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Evolutionary game analysis of multi-agent behaviour decisions about sustainable agriculture

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Abstract

Purpose – Global climate change has become a challenge for the development of agriculture in the new stage. This study aims to promote the transformation and development of agriculture and the construction of climate adaptive agriculture, efforts should be made to promote farmers' green production, realize the transformation of green agriculture and achieve the sustainability of agriculture in coping with climate change.

Design/methodology/approach – In response to the characteristics of incomplete information and limited rationality among the government, farmers and consumers, an evolutionary game model was constructed among the three stakeholders to determine the conditions for stakeholders to obtain the optimal strategic combination to promote farmers' green production behaviour (GB).

Findings – A high reward and high punishment policy means that the reward given by government for GB reaches 2m yuan, and the fines paid by farmers to the government for non-green production behaviour reaches 2m yuan, which can effectively encourage farmers to adopt GB. The cost of green production for farmers should be controlled within 2m yuan, and the additional cost for consumers to purchase green agricultural products is less than 7m yuan, which is conducive to promoting farmers to adopt GB.

Originality/value – For green production, only a small amount of research focuses on game evolution among the government, farmers and consumers, ignoring the important role of consumers. In this paper, an

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evolutionary game model among the government, farmers and consumers is constructed to promote the GB of farmers, which is conducive to green agriculture and curbing global climate warming.

Keywords Climate change, Sustainable agriculture, Green production behaviour, Multiagent behaviour decision, Evolutionary game

Paper type Research paper

1. Introduction

Climate change is a common challenge facing all people and concerns the well-being of future generations. The current climate change problem is becoming increasingly serious and urgent, so global joint efforts to build a community with a shared future for mankind are urgently needed (Wang *et al.*, 2021). The "double carbon" goal is proposed not only to cope with climate change but also to promote sustainable development. At the same time, with this goal, a new direction is highlighted, and new requirements for agricultural development are proposed (Yza *et al.*, 2020). According to the latest research report of the Food and Agriculture Organization of the United Nations in 2018, the carbon dioxide equivalent emitted by the food system reached 16 billion tons, an increase of 8% over the 1990 level (Wang *et al.*, 2021). The emissions from the food system account for 33% of the total anthropogenic greenhouse gas emissions, and the emissions from farm production and production upstream and downstream (mainly from the supply chain, consumption and waste) account for 2/3 of the carbon dioxide emissions. These data show that green agricultural development is an important path to achieving the "double carbon" goal (Agrimonti *et al.*, 2020; Tubiello *et al.*, 2021).

Agricultural production has a dual effect of carbon emissions and carbon sinks. "Carbon" refers to the standard carbon converted from greenhouse gases (methane, carbon dioxide, etc.), not just carbon dioxide (Sharma *et al.*, 2021). The fourth volume of the Intergovernmental Panel on Climate Change (IPCC) National Greenhouse Gas Inventory Guidelines explains that the agricultural carbon effect mainly comes from production activities on agricultural land, forestland and grassland, as well as soil respiration and the intestinal fermentation and faecal management of livestock (Halbert *et al.*, 2021; Czyewski and Michaowska, 2022). Promoting farmers' green production behaviour (GB) is conducive to low-carbon agriculture, carbon neutrality and sustainable agricultural development (Liu *et al.*, 2019; He *et al.*, 2021). As a sensitive and significantly affected area of global climate change, China has a warming rate that is significantly higher than the global average in the same period, and agricultural development in the new stage faces great challenges (Wang and Gong, 2000). Agriculture is one of the major contributors to greenhouse gas emissions. The IPCC (IPCC, 2019) estimates that agricultural sources account for 13.5% of global greenhouse gas emissions, and agriculture contributes 50% and 84% of the total human production of methane and nitrous oxide, respectively (Li *et al.*, 2020). Rice planting and nitrogen fertilizer application are important emission sources of methane and nitrous oxide, respectively, and China's rice planting area and total output rank first in the world; the corresponding nitrogen fertilizer use is high. Therefore, China's agricultural production is facing enormous pressure to reduce emissions and challenges to doing so. At the same time, due to the high exposure characteristics of agricultural production, climate change has a great impact on agricultural production. Changes in temperature and precipitation change the spatial distribution pattern of water and heat resources and have an important impact on the distribution of agricultural production (Li *et al.*, 2022). To ensure that climate change does not threaten the sustainable development of the ecosystem, food production, economy and society in a certain period of time and to stabilize the concentration of greenhouse gases in the atmosphere at a certain level so that the climate system is not subject to dangerous human interference, the emission of greenhouse gases must be controlled or reduced through policies and measures to mitigate climate change (Guan *et al.*, 2019). One effective means to mitigate climate change and reduce carbon dioxide emissions is to develop sustainable agriculture.

In recent years, countries around the world, including the USA, Canada, Australia and Japan, have proposed agricultural development models for developing green agriculture to address global climate change. Huang *et al.* (2019) analyzed the future trends of global green agriculture and water resources, and the results showed that in the coming decades, the development of global climate change will increasingly rely on changes in green agriculture and land use types; Sri Lanka is implementing a green agriculture development plan and has established two working groups, one of which is a task force on green Sri Lanka and sustainable solutions to climate change, to address climate issues from an agricultural perspective. Subitha *et al.* (2021) noted that the promotion of green agriculture in India involves addressing issues such as land pollution, biodiversity and climate change. To address these issues, it is necessary to address agricultural pollution, promote agricultural green transformation and ultimately carry out high-gain applications. In particular, China has made a solemn commitment to addressing global climate change by increasing its efforts to transform green agriculture and achieving a carbon peak by 2030 and carbon neutrality by 2060. Therefore, the development of green agriculture is an issue to which all countries in the world attach great importance. This study is committed to promoting the green transformation of agriculture from a multisubject perspective to address the increasingly serious problem of global climate change.

Green agriculture involves the behavioural decision-making of many subjects. Promoting the evolution of farmers' production behaviour from non-green to green is a key link to improve the sustainable development level of agriculture (Ji *et al.*, 2019; Mao *et al.*, 2021). Farmers' production behaviour is one of the key factors determining sustainable agriculture. As economic people, farmers pursue maximum interests and are mainly concerned about whether green agricultural products can bring more benefits (Tinc *et al.*, 2018). Whether the government takes reasonable and effective measures to promote farmers' GBs is crucial. Many scholars call on the state to implement subsidy policies, combine reasonable reward and punishment measures, form a reward and punishment mechanism for farmers' GBs and effectively encourage and guide farmers to take the initiative to engage in GBs (Nuttavuthisit and Thogersen, 2017; Shen *et al.*, 2020). At the same time, whether consumers are willing to pay higher fees for green agricultural products, which is related to consumers' acceptance of green agricultural products, has become an important factor in encouraging farmers to adopt GBs, and whether the government carries out safety supervision on agricultural products also affects consumers' purchasing behaviours (Waheed *et al.*, 2020). Therefore, the decision-making of the government, farmers and consumers is an evolutionary game problem. In evolutionary game theory, the assumption of complete rationality is discarded. From the perspective of the system, the adjustment process of group behaviour is regarded as a dynamic system, in which the behaviour of each individual and the relationship between each individual and the group are characterized separately. The formation mechanism from individual behaviour to group behaviour and the various factors involved therein can be incorporated into the evolutionary game model to form a macro model with a micro basis. Therefore, such a model can more truly reflect the diversity and complexity of actors and can provide a theoretical basis for macro-control of group behaviour.

