Promoting green development of agriculture based on low-carbon policies and green preferences: an evolutionary game analysis

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Abstract

Facilitating agro-food green planting and consumption is an effective way to reduce carbon emissions and achieve sustainability in global agriculture. Although many researchers have explored and analyzed this issue, there remains a gap between stakeholders of green agricultural development combined with low-carbon policies and green preferences that have been overlooked. To bridge this gap, a three-party evolutionary game model consisting of farmers, governments, and consumers is developed based on the government's low-carbon policies and stakeholders' green preferences. The six key parameters based on low-carbon policies and green preferences influencing strategic behavior are thoroughly discussed using numerical simulations. The findings reveal the following: (1) Appropriate subsidies policy and relatively high carbon prices are conducive to promoting agro-food green planting. (2) The three parties' green preferences improve people's low-carbon awareness in the market. (3) When the governments' green preference coefficient is less than 1, they will choose positive regulation and enhance farmers' and consumers' green preferences through publicity and education. As farmers' and consumers' green preferences increase to a certain high level, governments choosing negative regulation can also reach an advanced evolutionary stable strategy. The results provide theoretical and practical guidance for the green development of agriculture, help governments formulate scientific low-carbon policies, and provide referential significance for improving the green preference of farmers and consumers.

Keywords Green agriculture · Green preference · Low-carbon policy · Evolutionary game theory · Green development

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1 Introduction

There is a great urgency to explore and implement new models with low emissions and low pollution to promote green and low-carbon development (Lobell et al., 2011; Yang et al., 2022). Green development of agriculture (GDA) aims to promote organic fertilizers instead of chemical fertilizers (Khosravi et al., 2022) and the resource utilization of agricultural waste such as livestock and poultry manure, straw, and agricultural film (Chen et al., 2021; Yang et al., 2022). Compared to energy in industry, the world's largest source of carbon emissions (accounting for 24.2% of total carbon emissions), and energy in buildings, the world's third-largest source (accounting for 17.5% of total carbon emissions), agricultural carbon emissions is considered a critical sector, accounting for approximately 18.4% of total carbon emissions (Xu et al., 2020a) (second-largest carbon emission source globally), which should not be ignored (Moucheng & Lun, 2021). Therefore, GDA has become a key strategy to promote low-carbon development and has gained significant attention from local governments and academics.

Agricultural departments are indispensable for climate action and sustainable green development (Huisingh et al., 2015; Rebolledo-Leiva et al., 2017). However, China's agricultural production mode is dominated by high input and pollution, which poses a serious threat to the environment (Lin et al., 2015). To slow global warming, an increasing number of parties are joining the ranks of emission reduction (Fisher & Nasrin, 2021). Compared to other countries, China's agricultural production is still dominated by small-scale farmers who lack scale effects and cannot afford to produce green food (Ju et al., 2016). In 2018, China's Ministry of Agriculture and Rural Affairs released the "Management Measures for National Agricultural Sustainable Development Pilot Demonstration Zones", which required demonstration zones to summarize several GDA models and technology integration according to local conditions through GDA assessment and evaluation indicators, thus taking a crucial step forward for China's GDA.

Since 1970, evolutionary game theory based on the incomplete rational assumption of stakeholders, which can better reflect the impact of the complexity and uncertainty of different parties (Hofbauer & Sigmund, 2003), has been applied in a wide range of economic and social fields. Recently, the theory has been widely used in research related to green agriculture. However, it is insufficient to consider the evolutionary game between two enterprises or the evolutionary game between the enterprise and the government. For example, to obtain the best strategy for better green technology diffusion, Cui et al. (2019) establish evolutionary game models between the government, farmers, and agricultural enterprises; Xu et al. (2020b) consider local government, new agricultural operators, and traditional farmers in agricultural non-point source pollution control. To explore green agricultural production, Du et al. (2020) construct evolutionary game models between traditional farmers and new agricultural operations entities. As important subjects of the market, consumers also influence farmers' green planting through their purchasing behavior. Few studies, for example, Teng et al. (2021) have taken consumer demand into account in evolutionary game analysis, while they have neglected the influence of psychological factors, like green preference, on the subject's decision-making. Although Xi and Zhang (2022) consider the effect of consumers' green preferences on equilibrium, they ignore the influence of government policies, farmers' preferences, and government preferences. Therefore, this study explores the influence of government policies and subjects' green preferences on their decisions.

Governments play a significant role in GDA by developing and implementing low-carbon policies. Several low-carbon policies have been implemented in the agricultural field, including carbon taxes, cap-and-trade, and subsidies. The design of carbon tax neffectively reduces the carbon footprint of agricultural production by applying fertilizer, improving energy efficiency, and restrictions on straw burning (Xu et al., 2015). Patra (2018) highlights that the government's carbon cap-and-trade policies influence production decisions. These policies increase the income of small-scale farmers by 9% and effectively reduce their carbon emissions (Mello & Hildebrand, 2012). In contrast, carbon subsidy policies are more conducive to reducing carbon emissions and increasing social welfare (Cao et al., 2020). Moreover, providing green subsidies to farmers can improve agricultural production efficiency and promote GDA (Bakeshloo et al., 2022). Farmers' green production strategy is closely related to green policy attributes (Schulz et al., 2014), social responsibility (Jiang et al., 2022), and consumers' green preferences (Rana & Paul, 2017). More importantly, there is convincing evidence that consumers' increasing preference for environmentally friendly and low-carbon products has enabled the rapid development of green agriculture (Laureti & Benedetti, 2018). From consumers' perspective, many researchers examine various factors affecting their attitudes toward green agro-food. When consumers' valuation of green agro-food is greater than the product price, they would decide to purchase them, and this valuation generally depends on green preference and green cost (Ye & Liu, 2021). Sustainable labels provide consumers with information about green agro-food, reduce the drawbacks of information asymmetry in the sales process, and change consumers' purchasing behavior (Silva et al., 2017).

Green preference is the direct driving force that affects stakeholders' green behavior (Singh et al., 2014). However, the lack of green preference in China's agro-food is common. Farmers' green preference is to replace traditional fuels with biogas, biofuels, and biomass energy and promote production behavior using biodegradable plastic film and green planting technology. On the other hand, consumers' green preferences increase their willingness to purchase green agro-food, forcing them to change their consumption behavior (Du et al., 2019; Hou et al., 2020). However, farmers' lack of green preferences has resulted in a lack of investment in green production and the falsification of sales records to defraud government subsidies. China lacks a carbon footprint labeling system; owing to this information asymmetry, consumers cannot identify green-produced products, weakening their green preferences. Therefore, to promote green agro-food planting and the transformation of China's agricultural production, it is critical to properly regulate farmers' production behavior and encourage consumers to enhance their green preferences. However, the green preferences of the three parties and their effects on GDA have rarely been explored.

In summary, many studies have focused only on the evolutionary game analysis between two parties. Although a few studies have considered enterprises, governments, and consumers in GDA, most only considered the governments and consumers as constraints outside the subjects of the evolutionary game and did not analyze them as a unified whole. Some have focused on the effects of different green government policies on evolutionary game analysis; nevertheless, few have considered carbon trade policy. Moreover, a few scholars have realized that consumers are willing to pay higher prices for green food, and farmers are willing to produce green products out of market need and social responsibility. However, the existing literature does not apply this green preference well to evolutionary game analysis, and few studies discuss green preferences in government based on an evolutionary game perspective.

Therefore, to fill these gaps, we establish a stable evolution strategy of this model to determine the optimal action strategy of the three parties, namely, farmers, the government, and consumers, by combining the various carbon policies and the different degrees of green preference. We solve the evolutionary stable strategies (ESSs) of this model and their related conditions by carbon policies and green preferences. Numerical simulations are then applied to systematically analyze low-carbon policies and green preferences for stable evolutionary system strategies.

This study makes several practical contributions to the literature. First, this research contributes to the existing literature by combining government low-carbon policies and green preferences to explore GDA. Second, this study develops an analytical framework to identify game players' behavioral strategies based on the evolutionary game model. Third, this study analyzes the influence of multiple stakeholders on their green behavior and considers the pull effect of consumers' green demand, which has been ignored in previous studies. Finally, this study provides practical management insights to promote China's GDA modes, which are equally applicable to other countries facing similar challenges.

The remainder of this paper is shown below. Section 2 describes the hypothesis, parameter setting and model construction. Section 3 conducts the evolutionary game equilibrium analysis. Section 4 presents the simulation analysis. Furthermore, the last two parts provide discussion and conclusions.

2 Model Building

2.1 Problem description

The reality of "small land and large population" in China leads to the inability to effectively form economies of scale, which has become the main obstacle to China's GDA. Household operation in rural areas remains the main agricultural production form (Huang et al., 2022). Therefore, the key to accelerating green agricultural production is the transformation of farmers' family production behavior from traditional extensive to intensive green production mode (Zhang et al., 2022). Although green agricultural production has formed a broad consensus in society, farmers' behavior is often contrary to their willingness, and green production behavior is not common. Under the condition of a market economy, farmers, as rational economic individuals, tend to pursue the maximization of interests. The key for farmers to carry out green agricultural production is profit return. When making production decisions, farmers first consider the economic benefits of green production and whether they can achieve the expected returns. When such returns are greater than the costs, the probability of green production will be greater. Compared with traditional production methods, green agricultural production methods have higher input costs, although farmers with green preferences are reluctant to carry out green production.

