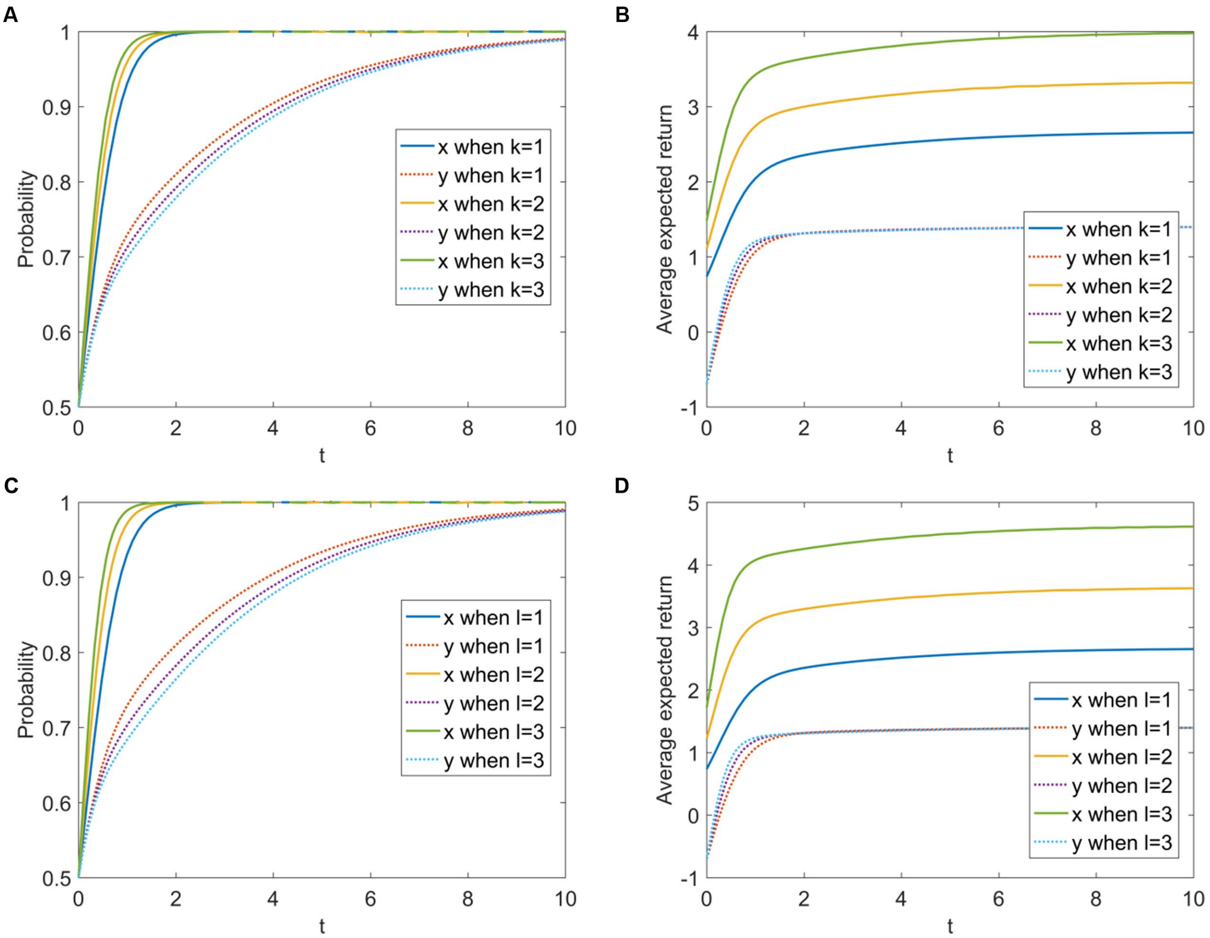

FIGURE 4
Impact of consumer green preferences on the evolution of the system. **(A)** Impact of *k* on the player behavior. **(B)** Impact of *k* on the player average expected returns. **(C)** Impact of *l* on the player behavior. **(D)** Impact of *l* on the player average expected returns.