Evolutionary game theory has been widely used in the field of sustainable agriculture (Tang *et al.*, 2021; Deng *et al.*, 2018; Du *et al.*, 2020). Based on sustainable agriculture, the study includes the government, farmers and consumers in an evolutionary game model to explore the game relationships and evolution paths of decision-making among the three stakeholders. Based on this, in view of the characteristics of incomplete information and limited rationality of the three stakeholders, this study analyses the income matrix of different decisions of the three stakeholders from the microeconomic perspective to obtain the progressive stability point under different circumstances (Xiao *et al.*, 2021). This is evaluated under the initial policy decision-making characteristics of the three parties and conditions change policy after the evolution trend of the three parties, seeking to improve the overall level of the sustainable agriculture effective policy and management scheme, building the main body behaviour decision should be based on sustainable agriculture. This is done to provide useful suggestions for the government to establish the incentive mechanism of farmers' GB and encourage consumers to buy green agricultural products.

2. Theoretical basis and assumptions

Evolutionary game theory, which combines Darwin's biological evolution theory and Lamarck's genetic theory, is an effective tool for analyzing the interaction between stakeholders. It effectively explains the evolutionary path and reason for the population to achieve balance by analyzing the dynamic evolution process. On the basis of limited rationality, all stakeholders tend to constantly imitate and adjust to improve strategies.

As shown in Figure 1, three stakeholders form an external cycle of interaction and an internal cycle of a decision-making game. In the interactive external circulation, consumers influence the formulation of government policies, and their purchasing behaviour is also affected by the supply of green and green agricultural products that farmers provide (Awaga *et al.*, 2020). Farmers are the "producers" of green and non-green agricultural products, and their behaviours are supervised by both the government and consumers. Because of the interactive influence of stakeholders, the three stakeholders play a game in decision-making, which constitutes the internal cycle of the decision-making game. In the inner circle of the decision-making game, farmers decide to choose GB or non-green production behaviour (NGB) according to the governments' regulatory attitude and consumers' demand for green agricultural products. Consumers choose to buy green agricultural products (BG) or not to buy green agricultural products (NBG) according to their own needs and market supply to maintain the balance of interests. The government formulates policies to implement incentive regulation (IR) or no incentive regulation (NIR) based on the actual situation. According to the dynamic interaction and behavioural decision-making among stakeholders, the following assumptions can be made.

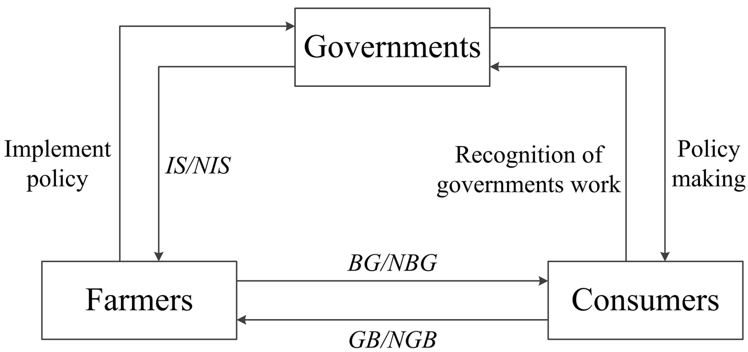

Figure 1. Dynamic interaction among stakeholders under the quality and safety of agricultural product
Source: Authors' own creation

2.2 Assumptions

The government, farmers and consumers are brought into the same game system, the three stakeholders perceive and choose strategies based on bounded rationality, and all follow the principle of utility maximization in the game process and tend to constantly imitate and adjust to improve strategies. The governments mentioned in this paper refer to county-level governments, and farmers and consumers are individuals with bounded rationality.

Assumption 1: The government is the advocate and overseer of green production. To promote the process of sustainable agriculture, the government needs to formulate relevant funding support policies and give farmers technical support and risk subsidies (Wan and Hong, 2020). To ensure that farmers adopt GBs, the government needs to invest human, material and financial resources in supervision. In the process of formulating agricultural policies, the government is faced with many challenges, such as more frequent fluctuations in agricultural prices, more complex competition in agricultural products and increasingly tight constraints on agricultural production resources and the environment (Zheng *et al.*, 2020). Policies on different issues have different priorities and directions, and the timing of their introduction is also uncertain, leading to instability. Therefore, it is supposed that the government is not completely rational, and the governments choose IR or NIR.

Assumption 2: Farmers are a subset of agricultural producers, including farmers, agricultural cooperatives, family farms and various new agricultural operating subjects. Because the main body of Chinese agricultural production is small-scale farmers, small-scale farmers also make up the largest share of agricultural producers. Because farmers' production behaviour preference is easily influenced by government behaviour, product market situations and consumer behaviour, the decision is not rational, which can better reflect the characteristics of China's agricultural production (Segrè Cohen *et al.*, 2020). Therefore, small-scale farmers are selected as representatives of agricultural producers in this study to reflect the preference and behavioural strategy evolution of producers in the development of green agriculture in China, so farmers choose GB or NGB.

Assumption 3: Consumers make up the demand side of agricultural products, and their green consumption intention and behaviour directly affects farmers' income from agricultural products. When consumers buy agricultural products, they consider the quantity and price of agricultural products. Since the green index system of agricultural products in China is not perfect, there is information asymmetry between consumers and farmers, and consumers have a deviation in their perception of the quality and price of green agricultural products (Peng *et al.*, 2021). Therefore, consumers choose to BG or NBG.

3. Decision-making model

3.1 Equation model description and establishment

The relevant parameters of governments are as follows. When governments choose IR, they need to provide basic expenditures (C_1) to farmers for the construction of green production. The cost of government incentive supervision (C_2) includes expenditures on publicity, education and supervision. Governments assess the management of farmers and allocate incentive subsidies (M_1) to those who are more active. According to China's Green Production Management Regulations, the government's administrative penalty for farmers is M_2. If consumers do not buy green agricultural products, the government saves the health subsidy of green agricultural products, which is T. Sustainable agriculture products are an important part of food health at present, and the government's performance and benefits brought by farmers' GBs under government supervision are W_1 (including building a Healthy China and beautiful countryside, etc.). If farmers do not adopt GB and consumers do not buy green agricultural products, this is not conducive to the healthy development of society, and the social maintenance cost of the government is W_2. When the governments choose NIR, the basic fund (C_1) is also provided by the government but is not invested in incentive measures. The government's performance benefits brought by farmers' GB are W_3, and $W_1 > W_3$. If farmers do not adopt GB and consumers do not buy green agricultural products, this is not conducive to the healthy development of society, and the maintenance cost of the government is W_2.

The relevant parameters of farmers are as follows. When farmers choose GB, their investment cost of adopting GB, including purchasing green agricultural materials and carrying out green agricultural methods, is E_1. Under government incentive supervision, the village collectives receiving government incentive subsidies are M_1. The extra income that farmers obtain from consumers buying green agricultural products is D_1. To gain the trust of consumers, they engage in GB, and the material compensation reward given by farmers to consumers (such as gifts and shopping points that can be exchanged for green and green agricultural products) is S. The economic loss of farmers caused by consumers not buying green agricultural products is D_2. When farmers choose NGB, their investment cost of adopting NGB (including purchasing ordinary agricultural materials and carrying out ordinary agricultural production) is E_2. The economic loss caused by farmers' failure to adopt GB is D_3. Under the supervision of the government, the penalty paid by farmers for NGB is M_2.