The key to solving this dilemma is to support GDA policies. Although policies have no direct effect on GDA, they can improve the efficiency and direction of agricultural development by changing the market prices and allocating production factors. The government is the macro regulator of farmers' production behavior, and its policies and regulations constrain such behavior to a certain extent. Under the guidance of the low-carbon policy, farmers' green preference increases, which becomes the internal driving force of green production. The policy orientation comprises three parts: green regulation and traceability mechanism for agricultural products, government subsidy mechanism for green

agricultural production, and application of green production technology. However, the government subsidy mechanism often faces speculative behavior from farmers, which hinders GDA in China (Lu et al., 2022). The deterioration of the ecological environment, the frequent occurrence of food safety incidents, and the incentive of low-carbon government policies have led to consumer demand for green agricultural products, forming a push-back mechanism for farmers to produce green agro-food (Ghosh et al., 2020).

2.2 Assumptions

Farmers' green planting and the government's low-carbon policies are critical for ensuring GDA and reducing carbon emissions in the agricultural field. Evolutionary game theory not only considers the bounded rationality of players but also provides a powerful analytical framework for how their decisions change over time and for predicting the outcomes of competitive strategies in dynamic environments (Smith, 1986). This study constructs a logical relationship between the three parties of the evolutionary game based on low-carbon policies and green preferences to promote GDA, as illustrated in Fig. 1. This evolutionary game system is composed of farmers, governments, and consumers. Each arrow in the Fig. 1 shows the strategy and revenue flow for each subject.

To construct a three-party game model that can analyze the stability strategy and equilibrium points of each party and the influence of each party's strategy, the following assumptions are made:

Assumption 1 Farmers (including small-scale farmers, family farms, and rural cooperatives) are participants 1. Government departments are participants 2. Consumers are participants 3. The three parties are participants of bounded rationality, and the strategy selection gradually evolves and stabilizes in the optimal strategy over time.

Assumption 2 Farmers have two pure strategies: green planting and traditional planting. The carbon emissions are relatively low when farmers conduct the former, but due to the emergence of biological pesticides, biodegradable agricultural films, and the resource utilization of agricultural wastes, the related costs are high, $C_1 = c_1 * q_1$. Since carbon emissions
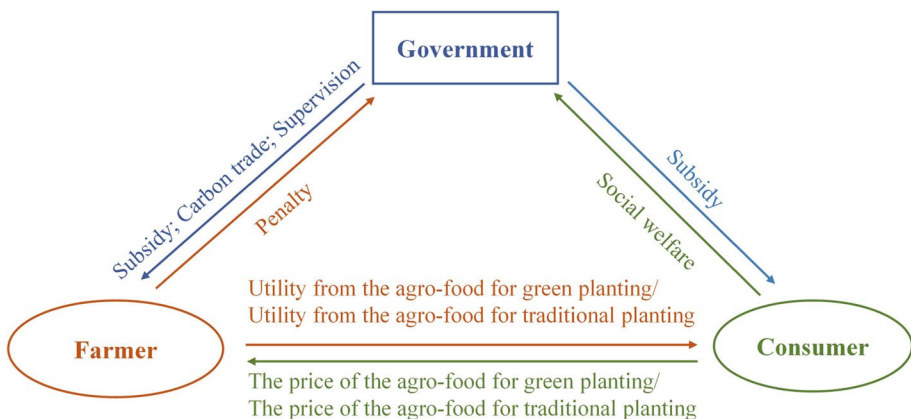

Fig. 1 The game tripartite relationship chart

are less than the share stipulated by the government, farmers could trade the excess carbon emissions share in the carbon trading market and obtain additional benefits as $R_3 = (N - \sigma_1 * q_1) * p_c$. Farmers receive subsidies $S_f = t_f * q_1 * p_1$ from the government for green planting. Compared with green planting, the cost of farmers' traditional planting is relatively low, $C_2 = c_2 * q_2$, but carbon emissions exceed the standard required by the government. Therefore, farmers buy the carbon emissions share in the carbon trading market and generate the corresponding cost, that is, $C_3 = (\sigma_2 * q_2 - N) * p_c$. Farmers' green preference is related to the cost difference between these two planting modes, that is, $G_f = \gamma_f * (C_1 - C_2)$, $C_1 > C_2$.

Assumption 3 Farmers carry out traditional planting after applying for subsidies from the government, which incurs the cost of speculation, that is, C_4, mainly including forgery of purchase records, false publicity, and other costs. This fee could have been used for reproduction, resulting in a certain opportunity cost, O. Moreover, farmers need to bear a penalty P under the government's positive regulation. The benefit of agro-food for green planting is $R_1 = p_1 * q_1$, and that for traditional planting is $R_2 = p_2 * q_2$.

Assumption 4 The government has two pure strategies: positive regulation and negative regulation. When the government adopts regulation, it needs to pay a certain supervision cost, and the government's green preference is related to the supervision cost (Long et al., 2021), which is $G_g = \gamma_g * C_g$. In addition, we define positive regulation as when the government spends more money on regulation; otherwise, it is negative regulation. Regardless of government regulation, the environmental improvement brought about by farmers' green planting will increase social welfare, that is, W, while the environmental degradation brought about by farmers' traditional planting will reduce social welfare, that is, D.

Assumption 5 Consumers have two pure strategies: (1) purchase and (2) not purchase. The government provides certain consumption subsidies $S_c = t_c * q_1 * p_1$ when consumers purchase agro-food based on green planting. Additionally, the utility of consumers purchasing agro-food for green planting is U_1, whereas U_2 is for traditional planting, $U_1 > U_2$. Moreover, consumers' green preference is related to the utility difference of products, $G_c = (U_1 - U_2) * \gamma_c$, $U_1 > U_2$.

Detailed parameter settings and its description are shown in Table 1.

2.3 The establishment of the payoff model

According to the above assumptions, the payoff matrix is based on the farmers, governments, and consumers, as shown in Table 2.

As shown in Table 2, the comprehensive prospective earnings of the farmer when choosing green planting (E_{11}) should be:

$$E_{11} = yz(R_1 + S_f + R_3 + G_f - C_1) + y(1 - z)(-C_1 + S_f + R_3 + G_f)$$
$$+ (1 - y)z(R_1 + S_f + R_3 + G_f - C_1) + (1 - y)(1 - z)(S_f + R_3 + G_f - C_1) \quad (1)$$

Similarly, the comprehensive prospective earnings of the farmer when adopting traditional planting (E_{12}) should be:

Table 1 Parameter setting and description

Parameters	Definition
Government payoff	
C_g	Supervision cost
t_f	Subsidy coefficient for farmers' green planting
t_c	Subsidy coefficient for consumers' purchase agricultural production for green planting
D	The cost of remediating environmental deterioration for farmer's traditional planting
W	social welfare is brought about by environmental improvement under farmer's green planting
N	Number of government carbon emission share
γ_g	Government's green preference
Farmer payoff	
c_1	The unit cost of green planting
c_2	The unit cost of traditional planting
σ_1	Unit carbon emissions from farmers' green planting
σ_2	Unit carbon emissions from farmers' traditional planting
p_c	The unit price of carbon trading
p_1	The unit price for green planting
p_2	The unit price for traditional planting
P	Penalty for fraudulent subsidy
O	The opportunity cost of defrauding subsidies
γ_f	Farmer's green preference
Consumer payoff	
q_1	Quantity of agro-food for green planting
q_2	Quantity of agro-food for traditional planting
U_1	Unit utility from the purchase of agro-food for green planting
U_2	Unit utility from the purchase of agro-food for traditional planting
γ_c	Consumer's green preference

Table 2 Payoff matrix of three-party evolutionary game

		Government	Consumers	
			Purchase z	Not purchase 1-z
Farmers	Green planting x	Positive regulation y	$R_1+S_f+R_3+G_f\text{-}C_1$; $W+G_g\text{-}C_g\text{-}S_f\text{-}S_c$; $-R_1+U_1+G_c+S_c$	$-C_1+S_f+R_3+G_f$; $G_g\text{-}S_f\text{-}C_g+W$; 0
		Negative regulation 1-y	$R_1+S_f+R_3+G_f\text{-}C_1$; $-S_f\text{-}S_c+W$; $-R_1+U_1+G_c+S_c$	$S_f+R_3+G_f\text{-}C_1$; $-S_f+W$; 0
	Traditional planting 1-x	Positive regulation y	$-C_2\text{-}P\text{-}O\text{-}C_4\text{-}C_3$; $-C_g+P+G_g\text{-}D$; 0	$R_2\text{-}C_2\text{-}P\text{-}O\text{-}C_4\text{-}C_3$; $-C_g+P+G_g\text{-}D$; $-R_2+U_2$
		Negative regulation 1-y	$-C_2\text{-}O\text{-}C_4\text{-}C_3+S_f$; $-D\text{-}S_f$; 0	$R_2\text{-}C_2\text{-}O\text{-}C_4\text{-}C_3+S_f$; $-D\text{-}S_f$; $-R_2+U_2$

$$E_{12} = yz(-C_2 - P - O - C_4 - C_3) + y(1-z)(R_2 - C_2 - P - O - C_4 - C_3)$$
$$+(1-y)z(-C_2 - O - C_4 - C_3 + S_f) + (1-y)(1-z)(R_2 - C_2 - O - C_4 - C_3 + S_f)$$

$$(2)$$

Thus, the prospective earnings of the farmer $\overline{E}_1$ can be obtained.