Similarly, as shown in Figures 4C,D, consumer brand preference for agricultural products significantly influences the decision-making of agricultural enterprises and governments. The greater their preference for a particular brand, the more motivated agricultural enterprises are to adopt strategies that reduce the use of pesticides and fertilizers. This phenomenon represents a prominent trend in consumption upgrading. As people's living standards gradually improve, they are less and less satisfied with crude agricultural products and are often willing to pay higher prices for green agricultural products, and this virtuous green consumption pattern can promote higher returns for agricultural enterprises and the sustainable development of agriculture.

7. Discussion

In this paper, we construct an evolutionary game model that takes into account the interests of the government, agricultural enterprises, and consumers. Our findings are consistent with the results of our field and literature research. Across China, pesticide and fertilizer use reduction is being vigorously promoted through various means. The government of Qinghai Province has issued policy documents such as the Implementation Plan for Fertilizer and Pesticide Use Reduction and Efficiency Increase (2019) and the Pilot Implementation Plan for Fertilizer and Pesticide Use Reduction and Efficiency Increase Insurance (2019). These policies have effectively resulted in a reduction of over 10 million mu in pesticide and fertilizer usage, as of the end of 2022 (China National Radio, 2023). This has played a significant role in facilitating the green transformation of the agricultural and livestock industry. Similarly, our investigation also unveiled noteworthy progress in Hainan Province, China since 2022 in shifting agricultural non-point source pollution control from "extensive management" to "precision management." This transition contributes to the reduction of fertilizer and pesticide utilization, while simultaneously improving their efficacy. However, in this social context, there are still practical difficulties in promoting the reduction of pesticide and fertilizer use. Firstly, the lack of government regulation directly weakens the effect of the reduction of pesticide and fertilizer use. For example, in Jishui County, Jiangxi Province, and Dongting Lake District, Hunan Province, relevant departments have been perfunctory in their deployment of the reduction of pesticide and fertilizer use work, leading some agricultural enterprises to engage in actions that undermine the effectiveness of such initiatives. Secondly, agricultural enterprises are the primary agents of the reduction of pesticide and fertilizer use, and their willingness to act determines the success of the reduction of pesticide and fertilizer use initiatives. Unfortunately, many agricultural enterprises have a weak subjective willingness to reduce pesticides and fertilizers due to potential yield reductions and the high cost of alternative technologies. Finally, the green preferences of consumers are also an important factor in the reduction of pesticide and fertilizer use. Due to income level limitations and a lack of mindset transformation, some consumers are not yet willing to pay a premium for green agricultural products, leading to a small market demand for such products that do not incentivize changes on the supply side.

The production behavior of agricultural enterprises is the most critical factor affecting the process of pesticide and fertilizer use. Some enterprises prioritize profits over safe production and misuse pesticides and fertilizers, leading to toxic chemical residues in agricultural products that affect public health (Ivey et al., 2012). To address these issues, many scholars have conducted detailed research on how to effectively promote the reduction of pesticide and fertilizer use by agricultural enterprises. For example, Ding et al. (2022) conducted a comprehensive assessment of vegetable producers in Beijing, analyzed direct and indirect risks, and proposed encouraging growing enterprises to choose high-quality, multidrug-resistant, and widely applicable vegetable varieties, as well as non-toxic and efficient pesticide and fertilizer varieties. Khanpae et al. (2020) argue that larger and higher-level enterprises have a greater social responsibility for food safety and are subject to more pressure from government regulation, making them more likely to adopt safe production practices. Therefore, the government must focus on regulating small and medium-sized agricultural enterprises. On the contrary, some research suggests that the more pressure producers receive from the government and consumers, the more likely they are to adopt safe production practices. Therefore, the government needs to increase regulation to force agricultural enterprises to reduce pesticide and fertilizer use and improve the safety of agricultural products (Zhu et al., 2013; Singh and Verma, 2017; Arthur and Yamoah, 2019).