The relevant parameters of consumers are as follows. When consumers choose BG, the extra cost for consumers to buy green produce over ordinary produce is L. The material compensation reward offered by farmers to consumers to gain their trust in their GB is S (for example, shopping points can be exchanged for green and green agricultural products). The beneficial effect of consumers' consumption of green agricultural products on their own health is V_1. When consumers choose NBG, in the case that farmers adopt GB, consumers still need to buy green agricultural products, and the extra cost higher than that of ordinary agricultural products is L. The negative health effect of consumers' consumption of inferior produce is V_2.

According to the content, eight strategic income combinations can be matched, as shown in Figure 2. The type of strategy combination includes whether the government regulates, whether farmers adopt green production, and whether consumers buy green agricultural products. The income matrix of the three-party game can be constructed according to the income mix, as shown in Table 1.

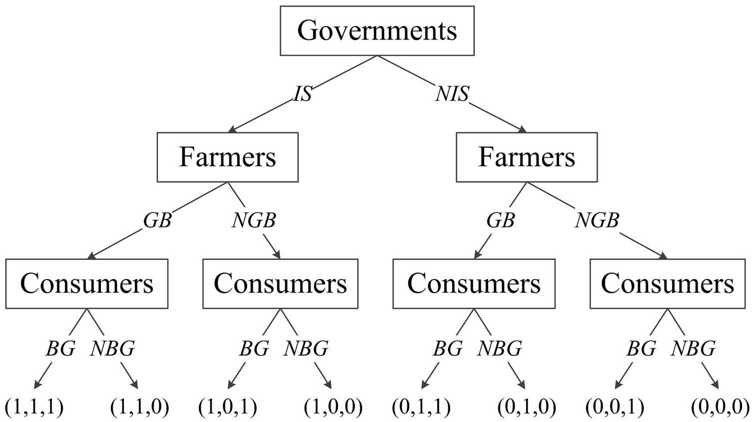

Figure 2. The decision tree of stakeholder
Source: Authors' own creation

Table 1. The tripartite game income matrix

Strategy selection	Benefits of governments	Benefits of farmers	Benefits of consumers
(IR, GB, BG)	$W_1 - C_1 - C_2 - M_1$	$C_1 + D_1 + M_1 - E_1 - S$	$S + V_1 - L$
(IR, GB, NBG)	$W_1 + T - C_1 - C_2 - M_1$	$C_1 + D_1 + M_1 - E_1 - D_2$	$-L - T$
(IR, NGB, BG)	$W_1 + M_2 - C_1 - C_2$	$C_1 + D_1 - E_2 - M_2$	$V_1 - L$
(IR, NGB, NBG)	$M_2 + T - C_1 - C_2 - W_2$	$C_1 - D_3 - E_2 - M_2$	$-V_2 - T$
(NIR, GB, BG)	$W_3 - C_1$	$C_1 + D_1 - E_1 - S$	$S + V_1 - L$
(NIR, GB, NBG)	$W_3 - C_1$	$C_1 + D_1 - E_1 - D_2$	$-L$
(NIR, NGB, BG)	$W_3 - C_1$	$C_1 + D_1 - E_2$	$V_1 - L$
(NIR, NGB, NBG)	$-W_2 - C_1$	$C_1 - E_2 - D_3$	$-V_2$

Source(s): Authors' own creation

3.2 Evolutionary game analysis of governments' replicator dynamics equation

The proportion of various subsequent pure strategies used by all individuals is used to represent the mixed strategies in the game model. Assuming the proportion of the governments choosing IR is x, the proportion of the governments choosing NIR is $1 - x$; the ratio of farmers choosing GB is y, and the ratio of NGB is $1 - y$; and the proportion of consumers who choose BG is z, and the proportion of consumers who choose NBG is $1 - z$.

As shown in Table 1, the respective perceived benefits of the governments' strategies of "IS" and "NIS", and the average perceived benefits to the governments are shown in V_X, V_{1-X} and $\overline{V_X}$:

$$\begin{aligned} V_X &= yz(W_1 - C_1 - C_2 - M_1) + y(1-z)(W_1 + T - C_1 - C_2 - M_1) + z(1-y)(W_2 + M_2 - C_1 - C_2) \\ &\quad + (1-x)(1-y)(M_2 + T - C_1 - C_2 - W_2) \\ &= (y + z - yz)(W_1 + W_2) - y(M_1 - M_2) + z(W_1 + W_2 - T) + T + M_2 - C_1 - C_2 - W_2 \end{aligned} \tag{1}$$

$$\begin{aligned} V_{1-X} &= yz(W_3 - C_1) + y(1-z)(W_3 - C_1) + z(1-y)(W_3 - C_1) + (1-x)(1-z)(-W_2 - C_1) \\ &= (y + z - yz)(W_2 + W_3) - C_1 - W_2 \end{aligned} \tag{2}$$

$$\overline{V_X} = xV_{1X} + (1-x)V_{2X} \tag{3}$$

According to the above perceived benefits, the replicating dynamic equation of governments is:

$$\begin{aligned} F(x) = \frac{dx}{dt} = x\left(V_{1X} - \overline{V_X}\right) = x(1-x)\left[y(1-z)(W_1 - W_3) - y(M_1 + M_2)\right. \\ \left. + z(W_1 - W_3 - T) + T + M_2 - C_2\right] \end{aligned} \tag{4}$$

The second derivative of formula (4) is:

$$F'(x) = (1-2x)\left[y(1-z)(W_1 - W_3) - y(M_1 + M_2) + z(W_1 - W_3 - T) + T + M_2 - C_2\right] \tag{5}$$

When $y = \frac{z(W_1 - W_3 - T) + T + M_2 - C_2}{(1-z)(W_1 - W_3) - (M_1 + M_2)} = y^*$, neither "IR" nor "NIR" is a stable strategy for the governments.

When $y \neq \frac{z(W_1 - W_3 - T) + T + M_2 - C_2}{(1-z)(W_1 - W_3) - (M_1 + M_2)}$, the evolutionarily stable point may $x = 0$ or $x = 1$. According to the stability theorem of replicated dynamic equations, if x is a stable strategy, it should conform to $F(x) = 0$ and $F'(x) < 0$. When $1 > y > y^*$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$ and $x = 0$ is the evolutionarily stable point. When $0 < y < y^*$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$ and $x = 1$ is the evolutionarily stable point.

Figure 3 shows that when the initial state of the game is located inside space *H11*, the governments eventually choose the "NIR" strategy after the model evolves; in contrast, if the initial state is inside space *H12*, the governments eventually choose the "IR" strategy after the model evolves.