$$\overline{E}_1 = xE_{11} + (1-x)E_{12} \tag{3}$$

The replication dynamic equation of the farmer is calculated as $F(x)$.

$$F(x) = \frac{dx}{dt} = x\left(E_{11} - \overline{E}_1\right) = x(1-x)[(y(P - S_f) + z(R_1 + R_2 - 2S_f)$$
$$+2S_f + R_3 + G_f - C_1 - R_2 + C_2 + O + C_3 + C_4)] \tag{4}$$

According to the differential equations stability theorem, the probability of farmers choosing green planting in a stable stage must satisfy: $F(x)=0$ and $\frac{dF(x)}{dx}<0$.

$$\frac{dF(x)}{dx} = (1-2x)[(y(P - S_f) + z(R_1 + R_2 - 2S_f) + 2S_f + R_3 + G_f - C_1 - R_2 + C_2 + O + C_3 + C_4)] \tag{5}$$

$$G(z) = y(P - S_f) + z(R_1 + R_2 - 2S_f) + 2S_f + R_3 + G_f - C_1 - R_2 + C_2 + O + C_3 + C_4 \tag{6}$$

Due to $\frac{dG(z)}{dz}>0$, $G(z)$ is an increasing function. Therefore, when $z = \frac{-2S_f - R_3 - G_f + C_1 + R_2 - C_2 - O - C_3 - C_4 - y(P - S_f)}{R_1 + R_2 - 2S_f} = z^*$, $G(z)=0$. It shows that the farmer will gain the same benefits when choosing green planting or traditional planting. When $z < z^*$, $G(z) < 0$, and $\frac{dF(x)}{dx}\Big|_{x=0} < 0$, the strategy of the farmer changes from "Green Planting" to "Traditional Planting", and a stable strategy of "Traditional Planting" is finally obtained. Similarly, when $z > z^*$, $G(z) > 0$, and $\frac{dF(x)}{dx}\Big|_{x=1} < 0$, and the strategy of the farmer changes from "Traditional Planting" to "Green Production", and a stable strategy of "Green Planting" is finally obtained.

Similarly, the comprehensive prospective earnings of the government when adopting positive regulation (E_{21}) should be:

$$E_{21} = xz(W + G_g - C_g - S_f - S_c) + x(1-z)(G_g - S_f - C_g + W)$$
$$+(1-x)z(-C_g + P + G_g - D) + (1-x)(1-z)(-C_g + P + G_g - D) \tag{7}$$

The comprehensive prospective earnings of the government when choosing negative regulation (E_{22}) should be:

$$E_{22} = xz(-S_f - S_c + W) + x(1-z)(-S_f + W)$$
$$+(1-x)z(-D - S_f) + (1-x)(1-z)(-D - S_f) \tag{8}$$

Therefore, the prospective earnings of the government $\overline{E}_2$ can be obtained.

$$\overline{E}_2 = y = E_{21} + (1-y)E_{22} \tag{9}$$

The replication dynamic equation of government is calculated as $F(y)$.

$$F(y) = \frac{dy}{dt} = y\left(E_{21} - \overline{E}_2\right) = y(1-y)\left[-x(P + S_f) + G_g + P - C_g + S_f\right] \quad (10)$$

The probability of the government's adopting positive regulation in a stable stage must satisfy: $F(y) = 0$ and $\frac{dF(y)}{dy} < 0$.

$$\frac{dF(y)}{dy} = (1 - 2y)\left[-x(P + S_f) + G_g + P - C_g + S_f\right] \quad (11)$$

$$G(x) = -x(P + S_f) + G_g + P - C_g + S_f \quad (12)$$

Due to $\frac{dG(x)}{dx} < 0$, $G(x)$ is a decreasing function. Therefore, when $x = \frac{G_g + P - C_g + S_f}{P + S_f} = x^*$, $G(x) = 0$, It implies that the benefits of the government are the same whether or not they choose positive regulation. When $x < x^*$, $G(x) > 0$, and $\frac{dF(y)}{dy}\big|_{y=1} < 0$, the strategy of the government changes from "Negative Regulation" to "Positive Regulation", and the government selects "Positive Regulation". When $x > x^*$, $G(x) < 0$, and $\frac{dF(y)}{dy}\big|_{y=0} < 0$, a stable "Negative Regulation" strategy is finally obtained.

Finally, the comprehensive prospective earnings of the consumer when making a purchase (E_{31}) should be:

$$E_{31} = xy(-R_1 + U_1 + G_c + S_c) + x(1 - y)(-R_1 + U_1 + G_c + S_c) \quad (13)$$

The comprehensive prospective earnings of the consumer when they do not make a purchase (E_{32}) should be:

$$E_{32} = (1 - x)y(-R_2 + U_2) + (1 - x)(1 - y)(-R_2 + U_2) \quad (14)$$

Therefore, the prospective earnings of the consumer $\overline{E}_3$ can be obtained.

$$\overline{E}_3 = zE_{31} + (1 - z)E_{32} \quad (15)$$

The replication dynamic equation of consumer is calculated as $F(z)$.

$$F(z) = \frac{dz}{dt} = z\left(E_{31} - \overline{E}_3\right) = z(1 - z)\left[x(U_2 - R_2 + U_1 - R_1 + G_c + S_c) + U_2 - R_2\right] \quad (16)$$

The probability of consumer to choose purchase agro-food for green planting in a stable stage must satisfy: $F(z) = 0$ and $\frac{dF(z)}{dz} < 0$.

$$\frac{dF(z)}{dz} = (1 - 2z)\left[x(U_2 - R_2 + U_1 - R_1 + G_c + S_c) + U_2 - R_2\right] \quad (17)$$

$$G(x) = x(U_2 - R_2 + U_1 - R_1 + G_c + S_c) + U_2 - R_2 \quad (18)$$

Due to $\frac{dG(x)}{dx} > 0$, $G(x)$ is an increment function. Therefore, when $x = \frac{R_2 - U_2}{U_2 - R_2 + U_1 - R_1 + G_c + S_c} = x^*$, $G(x) = 0$. It demonstrates that the benefits of consumers are the same whether they select to purchase or not purchase. When $x < x^*$, $G(z) < 0$, and $\frac{dF(z)}{dz}\big|_{z=0} < 0$, the strategy of consumer changes from "Purchase" to "Not Purchase", and

consumers take the "Not purchase". When $x > x^*$, $G(x) > 0$, and $\frac{dF(z)}{dz}\big|_{z=1} < 0$, and consumers choose the strategy for purchase.

3 Equilibrium analysis of evolutionary game model

In the replicated dynamic system, if $F(x)=0$, $F(y)=0$, and $F(z)=0$, then we can obtain the evolutionary stable equilibrium. Therefore, we discuss the asymptotic stability of the three parties' pure strategy equilibrium. As a result, this paper analyzes the asymptotic stability of the system at the following points: (0, 0, 0), (0, 1, 0), (0, 0, 1), (0, 1, 1), (1, 0, 0), (1, 1, 0), (1, 0, 1), (1, 1, 1).

We bring a stable equilibrium point into the Jacobian matrix for further analysis. The Jacobian matrix of the replicated dynamic system is J:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{19}$$

Among them:

$$\frac{\partial F(x)}{\partial x} = (1 - 2x)\big[y(P - S_f) + z(R_1 + R_2 - 2S_f) + 2S_f + R_3 + G_f - C_1 - R_2 + C_2 + O + C_3 + C_4\big] \tag{20}$$

$$\frac{\partial F(x)}{\partial y} = x(1 - x)(P - S_f) \tag{21}$$

$$\frac{\partial F(x)}{\partial z} = x(1 - x)(R_1 + R_2 - 2S_f) \tag{22}$$

$$\frac{\partial F(y)}{\partial x} = y(1 - y)(-P - S_f) \tag{23}$$

$$\frac{\partial F(y)}{\partial y} = (1 - 2y)\big[-x(P + S_f) + G_g + P - C_g + S_f\big] \tag{24}$$

$$\frac{\partial F(y)}{\partial z} = 0 \tag{25}$$

$$\frac{\partial F(z)}{\partial x} = z(1 - z)(U_2 - R_2 + U_1 - R_1 + G_c + S_c) \tag{26}$$

$$\frac{\partial F(z)}{\partial y} = 0 \tag{27}$$

$$\frac{\partial F(z)}{\partial y} = (1 - 2z)\big[x\big(U_2 - R_2 + U_1 - R_1 + G_c + S_c\big) + U_2 - R_2\big] \tag{28}$$

According to evolutionary game theory, only all the eigenvalues of the Jacobian matrix are nonpositive; thus, this system's asymptotic stability point can be obtained. The eigenvalues of the Jacobian matrices for each point are listed in Table 3.