Insights can be gained from analyzing effective strategies to promote the reduction of pesticide and fertilizer use by agricultural enterprises. First, regulations and enforcement should be strengthened by improving regulation and management in the approval, production, sale and storage of pesticide and fertilizer products to ensure their quality meets standards. Regular assessments and inspections of agricultural enterprises should result in timely punishments for any problems found while encouraging green and sustainable practices and advocating business concepts and ethics. Government regulators should also be reregulated to prevent lax and perfunctory enforcement. Secondly, incentive mechanisms and market guidance should be established. Policies such as special subsidies and interest-free loans should be formulated to support environmentally friendly agricultural enterprises and encourage them to contribute to rational medicine use and reduction in pollution. Tax measures or reducing price increases can encourage the reduction of pesticide and fertilizer use, particularly biodegradable and low-toxicity options. Finally, science and technology are critical, and research and technology promotion must be actively carried out to accelerate the development of low-cost and high-efficiency alternatives to pesticides and fertilizers.

8. Conclusion

This study examines the relationship between the interests of the government, agricultural enterprises, and consumers by building an evolutionary game model. Different boundary conditions are analyzed to determine the stability of the strategy choices of the participants for the reduction of pesticide and fertilizer use. A dynamic evolutionary simulation using MATLAB was conducted to investigate the influence of factors such as initial willingness of participants, government regulations, and consumer green preferences on the strategies of both government and agricultural enterprises. The conclusions are supported by current knowledge on how to effectively promote reduction of pesticide and fertilizer use by agricultural enterprises. The paper draws the following conclusions.

(1) When certain conditions are met, the evolutionary game of the reduction of pesticide and fertilizer use governance constructed in this paper can achieve four stable evolutionary strategies, among which the government chooses the regulatory strategy and agricultural enterprises choose the reduction of pesticide and fertilizer use strategy as the ideal stable equilibrium strategy under the perspective of polycentric governance.

(2) The greater the initial probability of agricultural enterprises choosing a pesticide and fertilizer use reduction strategy, the less active the government is in choosing to implement a regulatory strategy. The greater the initial probability of government regulatory decisions, the greater the enthusiasm of agricultural enterprises to choose pesticide and fertilizer use of agricultural enterprises. Agricultural enterprises are subject to the more obvious binding effect of government regulation, and government governance of the reduction of pesticide and fertilizer use is important.

(3) Government regulatory measures have a significant impact on agricultural enterprise strategy choice, especially the impact of incentive measures is more pronounced. There is little difference in the effect of incentive and punishment measures on the choice of agricultural enterprises strategy, but the difference in the effect of incentive and punishment measures on the choice of government strategy is significant. In addition, incentives change the expected returns to stable equilibrium for both agricultural enterprises and the government, but penalty measures do not fundamentally change their expected returns. Incentives have a more pronounced effect on both subjects, and in the actual regulation process, incentives should be used judiciously and the construction of a binding regulatory mechanism should be strengthened.

(4) The green preferences of consumers are the key exogenous variable that significantly influences the decisions of agricultural enterprises and government decisions. The higher the green preference of the consumer, the higher the incentive for agricultural enterprises to choose products with pesticide and fertilizer use and the lower the incentive for government regulation. Meanwhile, consumers' brand preferences for agricultural products significantly influence the decisions of agricultural enterprises and the government. The higher the brand preference, the higher the motivation of agricultural enterprises for pesticide and fertilizer use of agricultural enterprises.

The study highlights the unique role that agricultural enterprises play in reducing pesticide and fertilizer usage by incorporating the government and enterprises into an evolutionary game model. The analysis enhances policy analysis within the Chinese context of reducing pesticide and fertilizer use, offering fresh insights for constructing the policy system. However, there are limitations to the study. The model is constructed based on certain simplified assumptions for analytical purposes, which may not fully capture the complexity and nuanced distinctions of the real world. It is important to recognize that the dynamics of the real world may deviate from the assumptions made in the model. Therefore, future research needs to validate this model in real-world settings, including conducting experimental studies and surveys, to uncover the intricacies and subtle differences of the real world and address the aforementioned limitations. Furthermore, agricultural enterprises in China exhibit variations in size, type, and level, and are differently influenced by the government and consumers. Future research should differentiate these types of enterprises to effectively promote the reduction of pesticide and fertilizer usage and ensure the quality and safety of agricultural products.

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 authors.

Author contributions

QH designed the research framework and methodology. QH and YS constructed the game model and simulation analyses. YS and MY were responsible for the literature analysis and strategy research. QH and HH edited the manuscript. All authors contributed to the article and approved the submitted version.

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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.

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