3.3 Evolutionary game analysis of farmers' replicator dynamics equation

As shown in Table 1, the respective perceived benefits of the farmers' strategies of "GB" and "NB", and the average perceived benefits to the governments are shown in V_Y, V_{1-Y} and $\overline{V_Y}$:

$$\begin{aligned} V_Y &= xz(C_1 + D_1 + M_1 - E_1 - S) + x(1-z)(C_1 + D_1 + M_1 - E_1 - D_2) \\ &\quad + z(1-x)(C_1 + D_1 - E_1 - S) + (1-x)(1-z)(C_1 + D_1 - E_1 - D_2) \\ &= xM_1 + z(D_2 - S) + C_1 + D_1 - E_1 - D_2 \end{aligned} \tag{6}$$

$$\begin{aligned} V_{1-Y} &= xz(C_1 + D_1 - E_2 - M_2) + x(1-z)(C_1 - D_3 - E_2 - M_2) \\ &\quad + z(1-x)(C_1 + D_1 - E_2) + (1-x)(1-z)(C_1 - D_3 - E_2) \\ &= -xM_2 + z(D_1 + D_3) + C_1 - E_2 - D_3 \end{aligned} \tag{7}$$

$$\overline{V_Y} = \mathrm{y}V_{1Y} + (1-y)V_{2Y} \tag{8}$$

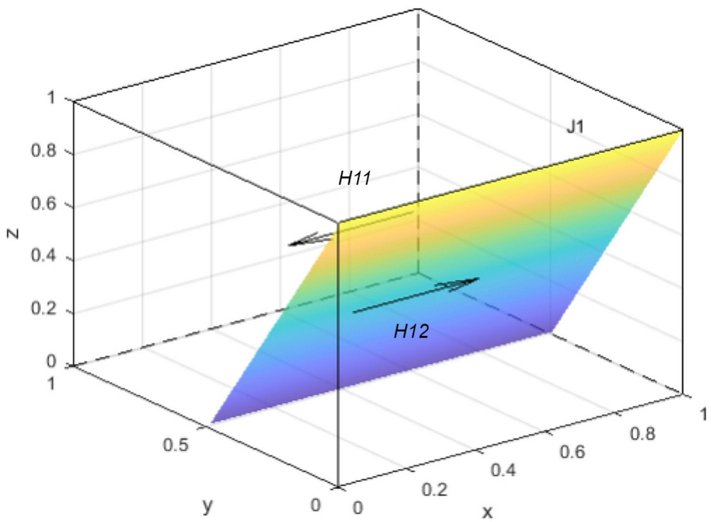

Figure 3. Dynamic trend of government behaviour decision
Source: Authors' own creation

According to the above perceived benefits, the replicating dynamic equation of farmers is:

$$F(y) = \frac{dy}{dt} = y\left(V_{1Y} - \overline{V_Y}\right) = y(1-y)\left[x(M_1+M_2) + z(D_2 - D_1 - S - D_3) + E_2 + D_1 + D_3 - D_2 - E_1\right] \quad (9)$$

The second derivative of formula (9) is:

$$F'(y) = (1-2y)\left[x(M_1+M_2) + z(D_2 - D_1 - S - D_3) + E_2 + D_1 + D_3 - D_2 - E_1\right] \quad (10)$$

When $x = \frac{z(D_1+S+D_3-D_2)+D_2+E_1-E_2-D_1-D_3}{M_1+M_2} = x^*$, neither "GB" or "NB" is a stable strategy for the farmers.

When $x \neq \frac{z(D_1+S+D_3-D_2)+D_2+E_1-E_2-D_1-D_3}{M_1+M_2}$, the evolutionarily stable point may $y=0$ or $y=1$. According to the stability theorem of replicated dynamic equations, if y is a stable strategy, it should conform to $F(y)=0$ and $F'(y)<0$. When $0<x<x^*$, $\frac{dF(y)}{dy}|_{y=0}<0$, $\frac{dF(y)}{dy}|_{y=1}>0$ and $y=0$ is the evolutionarily stable point. When $1>x>x^*$, $\frac{dF(y)}{dy}|_{y=0}>0$, $\frac{dF(y)}{dy}|_{y=1}<0$ and $y=1$ is the evolutionarily stable point.

Figure 4 shows that when the initial state of the game is located inside space *H21*, the farmers eventually choose the "NB" strategy after the model evolves; in contrast, if the initial state is inside space *H22*, the farmers eventually choose the "GB" strategy after the model evolves.

3.4 Evolutionary game analysis of consumers' replicator dynamics equation

As shown in Table 1, the respective perceived benefits of the consumers' strategies of "BG" and "NBG", and the average perceived benefits to the governments are shown in V_Z, V_{1-Z} and $\overline{V_Z}$:

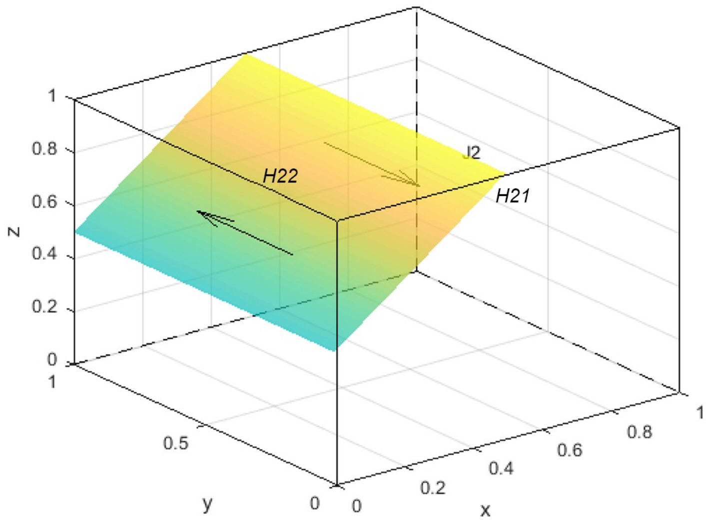

Figure 4. Dynamic trend of farmer behaviour decision
Source: Authors' own creation

$$V_Z = xy(S+V_1-L) + x(1-y)(V_1-L) + y(1-x)(S+V_1-L) + (1-x)(1-y)(V_1-L) \\ = yS + V_1 - L \tag{11}$$

$$V_{1-Z} = xy(-L-T) + x(1-y)(-V_2-T) + y(1-x)(-L) + (1-x)(1-y)(-V_2) \\ = y(V_2-L) - xT - V_2 \tag{12}$$

$$\overline{V_Z} = zV_{1Z} + (1-z)V_{2Z} \tag{13}$$

According to the above perceived benefits, the replicating dynamic equation of consumers is:

$$F(z) = \frac{dz}{dt} = z(V1Z - \overline{VZ}) = z(1-z)[xT + y(S+L-V_2) + V_1 + V_2 - L] \tag{14}$$

The second derivative of formula (14) is:

$$F'(z) = (1-2z)[xT + y(S+L-V_2) + V_1 + V_2 - L] \tag{15}$$

When $y = \frac{xT+V_1+V_2-L}{S+L-V_2} = y^{**}$, neither "BG" nor "NBG" is a stable strategy for the consumers.

When $y \neq \frac{xT+V_1+V_2-L}{S+L-V_2}$, the evolutionarily stable point may $z=0$ or $z=1$. According to the stability theorem of replicated dynamic equations, if z is a stable strategy, it should conform to $F(z)=0$ and $F'(z)<0$. When $0<y<y^{**}$, $\frac{dF(z)}{dz}|_{z=0}<0$, $\frac{dF(z)}{dz}|_{z=1}>0$ and $z=0$ is the evolutionarily stable point. When $1>y>y^{**}$, $\frac{dF(z)}{dz}|_{z=0}>0$, $\frac{dF(z)}{dz}|_{z=1}<0$ and $z=1$ is the evolutionarily stable point.