If the above equilibrium points satisfy the corresponding conditions, they are asymptotically stable; otherwise, they are unstable or saddle points. The evolution of the behavioral strategies of participants in the GDA is influenced by many parameters. However, there are only two stable equilibrium points. When a certain condition is reached, the three parties will continue to evolve to (1,0,1) or (1,1,1), as illustrated in Fig. 2.

If Condition (1) is met, the evolutionary trajectories of the three participants under (1, 0, 1) are illustrated in Fig. 2(a). When the government's regulation cost is higher than their green preference, they will choose to regulate loosely. Moreover, farmers will choose green planting, and consumers will purchase agro-food for green planting.

Table 3 Income matrix under corresponding strategies

| Equilibrium point	Eigenvalue	Stability		Condition
(0, 0, 0)	$\lambda_1 = 2S_f + R_3 + G_f - C_1 - R_2 + C_2 + O + C_3 + C_4$ $\lambda_2 = G_g + P - C_g + S_f$ $\lambda_3 = U_2 - R_2$	$(\times, \times, +)$	Saddle	/
(0, 0, 1)	$\lambda_1 = R_1 + R_3 + G_f - C_1 + C_2 + O + C_3 + C_4$ $\lambda_2 = G_g + P - C_g + S_f$ $\lambda_3 = R_2 - U_2$	$(+, \times, -)$	Saddle	/
(0, 1, 0)	$\lambda_1 = P + S_f - R_2 + R_3 + G_f - C_1 + C_2 + O + C_3 + C_4$ $\lambda_2 = -G_g - P + C_g - S_f$ $\lambda_3 = U_2 - R_2$	$(\times, \times, +)$	Saddle	/
(0, 1, 1)	$\lambda_1 = P - S_f + R_1 + R_3 + G_f - C_1 + C_2 + O + C_3 + C_4$ $\lambda_2 = -G_g - P + C_g - S_f$ $\lambda_3 = R_2 - U_2$	$(+, \times, -)$	Saddle	/
(1, 0, 0)	$\lambda_1 = -2S_f - R_3 - G_f + C_1 + R_2 - C_2 - O - C_3 - C_4$ $\lambda_2 = G_g - C_g$ $\lambda_3 = 2U_2 - 2R_2 + U_1 - R_1 + G_c + S_c$	$(\times, \times, +)$	Saddle	/
(1, 1, 0)	$\lambda_1 = -S_f - P - R_3 - G_f + C_1 + R_2 - C_2 - O - C_3 - C_4$ $\lambda_2 = C_g - G_g$ $\lambda_3 = 2U_2 - 2R_2 + U_1 - R_1 + G_c + S_c$	$(\times, \times, +)$	Saddle	/
(1, 0, 1)	$\lambda_1 = -R_1 - R_3 - G_f + C_1 - C_2 - O - C_3 - C_4$ $\lambda_2 = G_g - C_g$ $\lambda_3 = 2R_2 - 2U_2 - U_1 + R_1 - G_c - S_c$	$(-, \times, -)$	Asymptotic stability point ①	
(1, 1, 1)	$\lambda_1 = -P + S_f - R_1 - R_3 - G_f + C_1 - C_2 - O - C_3 - C_4$ $\lambda_2 = C_g - G_g$ $\lambda_3 = 2R_2 - 2U_2 - U_1 + R_1 - G_c - S_c$	$(-, \times, -)$	Asymptotic stability point ②	

Note: $G_g - C_g < 0$, $-G_g + C_g < 0$
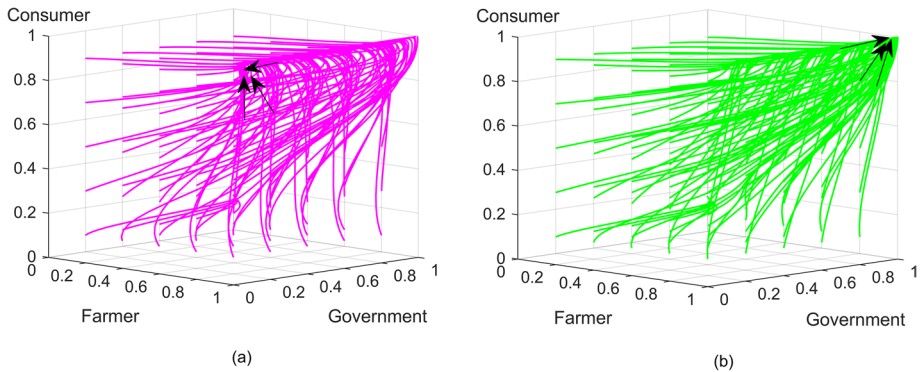
Fig. 2 Evolutionary trajectories of the farmer, government, and consumer under different stable states: **a** (1, 0, 1), **b** (1, 1, 1)

When Condition (2) is satisfied, the evolutionary trajectories of the tripartite under (1, 1, 1) are illustrated in Fig. 2(b). This reveals that local government prefers positive regulation when its green preference is higher than the regulation cost. Meanwhile, farmers will select green planting in a tightly regulated environment, and consumers will choose to purchase agro-food produced in a green manner.

4 Numerical simulations

To confirm the validity of this model, we further investigate the effect of different settings of relevant parameters on the evolutionary game process of each participant under (1, 0, 1) and (1, 1, 1). MATLAB is employed to conduct simulation analysis.

4.1 Initial parameters

Several significant initial parameters are selected or calculated depending on the relevant regulations or situations, focusing on China's real-world situation and strategy. Taking a rural area in Zhejiang Province as an example, the initial parameters are set by analogy with the same proportional adjustment based on real data to make our discussion more general. Typical initial parameters for this evolutionary game analysis are presented in Table 4, in which "¥/ha" represents yuan per hectare.

In a field survey of a village in Zhejiang Province, we asked local farmers and learned that their traditional crop planting cost is 3,000 yuan per hectare. If they use biodegradable agricultural films, organic fertilizer, and green treatment of agricultural production waste, the cost will increase to 4,000 yuan per hectare. Traditional crops can be sold for 5,000 yuan per hectare, and the profit of green crops is 6,000 yuan per hectare. According to interviews with local farmers and the experience data of relevant agricultural technicians (Ministry of Agriculture and Rural Affairs of China, 2021a), one hectare of land can produce 2,000 kg of crops. The carbon trading price is 60 yuan per ton (Ministry of Ecology and Environment of China, 2021b). As Lal (2004) noted, compared to traditional production, one hectare of green production may reduce carbon emissions by 1.3 tons. Therefore, the carbon transaction cost is 78 yuan per ton. According to the relevant policies of the

Table 4 Initial parameters for numerical simulations (unit: ¥/ha)

Participants	Parameters	Variables	Value
Farmers	The cost of green planting	C_1 (interview)	40
	The cost of traditional planting	C_2 (interview)	30
	The benefit of agro-food for green planting	R_1 (interview)	60
	The benefit of agro-food for traditional planting	R_2 (interview)	50
	The cost of carbon trading for traditional planting	C_3 Ministry of Ecology and Environment of China, (2021b; Lal, 2004)	0.78
	The benefit of carbon trading for green planting	R_3 Ministry of Ecology and Environment of China, (2021b; Lal, 2004)	0.78
	The cost of speculation	C_4 (Expert valuation)	5
	opportunity cost	O (Expert valuation)	5
	Farmers' green preference	G_f (Expert valuation)	2
Government	The subsidy for green purchase	S_c (Expert valuation)	22.5
	The subsidy for green planting	S_f Ministry of Agriculture and Rural Affairs of China, (2020)	15
	Penalty for fraudulent subsidy	P (interview)	15
	The supervision cost	C_g (interview)	10
	government' green preference	G_g (Expert valuation)	2
Consumers	Consumers' green preference	G_c (Expert valuation)	3
	Unit utility from the purchase of agro-food for green planting	U_1 (Expert valuation)	65
	Unit utility from the purchase of agro-food for traditional planting	U_2 (Expert valuation)	50

Chinese Supply and Marketing Cooperatives, farmers receive an average subsidy of 1,500 yuan per hectare for green planting; the subsidy coefficient is 0.375 (Ministry of Agriculture and Rural Affairs of China, 2020). The government's supervision cost comprises administrative burdens, such as paperwork, application forms involving supervision, and information disclosure for implementing supervision. Based on the interviews, we set this to 1,000 yuan (House, 2019). According to relevant news reports, the government's punishment for fraudulent subsidies is roughly the same as the value of the subsidies. Therefore, we set the initial value of the fraudulent subsidy penalty to 1,500 yuan per hectare.

Because the speculative cost of subsidy fraud, opportunity cost, consumer utility, and subject preferences are difficult to measure, we determine the values of these parameters through expert evaluation. To ensure scientific validity, reliability, and accuracy, five experts in the field of behavioral economics and five in agriculture were invited to evaluate these parameters. The specific assessment process consists of the following five steps:

1. Experts in both fields were randomly divided into five groups, and the meaning and significance of this model and its parameters were explained to them.
2. The settings of each parameter were evaluated anonymously between the groups.
3. Summarize and give feedback on these results to the other groups, and the experts were asked to provide their further judgments based on the initial evaluation criteria.
4. Further collate and summarize these parameter values and invite experts to discuss and optimize the parameter criteria together.
5. Use the averaging method to calculate the final parameters.

Based on the above expert evaluation process, we set the initial green preference coefficient to 0.2, and further calculations were performed: $G_g = 200$, $G_c = 300$, $G_f = 200$. However, the criteria for the given parameters are incongruent. Therefore, to make the simulation results realistic and scientific, we adjusted the above parameters proportionally (all parameters are converted to 1 hectare as the basic unit and multiplied by 1/100).

4.2 Effect analysis of typical parameters

This section presents a sensitivity analysis to examine how the evolutionary trajectories of farmers, government and consumers are affected when the parameters are changed, which aids policymakers and agricultural managers in developing practical solutions for GDA.

4.2.1 Condition of (1, 0, 1)

Evolutionary trajectories of the farmer, government and consumer under (1, 0, 1) are investigated in this section. The sensitivity analysis results of the low-carbon policies and green preferences are presented in Figs. 3, 4, 5, 6, 7, 8.

To explore the influence of carbon trading costs, C_3 is set as 0.78, 3.9, and 7.8, respectively. Under different carbon trading costs, the evolutionary trajectory results for farmers, governments, and consumers exhibit different characteristics, as presented in Fig. 3a, b, and c, respectively. From Fig. 3a-c, with an increase in C_3, the probability of farmers or consumers choosing green behavior increases significantly until a steady state is reached. Because farmers trade the reduced carbon emissions from green production, increasing additional income and offsetting the high cost of green planting, it increases their green behavior. On the contrary, when the carbon trading price is low,
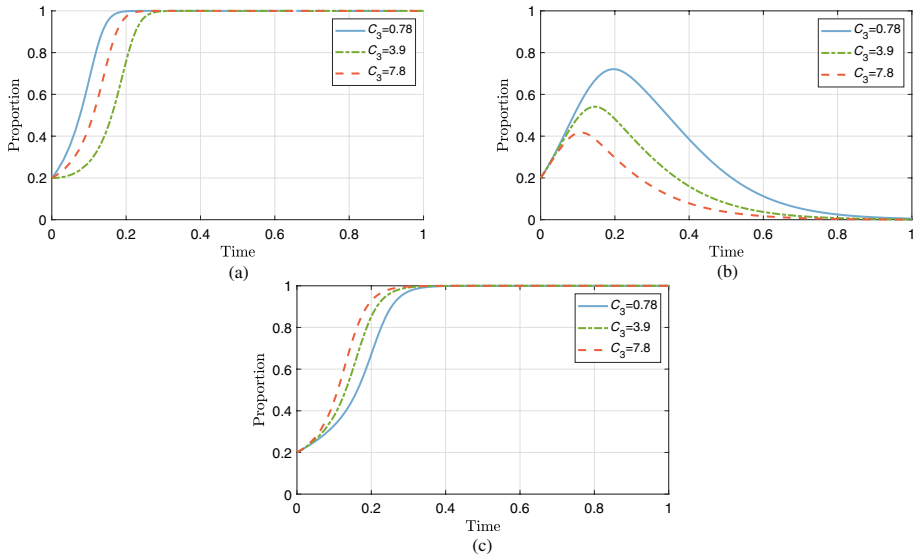
Fig. 3 Effects of carbon trading cost on tripartite under the ESS (1, 0, 1) **a** impact on farmers, **b** impact on governments and (c) impact on consumers
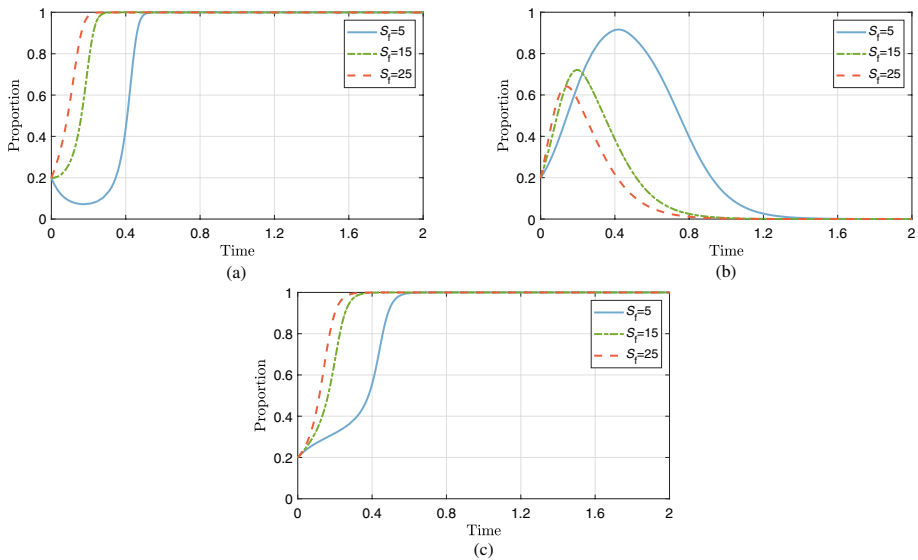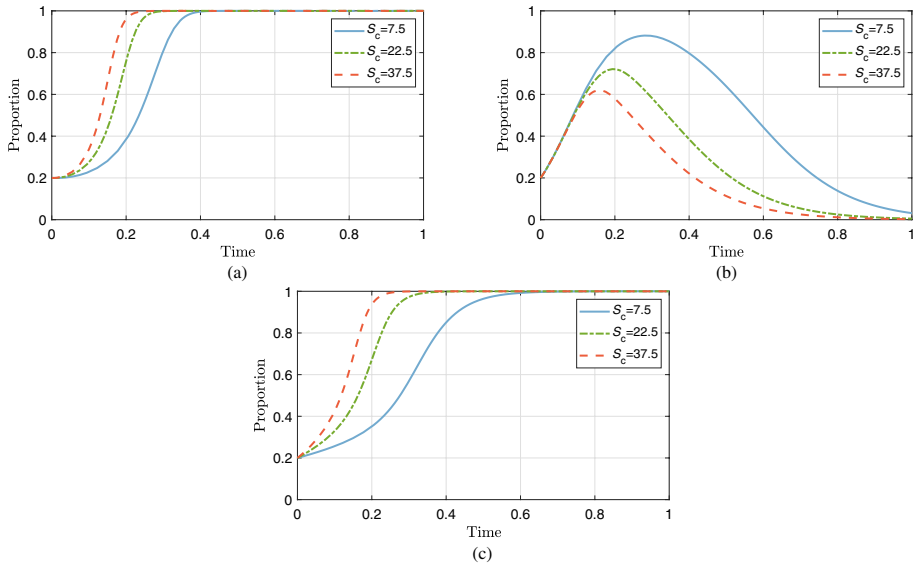

Fig. 4 Effects of farmer's subsidy on tripartite under the ESS (1, 0, 1) **a** impact on farmers, **b** impact on governments and (c) impact on consumers

the probability of the government's positive regulation increases and decreases until stability is reached, as illustrated in Fig. 3(b). This means that farmers lack incentives to choose green planting, and the possibility of fraudulent subsidy behavior

Fig. 5 Effects of consumer's subsidy on tripartite under the ESS (1, 0, 1) **a** impact on farmers, **b** impact on governments and (c) impact on consumers
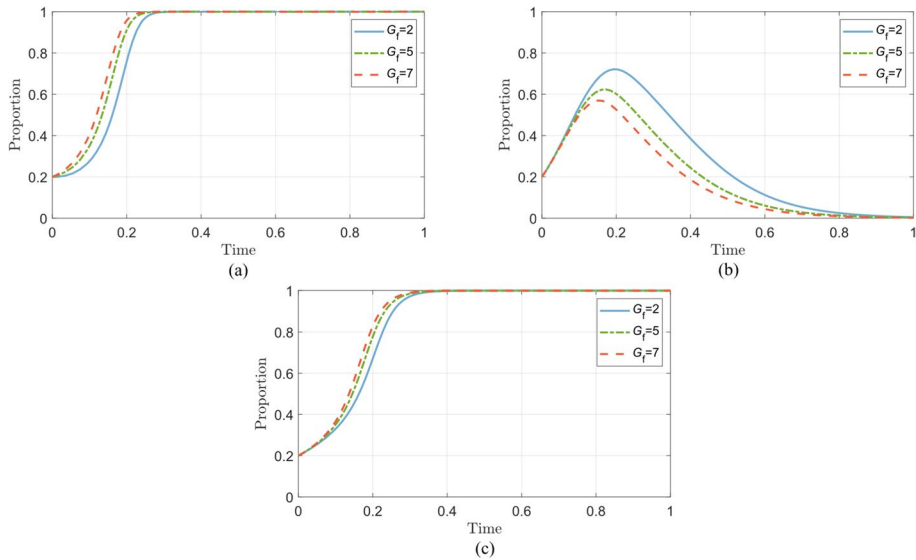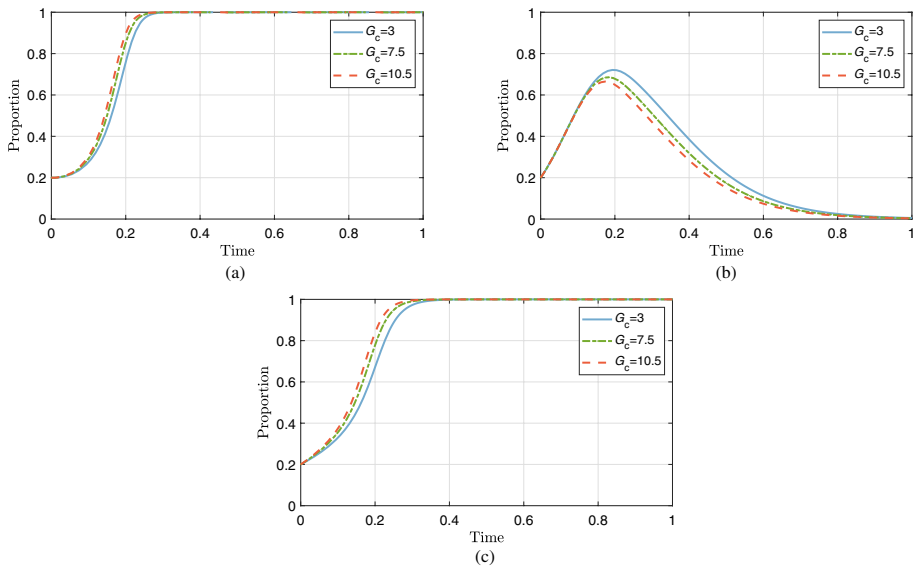