Figure 5 shows that when the initial state of the game is located inside space *H31*, the consumers eventually choose the "BG" strategy after the model evolves; in contrast, if the

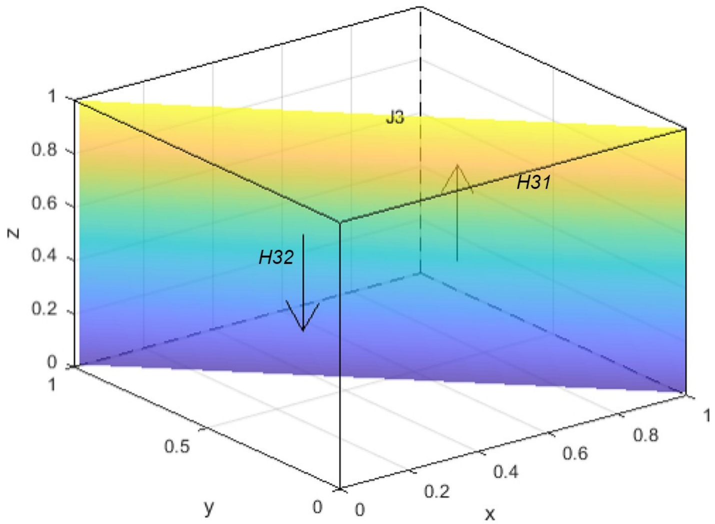

Figure 5. Dynamic trend of consumer behaviour decision
Source: Authors' own creation

initial state is inside space *H32*, the consumers eventually choose the “NBG” strategy after the model evolves.

3.5 Evolutionary stability strategy

According to the equations (4), (9) and (14), eight special equilibrium points can be determined as $X_1(0, 0, 0)$, $X_2(1, 0, 0)$, $X_3(0, 1, 0)$, $X_4(0, 0, 1)$, $X_5(1, 1, 0)$, $X_6(1, 0, 1)$, $X_7(0, 1, 1)$ and $X_8(1, 1, 1)$. There is also a hybrid strategy Nash equilibrium point in the dynamical system. $X_9(x^*, y^*, z^*)$ However, the equilibrium of the tripartite evolutionary game must be a strict Nash equilibrium and, therefore, a pure strategy Nash equilibrium. The other points in the dynamic replication system of the tripartite game are non-asymptotically stable, and only the asymptotic stability of the eight special points mentioned above needs to be discussed. Following Friedman’s method for judging the evolutionary equilibrium strategy, the stability of the differential equation can be analyzed by Jacobin matrix *J*. The Jacobin matrix *J* is shown in (5) and the details in formula (16):

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)\left[y(1-z)(W_1 - W_3) - y(M_1 + M_2) + z(W_1 - W_3 - T) + T + M_2 - C_2\right] = 0 \\ \dfrac{dy}{dt} = y(1-y)\left[x(M_1 + M_2) + z(D_2 - D_1 - S - D_3) + E_2 + D_1 + D_3 - D_2 - E_1\right] = 0 \\ \dfrac{dz}{dt} = z(1-z)[xT + y(S + L - V_2) + V_1 + V_2 - L] = 0 \end{cases} \tag{16}$$

$$J = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \tag{17}$$

Among them:

$$\begin{cases} J_{11} = (1-2x)\left[y(1-z)(W_1 - W_3) - y(M_1 + M_2) + z(W_1 - W_3 - T) + T + M_2 - C_2\right] \\ J_{12} = x(1-x)(-M_1 - M_2) \\ J_{13} = x(1-x)(W_1 - W_3 - T) \\ J_{21} = y(1-y)(M_1 + M_2) \\ J_{22} = (1-2y)\left[x(M_1 + M_2) + z(D_2 - D_1 - S - D_3) + E_2 + D_1 + D_3 - D_2 - E_1\right] \\ J_{23} = y(1-y)(D_2 - D_1 - S - D_3) \\ J_{31} = z(1-z)T \\ J_{32} = z(1-z)(S + L - V_2) \\ J_{33} = (1-2z)[xT + y(S + L - V_2) + V_1 + V_2 - L] \end{cases} \tag{18}$$

Substituting the above eight equilibrium points into this Jacobin matrix (Lyapunov, 1992), the corresponding eigenvalues are obtained, as shown in Table 2. According to the eigenvalues given in Table 2, combined with the actual situation, the eigenvalues (the eigenvalues are the lambda columns) are judged, and the stability of the equilibrium point is analyzed. In Table 3,

Table 2. Eigenvalues at equilibrium points

Equilibrium points	Eigenvalues λ_1	λ_2	λ_3
$X_1(0, 0, 0)$	$T - C_2 + M_2$	$D_1 + D_3 + E_2 - D_2 - E_1$	$V_1 + V_2 - L$
$X_2(1, 0, 0)$	$C_2 - M_2 - T$	$D_1 + D_3 + E_2 - D_2 - E_1 + M_1 + M_2$	$V_1 + V_2 - L + T$
$X_3(0, 1, 0)$	$T - C_2 - M_1 + W_1 - W_3$	$D_2 + E_1 - D_1 - D_3 - E_2$	$V_1 + L$
$X_4(0, 0, 1)$	$-C_2 + M_2 + W_1 - W_3$	$E_2 - E_1 - S$	$L - V_1 - V_2$
$X_5(1, 1, 0)$	$C_2 + M_1 - T - W_1 + W_3$	$D_2 + E_1 - D_1 - D_3 - E_2 - M_1 - M_2$	$V_1 + L + T$
$X_6(1, 0, 1)$	$C_2 - M_2 - W_1 + W_3$	$E_2 - E_1 - S + M_1 + M_2$	$L - T - V_1 - V_2$
$X_7(0, 1, 1)$	$-C_2 + M_1 + W_1 - W_3$	$E_1 + S - E_2$	$-V_1 - L$
$X_8(1, 1, 1)$	$C_2 - M_2 - W_1 + W_3$	$E_1 + S - E_2 - M_1 - M_2$	$-V_1 - L - T$

Source(s): Authors' own creation

Table 3. Stable conditions at equilibrium points

Equilibrium points	λ_1	λ_2	λ_3	Result	Stable conditions
$X_1(0, 0, 0)$	–	–	–	ESS	$T + M_2 < C_2, D_1 + D_3 + E_2 < D_2 + E_1, V_1 + V_2 < L$
$X_2(1, 0, 0)$	–	–	–	ESS	$T + M_2 > C_2, D_1 + D_3 + E_2 < D_2 + E_1 - M_1 - M_2, V_1 + V_2 + T < L$
$X_3(0, 1, 0)$	S	S	+	Instability point	\
$X_4(0, 0, 1)$	–	–	–	ESS	$C_2 - M_2 > W_1 - W_3, V_1 + V_2 > L$
$X_5(1, 1, 0)$	S	S	+	Instability point	\
$X_6(1, 0, 1)$	–	–	–	ESS	$C_2 - M_2 < W_1 - W_3, E_2 + M_1 + M_2 > E_1 + S, V_1 + V_2 + T > L$
$X_7(0, 1, 1)$	S	+	–	Instability point	\
$X_8(1, 1, 1)$	–	–	–	ESS	$C_2 - M_2 < W_1 - W_3, E_2 + M_1 + M_2 > E_1 + S$

Source(s): Authors' own creation

the symbols in parentheses indicate the positive or negative characteristic value, and "S" indicates that the positive or negative characteristic value is unknown.