Fig. 6 Effects of farmer's green preference on tripartite under the ESS (1, 0, 1) **a** impact on farmers, **b** impact on governments and (c) impact on consumers

will increase. Therefore, the government is more likely to choose positive regulation initially.
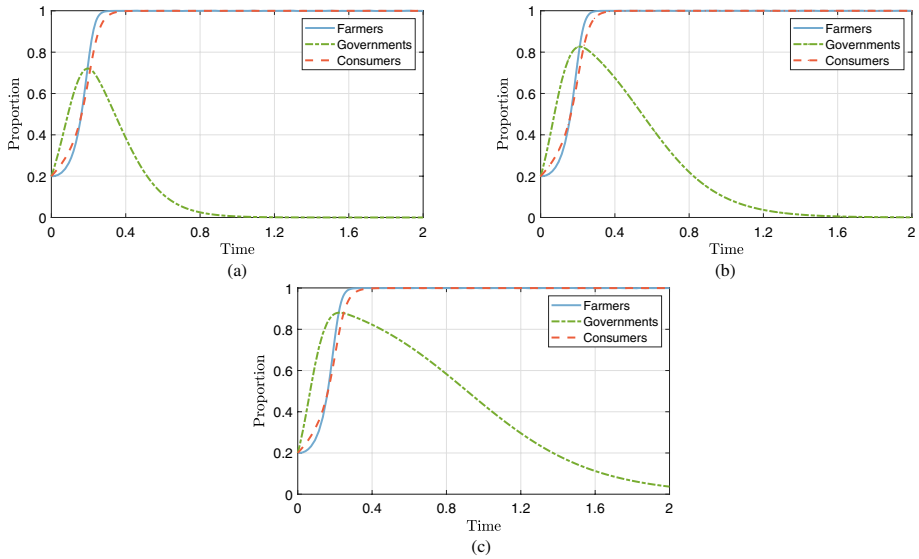
Fig. 7 The influence of government green preference under the ESS (1, 0, 1) **a** $G_g=2$ **b**, $G_g=5$ and (c) $G_g=7$

Fig. 8 Effects of consumer's green preference on tripartite under the ESS (1, 0, 1) **a** impact on farmers, **b** impact on governments and (**c**) impact on consumers

To explore the influence of farmers' subsidies of different intensities on tripartite decision-making, we set S_f as 5, 15, and 25, representing low, medium, and high intensity, respectively. The evolutionary trajectory results of three stakeholders at different subsidy coefficients for farmers' green planting are described in Fig. 4a, b, and c. These results

indicate that government subsidies to farmers have a crucial impact on tripartite strategic decisions. Figure 4 shows that as S_f increases, the tripartite's willingness for green behavior increases while the probability of the government's willingness for positive regulation decreases. These findings suggest that when government subsidies to farmers are insufficient to cover the cost of green planting, they may opt for traditional planting. Increasing farmer subsidies can effectively promote their willingness to adopt green planting and make consumers more willing to buy agro-food produced in a green manner.

For different government subsidy coefficients for consumers (we set 0.125, 0.375, 0.625), the evolutionary trajectory results of farmers, governments, and consumers under (1, 0, 1) are illustrated in Fig. 5a, b, and c. As S_c increases, the rates of consumers' and farmers' green behavior willingness increases (see Fig. 5a and c, respectively), while the probability of the government's willingness for positive regulation decreases (see Fig. 5b). Consumers increase demand for green products in the market as government subsidies compensate for the additional cost of buying agro-food for green planting, further increasing farmers' motivation for green planting.

The evolutionary trajectory results of farmers, governments, and consumers for different farmers' green preference coefficients are presented in Fig. 6a, b, and c, respectively. As farmers' green preferences rise, so does green behavior among farmers and consumers, and the possibility of the government's positive regulation falls. Because farmers actively choose green planting due to their green preference, the need for the government's positive regulation is reduced.

The evolutionary process results of the tripartite at different government green preference coefficients ($G_g = 2$, $G_g = 5$, and $G_g = 7$) are described in Fig. 7a, b, and c, respectively. The results indicate that G_g increases the probability of the government's positive regulation but slows the evolutionary time for the government strategy to reach a steady state. When G_g is higher, the government may enact more generous subsidy policies, increasing the likelihood of fraud and forcing the government to actively regulate it. However, due to the high cost of government supervision, the government prefers to urge farmers' green behavior through low-carbon awareness publicity and education rather than through positive regulation.

We set G_c to 3, 7.5, and 10.5 to indicate low, medium, and high levels of green preference, respectively. For different consumers' green preferences, differences in evolutionary trajectories can be found in Fig. 8a, b, and c. Increased G_c helps farmers select green planting more quickly while also increasing customers' likelihood of buying agro-food produced in a green way. However, it also inhibits the government's positive regulation. The increase in effective demand has raised farmers' enthusiasm for green planting as consumers with greater green preferences will purchase more agro-food for green planting. The market has formed a low-carbon and environmental protection atmosphere at this moment. As a result, the government tends to regulate loosely.

4.2.2 Condition of (1, 1, 1)

This section investigates the evolutionary trajectories of farmers, government, and consumers under (1, 1, 1). The sensitivity analysis results of low-carbon policies and green preferences are presented in Figs. 9, 10, 11, 12, 13, 14.

To test the impact of carbon trading price on participants, we set the carbon trading cost as 0.78, 3.9, and 7.8, respectively. The behavioral choices of farmers, governments, and consumers are shown in Fig. 9a, b, and c, respectively. Fig illustrates the effects of
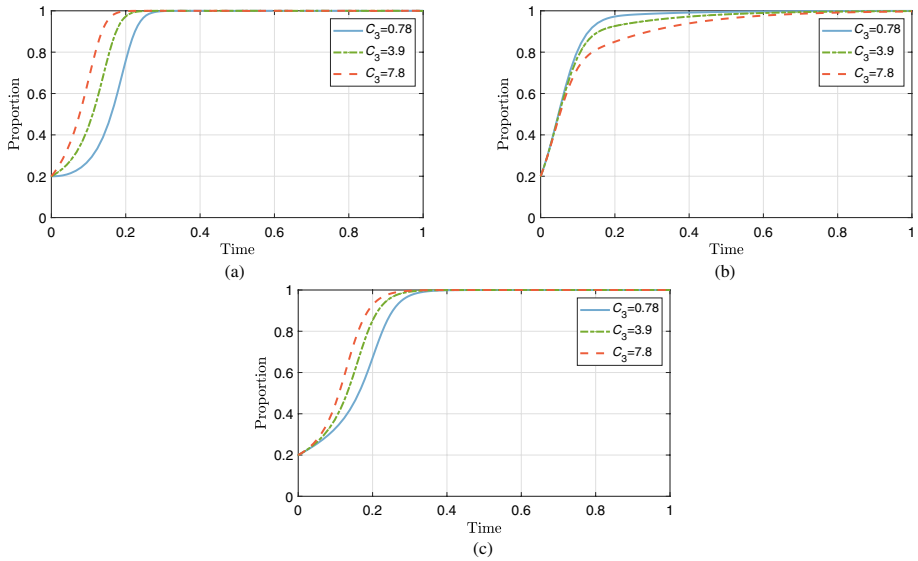
Fig. 9 Effects of carbon trade cost on tripartite under the ESS (1, 1, 1) **a** impact on farmers, **b** impact on governments and **c** impact on consumers
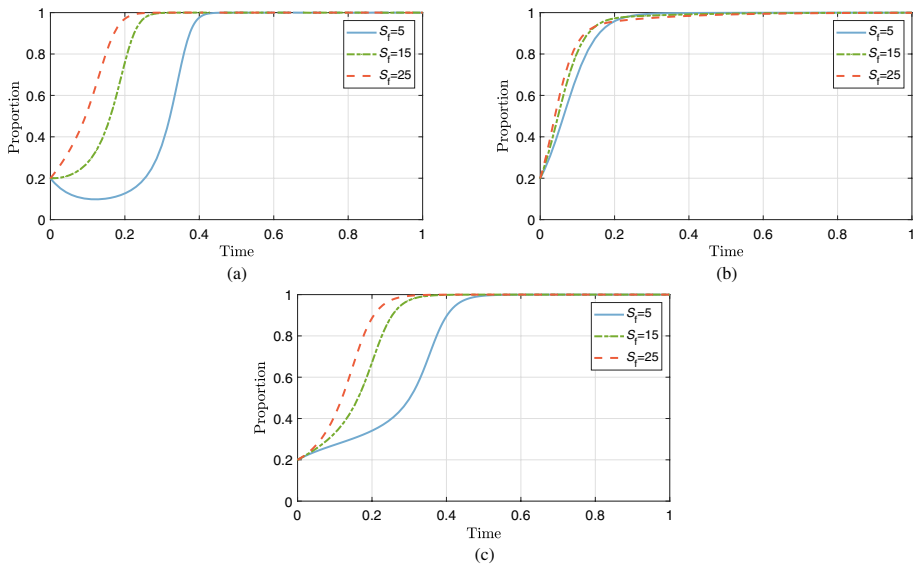