4. Simulation analysis

To intuitively observe the evolution of green production in China under the initial conditions and the influence of the parameters on the stability of the system under stable conditions, it is necessary to use MATLAB to carry out numerical simulations and analyze the dynamic evolution trajectory of stakeholders' behaviours.

4.1 Initial allocation of model parameters

So that constructive suggestions based on the actual situation can be proposed, in this paper, values were assigned to model parameters based on the actual situation and then the influence of numerical changes in various factors on the behaviour selection of each subject in the actual state to improve green production is analyzed. The data of parameters are mainly derived from the statistical yearbooks of Henan Province, news reports and actual rural interviews, and the model parameters are assigned according to proportions in line with the real situation. Then, MATLAB simulation is performed to analyze the evolution and stable path of the tripartite game model under actual conditions.

Biyang County, Henan Province Green Production Demonstration Zone, is established in Biyang County, has convenient transportation and involves 350 farmers. The demonstration zone covers an area of 200 hm^2 (3,000 mu), radiating 667 hm^2 to the surrounding area, and green production is carried out in this demonstration zone. Based on the above data and combined with the investigation and interviews from the green production demonstration area in Biyang County, Henan Province, a simulation hypothesis was made for each parameter. This paper takes a demonstration area as the unit of numerical magnitude, and the unit is one hundred thousand yuan. Table 4 lists the initial parameters.

As the other variables are all abstract variables, the values are mainly obtained through rural practical interviews and estimations of experts, as shown in Table 5.

4.2 Evaluation of the implementation effect of the initial policy

MATLAB R2018b is used to process the replication dynamic equation of government, farmers and consumers. The initial probability of the three-party subject is set as 0.1, the step size as 0.15 and the final probability as 0.9. A total of 216 simulations have been carried out on the evolution stable path selected by the actual three-party strategy, as shown in Figure 6. In the simulation process, the evolution of the three-party strategy finally tends to the stable point (1,1,1), that is, the government chooses IR, farmers choose GB and consumers choose BG.

Table 4. Initial assignment of variable parameters based on real data

Parameters	The source of data	No.
C_1	The government invested 5,000,000 yuan to improve the construction of green production infrastructure in the demonstration area. Implementation Plan of Farmland Fertility Protection Subsidy of Henan Province, the subsidy standard for each mu is 107.48 yuan (5,000,000 + 107.48 × 3,000 = 5,322,440 yuan)	50
C_2	The government invests 500,000 yuan in supervision for green production demonstration zones in 2019	5
M_1	In 2019, the subsidy per mu is 273.22 yuan (273.22 × 3,000 = 816,990 yuan)	8
M_2	Individuals who do not cooperate shall be fined below 10,000 yuan (assuming that the average penalty is calculated, 0.65 × 46 = 299,000 yuan)	3
T	The average yield per mu of farmers adopting green production behaviour is 2,460 kg, and the government can give 0–1 yuan subsidy per kg of green agricultural products (2,460 × 3,000 × 0.5 = 3,690,000 yuan)	37
E_1	The annual cost of green production for farmers in the demonstration area is approximately 1,200,000 yuan	12
E_2	The average production cost of farmers in the demonstration area is approximately 700,000 yuan	7
S	Good information communication channels between farmers and consumers in the demonstration area have been established, and the material compensation given by farmers to consumers is approximately 200,000 yuan	2
D_1	Green produce is 1–3 yuan more expensive per kilogram than ordinary produce (Calculated from the median, 2,460 × 3,000 × 1.5 = 11,070,000 yuan)	111
D_2	The extra production cost of green production for farmers plus the extra income for farmers to get consumers to buy green agricultural products (300,000–160,000 + 11,070,000 = 11,210,000 yuan)	112
D_3	Farmers get extra income from consumers' purchase of green agricultural products plus incentive subsidies from the government (11,070,000 + 816,990 = 11,887,000 yuan)	119
L	The cost of consumers' purchase of green agricultural products minus the government's subsidies for green agricultural products [2,460 × 3,000 × (1.5–0.75) = 5.450,000 yuan]	55

Source(s): Authors' own creation

Table 5. The initial assignment of abstract parameters

Parameters	The source of data	No.
W_1	By interviewing government personnel, we learned that the government's performance and benefits brought by farmers' green production behaviours under government supervision is 15,000,000 yuan	150
W_2	By interviewing government personnel, we learned that if farmers do not adopt green production behaviour and consumers do not buy green agricultural products, the social maintenance cost of the government is 12,000,000 yuan	120
W_3	By interviewing government personnel, we learned that the government's performance benefit brought by farmers' green production behaviour is 9,000,000 yuan	90
V_1	By interviewing consumers, we learned that the beneficial effect of consumers' consumption of green agricultural products on their own health is 7,000,000 yuan	70
V_2	By interviewing consumers, we learned that the negative health effect of consumers' consumption of inferior agricultural produce on their own health is 3,000,000 yuan	30

Source(s): Authors' own creation

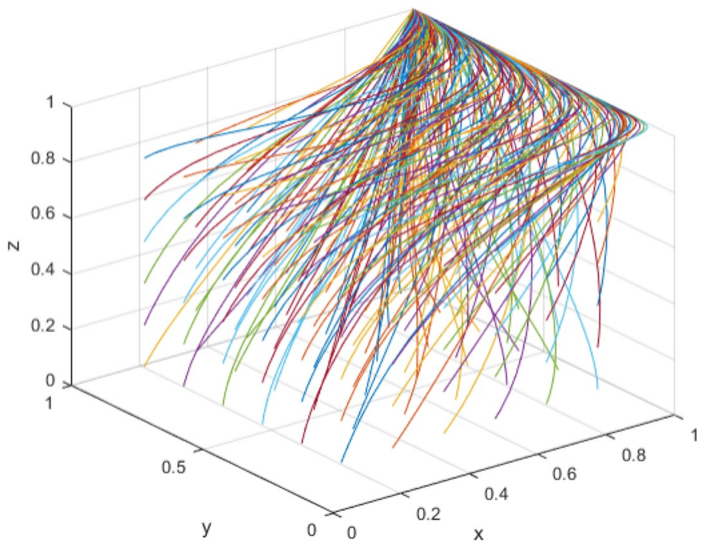

Figure 6. Actual situation evolution path of three-party policy
Source: Authors' own creation

The probability in the figures represents that the governments, farmers and consumers choose IR, GB and BG, respectively, and the unit of "Time" is year. In this paper, $(x_0, y_0, z_0) = (0.5, 0.5, 0.6)$ is taken as an example to observe the influence of the changes in supervision cost (C_2), reward and penalty (M_1,M_2), green production cost (E_1) and consumption cost (L) on the evolutionary trend of the game model.

4.3 Effect of C_2 on strategy selection

C_2 = 2, 10, 20 and 40 are assigned. The simulation results are shown in Figures 7 and 8.

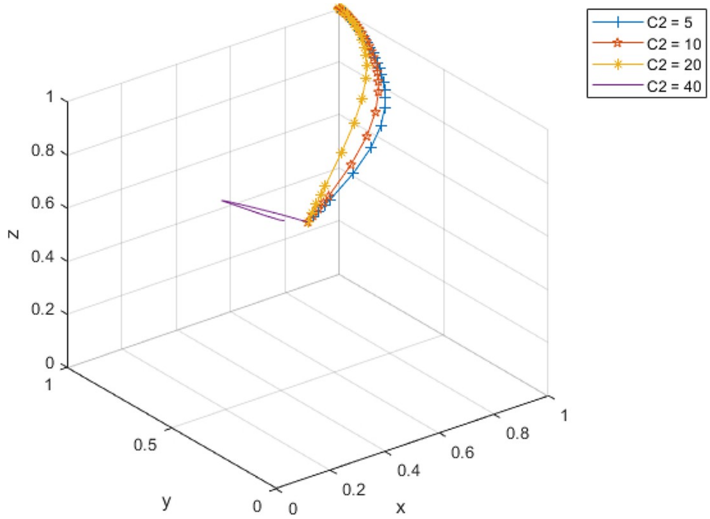

Figure 7. Tripartite game model sensitivity to changes in C_2
Source: Authors' own creation

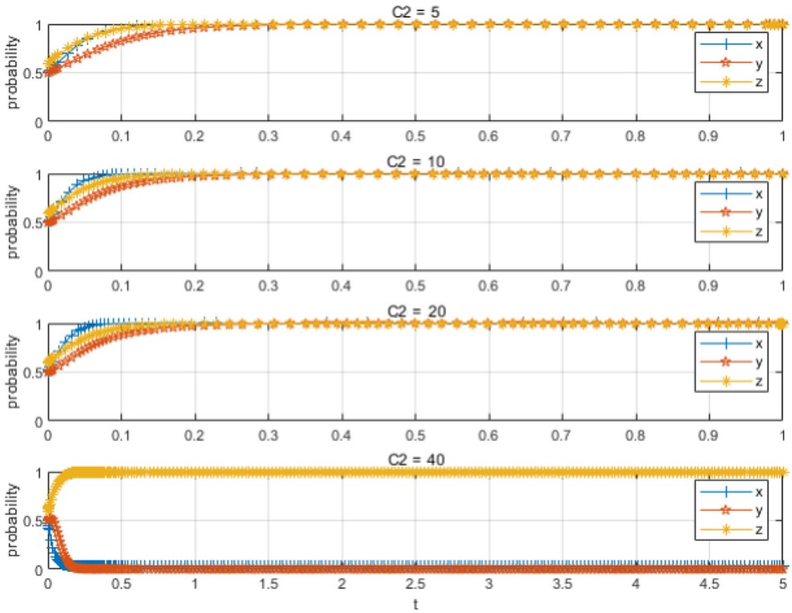

Figure 8. Each stakeholder's sensitivity to changes in C_2
Source: Authors' own creation

Figure 7 shows that as the cost of government regulation increases, the convergence speed of the probability of choosing regulation gradually accelerates and the time decreases. When the value exceeds a certain value, such as when $C_2 = 40$, because of the high input costs and current fiscal considerations, the government will obtain a return that is lower than the expenditure, so it is difficult to maintain the ideal state. The probability drops to 0 and remains unchanged, and finally, it is preferable to choose the strategy of no regulation. It can be observed from Figure 8 that with the increase in C_2, the probability of the government choosing IR will increase slowly, while the probability of farmers choosing GB will decrease rapidly. Because of the high cost of supervision, it increases the financial burden of the government, reduces the possibility of choosing IR and makes farmers face the dual pressure of fund shortage and government assessment. Therefore, there is a certain limit to the regulation cost provided by the government to guarantee farmers' GB. If the limit is exceeded, the government will choose not to regulate, leading to great changes in the evolutionary path. The government needs to choose an appropriate regulatory cost, that is, less than 40, to slow down the trend of farmers choosing NGB and prevent the government's regulation input from being disproportionate to the harvest.

4.4 Effect of M_1 and M_2 on strategy selection

We set $M_1 = 5$, $M_2 = 5$ (low reward, low penalty); $M_1 = 5$, $M_2 = 20$ (low reward, high penalty); $M_1 = 20$, $M_2 = 5$ (high reward, low penalty); $M_1 = 20$, $M_2 = 20$ (high reward and high penalty). The simulation results are shown in Figures 9 and 10.

It can be observed from Figure 9 that when the reward and penalty are low, the system eventually stabilizes at (1,0,1). In this case, the government has the least binding force on farmers. Farmers neither have enough incentive and subsidy support nor are completely constrained by fines, which will not affect their strategy of choosing GB. When the reward is low and the penalty is high, the system eventually stabilizes at (1,1,1). A high fine has a

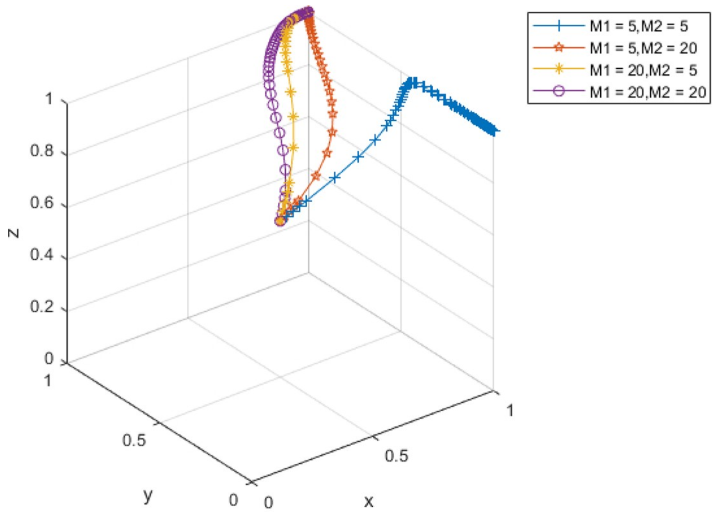

Figure 9. Tripartite game model sensitivity to changes in M_1 and M_2
Source: Authors' own creation

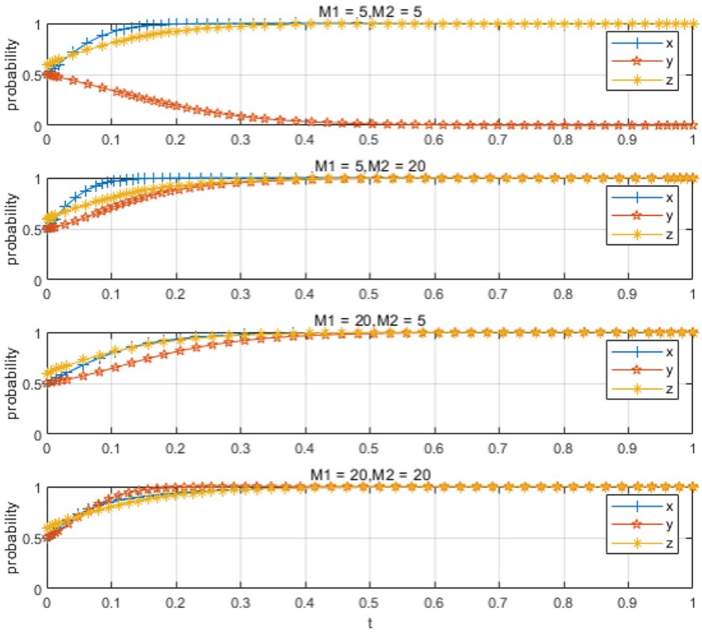

Figure 10. Each stakeholder's sensitivity to changes in M_1 and M_2
Source: Authors' own creation

certain binding force on farmers. If the fine is large enough, farmers can carefully weigh the advantages and disadvantages and choose GB. In reality, it is difficult to realize high fines, it is difficult for farmers to accept high fines and it is extremely difficult to promote them on a large scale. When the reward is high and the penalty is low, the system eventually stabilizes at (1,1,1), which occurs faster than when the reward is low and the punishment is high. In this mode, because the government can give sufficient incentives and subsidies to farmers, farmers have funds to adopt GB and form long-term operations, and farmers do not have the pressure brought by fines, making the reward and penalty mode more ideal. At present, the mode of high reward and low punishment has become a method that some provinces and cities with mature green production are exploring. When the reward and penalty are high, the system finally stabilizes at (1,1,1), and the evolution system of three-party subjects converges to the ideal state at the fastest speed.