Fig. 10 Effects of farmer's subsidy on tripartite under the ESS (1, 1, 1) **a** impact on farmers, **b** impact on governments and **c** impact on consumers
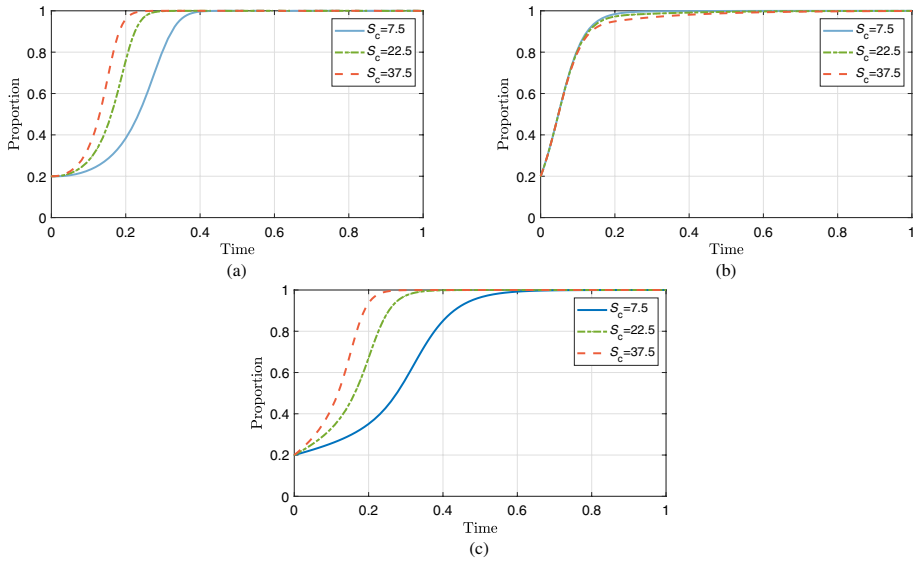
Fig. 11 Effects of consumer's subsidy on tripartite under the ESS (1, 1, 1) **a** impact on farmers, **b** impact on governments and **c** impact on consumers
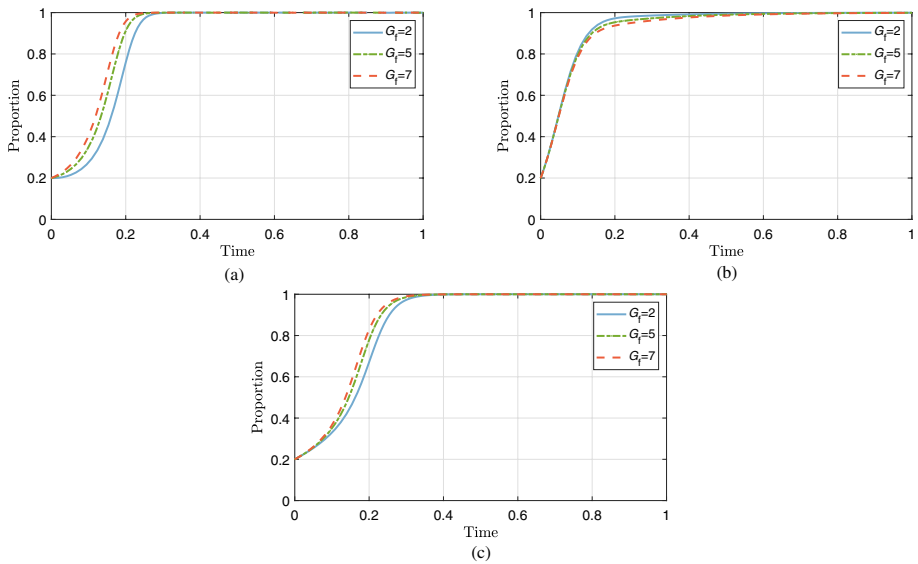

Fig. 12 Effects of farmer's green preference on tripartite under the ESS (1, 1, 1) (**a**) impact on farmers, **b** impact on governments and c impact on consumers

Fig. 13 The influence of government green preference under the ESS (1, 1, 1) **a** $G_g = 12$ **b**, $G_g = 15$ and **c** $G_g = 17$

Fig. 14 Effects of consumer's green preference on tripartite under the ESS (1, 1, 1) **(a)** impact on farmers, **(b)** impact on governments and **(c)** impact on consumers
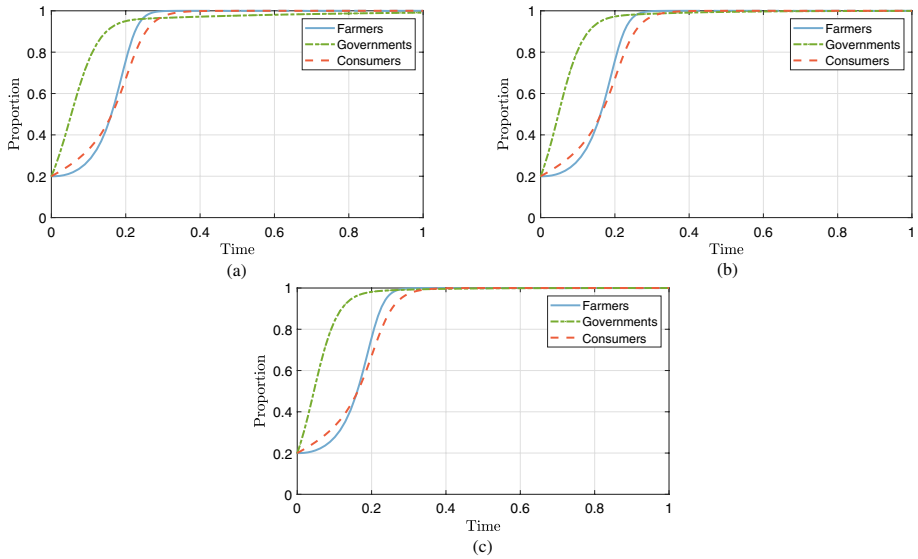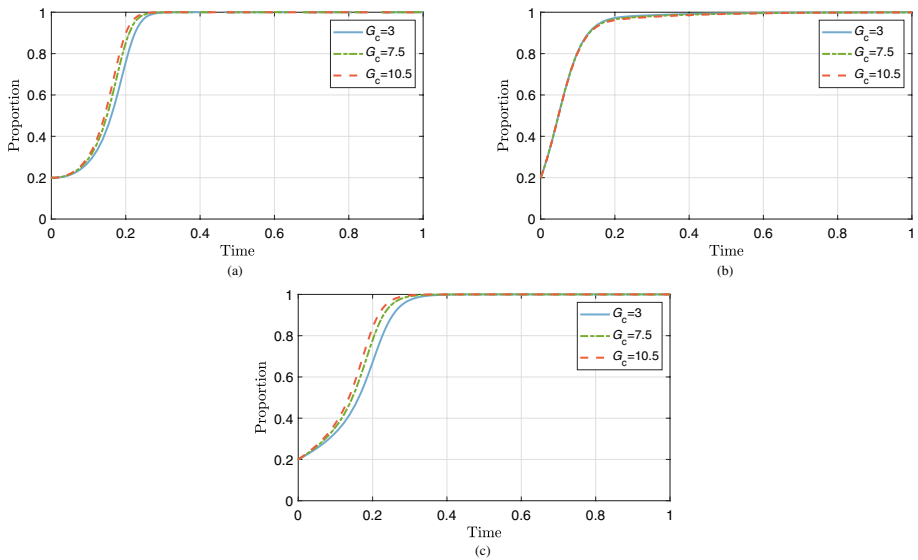
the carbon trade price on the three participants under the mode of (1, 1, 1). Similar to the results in Fig. 3a–c, with C_3 increased, the green behavior willingness of both farmers and consumers can maintain a high, increasing rate and quickly reach 1. By contrast, a higher

carbon trade price suppresses the government's positive regulation. The reason is similar to the discussion of the results in Fig. 3b.

Under the strategy (1,1,1), we set the farmers' subsidies as 5, 15, and 25 to test the impact of farmers' subsidies on the tripartite strategy selection. The behavioral choices of farmers, government, and consumers are presented in Fig. 10a, b, and c, respectively. Similarly, we set the consumer's subsidies to 7.5, 22.5, and 37.5, respectively. The behavior choices of the three parties are illustrated in Fig. 11a, b, and c, respectively. The results reveal that increases in S_f and S_c can increase farmers' and consumers' green behavior willingness, but the influence on governments is not obvious. However, a higher farmer subsidy accelerates the strategic choice for the government's positive regulation to prevent potential subsidy fraud.

Farmers' green preference has a certain influence on the tripartite of the evolutionary game system. To do this, we set G_f to 2, 5, and 7, respectively. The effects of G_f on three subjects under the mode of (1, 1, 1) are presented in Fig. 12a, b, and c, respectively. The results illustrate that the impacts of G_f on the three parties are small. The increase in farmers' green preferences can improve farmers' and consumers' willingness to engage in green behavior to some extent. The reason is similar to the discussion of the results in Fig. 6.

To explore the influence of government green preference on the behavior of game players, we set $G_g = 12$, $G_g = 15$, and $G_g = 17$, the evolutionary process of the three parties under the strategy of (1, 1, 1) for different G_g as illustrated in Fig. 13a, b, and c, respectively. Compared with Fig. 7, despite the increase in G_g, the growth rate of the government's strategy for positive regulation has increased. However, when the government's green preference coefficient is greater than 1, its strategy shifts from loose to positive regulation. This is because when the government's green preference can compensate for its regulatory costs, the role of positive regulation will be greater than that of implementing education and training for farmers.

Finally, consumers' green preference also significantly impacts the three parties' strategic choices. Therefore, we set consumers' green preferences as 3, 7.5, and 10.5 to investigate the influence of different intensities of green preference on the three parties. The behavioral evolution trends of farmers, government, and consumers are presented in Fig. 14a, b, and c, respectively. According to Fig. 14, as G_c increases, the increasing rates of farmers and consumers both augment. However, this has little effect on the government's regulation strategy. This is because consumers' green preference forces farmers to choose green planting, which is demand-driven production. As the pioneer of green preference, the government has almost no influence on consumers' green preference. The government's green preference prompts it to implement low-carbon policies and green propaganda, making farmers and consumers more motivated to make green behavior decisions.

5 Discussion

This study investigats the effects of six typical parameters on this system. According to the results and analyses in Sect. 4.2, we further discuss the impact of low-carbon policies and green preferences on tripartite subjects.

5.1 Impacts of low-carbon policies on tripartite subjects

The low-carbon policies explored in this study are mainly carbon trading and subsidy policies for the low-carbon behavior of farmers and consumers. The increase in carbon trading price could curb farmers' carbon emissions behavior, but this curbing effect is not obvious. As to Abdul-Salam et al. (2019), to make the carbon trading system more effective, the government could encourage farmers to be aware of the externality costs of carbon emissions and establish a market system with a recognized premium for low-carbon products. In addition, government subsidies for farmers to reduce their carbon emissions can significantly increase their green planting behavior. Li et al. (2014) argue that increasing the intensity of agricultural subsidies can encourage farmers to join green and low-carbon agriculture and achieve GAD. Consistent with Carter et al. (2021), subsidies to farmers can create a technological spillover effect for them to make radical green changes through active learning as well as financial investment in green revolution technologies, so much so that a subsequent reduction in subsidies will not significantly reduce their green planting behavior. However, excessive subsidies are detrimental to the long-term GDA (Jiang et al., 2022). Therefore, it is worth noting that higher green planting subsidies for farmers may lead to speculative behavior, such as subsidy fraud, which is not conducive to the healthy development of the market and requires government positive regulation. In addition, the subsidy from the government is also significant for consumers' strategies. However, GDA could not be based solely on subsidy policies. The government could appropriately reduce subsidies to support consumers in developing green consumption habits.

5.2 Impacts of green preferences on tripartite subjects

The introduction of green preference explains the subjects' motivation to reduce carbon emissions in terms of psychology and subjective willingness. From the farmers' perspective, both farmers' and consumers' green preferences considerably impact their decisions. Farmers' willingness to adopt green planting is stimulated by increased consumer awareness of environmental protection and social responsibility, but this may not increase farmers' earnings (Yu et al., 2016). In addition, due to the lack of effective agricultural product quality rating and green certification, it is difficult for green agro-food to gain market competitive advantages, reducing the practical economic benefits and weakening farmers' willingness to switch to the green planting mode. Therefore, improving green agro-food certification and carbon labeling systems will increase farmers' green preferences and effectively guide their green production.

The government's choice of positive regulation is determined by its green preferences. When the government's green preference coefficient is less than 1, the benefits of such preference are insufficient to compensate for the loss of its regulation cost; therefore, they will choose negative regulation. In this case, the government attempts to change farmers' planting modes by promoting green and low-carbon awareness and providing green education and training instead of positive regulation. However, when the government's green preference coefficient is sufficiently large to compensate for the loss of their regulatory costs, positive regulation could be a better choice. However, the analysis in Sect. 4.2.1 illustrates that although the government has relatively high green preferences, it still chooses to regulate negatively in the equilibrium state. When the government's green preferences grow, it will raise environmental awareness among farmers and consumers, educate them on green production and consumption, and improve low-carbon policies. Moreover, the phenomenon

of "bad money driving out good money" in agricultural markets will gradually disappear. This process leads to a low-carbon and environmental protection atmosphere in the market. At this time, even though the government adopts negative regulations, the goal of the GDA can still be achieved.

Green preferences are also a key factor in consumers' decisions to buy green agro-food, and their green preferences are influenced by government green propaganda and low-carbon technology training. However, due to information asymmetry, they often have difficulty identifying agro-food produced in a green way. As in Rousseau and Vranken (2013), the key is to have a corresponding mechanism for identifying green agro-food, such as carbon labels, so that consumers with strong green preferences can effectively identify and purchase them. In addition, consumers' willingness to pay higher prices for green food mainly stems from the utility the food provides them. Based on Wang et al. (2022), this utility mainly comes from brand premium, food quality assurance, and nutritional value. As a result, to increase consumer utility, green agro-food must be branded, standardized, and given a higher cultural premium.

6 Policy Implications and Conclusions

6.1 Policy implications

Based on the above analysis conclusions, we provide some management insights.

First, a higher carbon trading price effectively reduces farmers' carbon emissions behavior. The government could establish a perfect carbon trading system and popularize it to increase farmers' awareness of carbon emissions. Moreover, a more reasonable subsidy policy is also an effective way to motivate farmers to take the initiative to use biodegradable agricultural films, biomass energy, and green planting technologies and promote GDA. Furthermore, farmers' opportunistic behavior in green production will be reduced by establishing a green food safety traceability system to improve the information record of green agro-food in the planting, processing, transportation, and sales process. In addition, training in green skills and learning social responsibility are also effective means to increase farmers' initiative in green planting radically.

Second, reasonable consumer subsidies can stimulate consumers to purchase agro-food produced in a green manner. However, relying solely on subsidies to drive GDA is not sustainable. Therefore, the government could enhance consumers' green preferences through education and publicity and establish a more comprehensive carbon labeling system to reduce the inconvenience caused by information asymmetry and help them better identify green agro-food in the market. In addition, farmers could stimulate consumption at the source by increasing consumers' utility by making green agro-food branded and standardized and giving them a higher cultural premium.

6.2 Limitations

This study enriches the existing research from a new perspective and provides management insights for the government to promote GDA. However, some limitations need to be addressed. First, the three-party game process simplifies the real-world situation. Second, this study only uses numerical simulation to simulate the real situation, which does not

fully reveal all of the multi-subject participation in GDA. The combination of case and empirical studies should be considered in future.

6.3 Conclusions

This study constructs a new three-party evolution game model with important practical and management implications for GDA. We construct a general tripartite evolutionary game model consisting of three parties, namely, farmers, government, and consumers, based on government low-carbon policies and green preferences. We discuss the different strategies under different situations in this system. The main conclusions are as follows: (1) A suitable carbon trading price will promote farmers' green planting and achieve the final stable equilibrium. (2) Appropriate low-carbon subsidies successfully encourage farmers to adopt green planting and customers to purchase green agro-food, accelerating the evolution of these strategies. (3) The increase in the three parties' green preferences can enhance farmers' and consumers' green behavior willingness. When the government's green preference coefficient is less than 1, it will choose positive regulation and enhance farmers' and consumers' green preference through publicity and education. As farmers' and consumers' green preferences increase to a certain high level, the government choosing negative regulation can also reach an advanced evolutionary stable strategy. (4) The increase in consumers' green preferences is closely related to the utility they derive from purchasing agro-food produced in a green manner, in addition to the knowledge dissemination and the promotion of carbon labeling technology.

Data Availability Statement Publicly available datasets were analyzed in this study. Data can be shared on request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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