It can be observed from Figure 10 that the convergence speed of farmers in the mode of high reward and high punishment to the ideal state is the fastest, indicating that this policy can make farmers both have enough reward and be constrained by fines. Therefore, in view of the actual situation, adopting harsh measures combined with kindness and threat can achieve the ideal decision faster, which is more consistent with current policy-making and can provide a reference for maintaining current government management.

4.5 *Effect of E_1* on strategy selection

E_1 = 5, 12, 20 and 25 are assigned. The simulation results are shown in Figures 11 and 12.

It can be observed from Figure 11 that the reduction in investment costs for farmers to adopt GB can accelerate the convergence rate of the evolutionary system of the three parties.

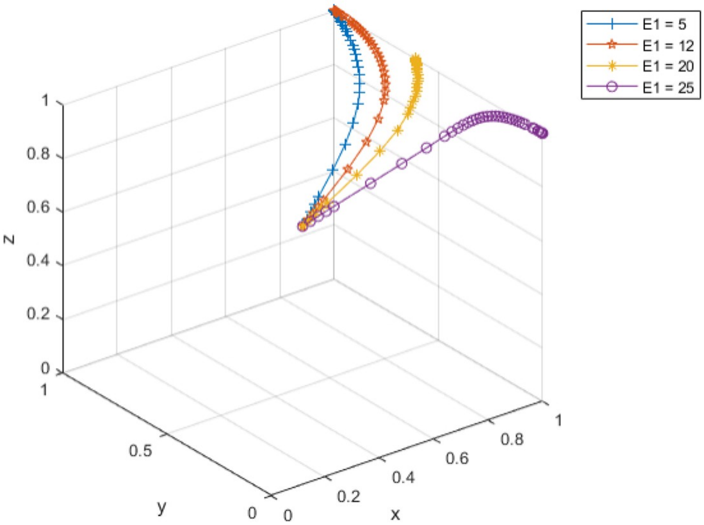

Figure 11. Tripartite game model sensitivity to changes in E_1
Source: Authors' own creation

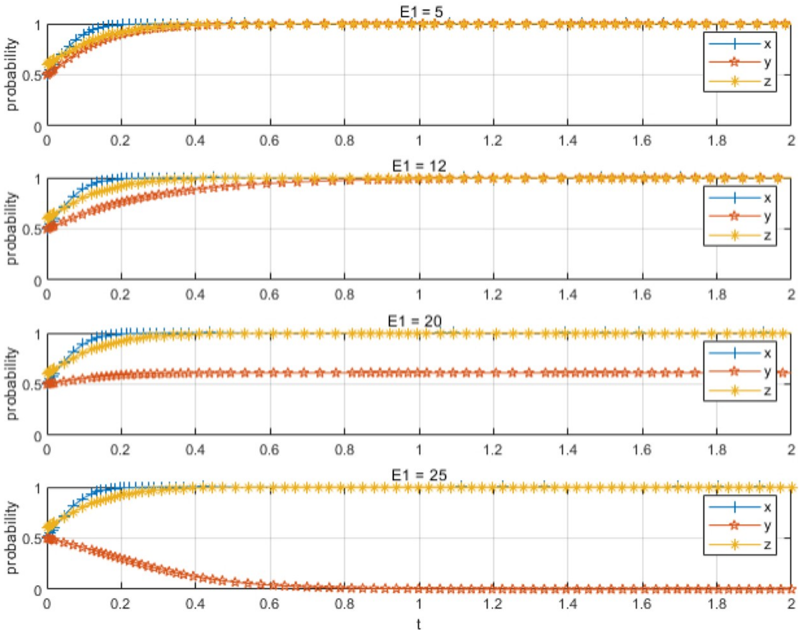

Figure 12. Each stakeholder's sensitivity to changes in E_1
Source: Authors' own creation

Within a certain limit, when the investment cost for farmers to adopt GB is lower, farmers are more likely to adopt GB. At this time, the convergence speed of the three-party evolutionary system is faster, and the time required to converge to the ideal state is shorter. It can be observed from Figure 12 that when E_1 is 25, it is difficult to maintain the ideal state due to the increase in the investment cost for farmers to adopt GB, and the probability decreases to 0 and remains unchanged. Therefore, under the ideal decision, there is a certain limit on the investment cost for farmers to adopt GB. Beyond this limit, farmers can only maintain the current decision due to consideration of their own interests, which leads to a great change in the evolutionary path and destroys the current ideal decision.

4.6 Effect of L on strategy selection

L= 10, 30, 50 and 70 are assigned. The simulation results are shown in Figures 13 and 14.

It can be observed from Figure 13 that within a certain limit, when the extra cost of purchasing green agricultural products is lower than that of purchasing ordinary agricultural products, the evolution system of the three parties converges at the fastest speed and takes the shortest time to converge to the ideal state, and consumers are more likely to choose BG. It can be observed from Figure 14 that when 70 is selected, it is difficult to maintain the ideal state because of the excessive extra cost of purchasing green agricultural products. Therefore, in the actual situation, there is a certain limit to the extra cost when consumers choose BG. When the limit is exceeded, consumers can only maintain the current decision due to consideration of their own interests, leading to great changes in the evolutionary path and breaking the current ideal decision.

5. Conclusion and policy recommendations

5.1 Conclusion

Based on evolutionary game theory, in this paper, a tripartite evolutionary game model of government, farmers and consumers is constructed; replication dynamic equation analysis,

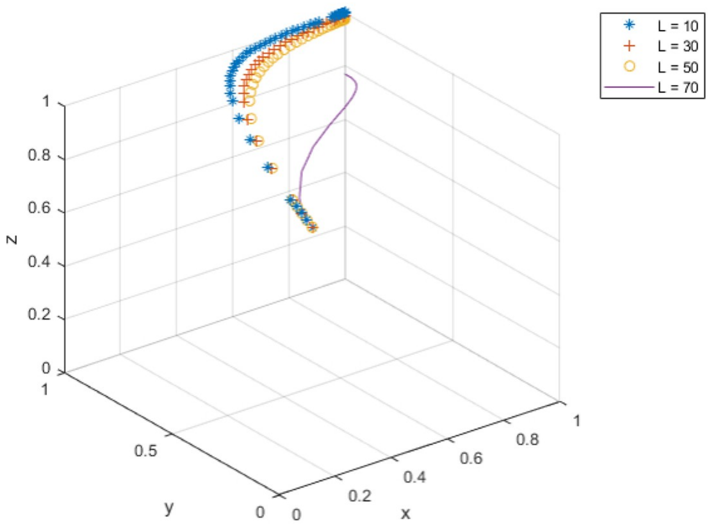

Figure 13. Tripartite game model sensitivity to changes in L
Source: Authors' own creation

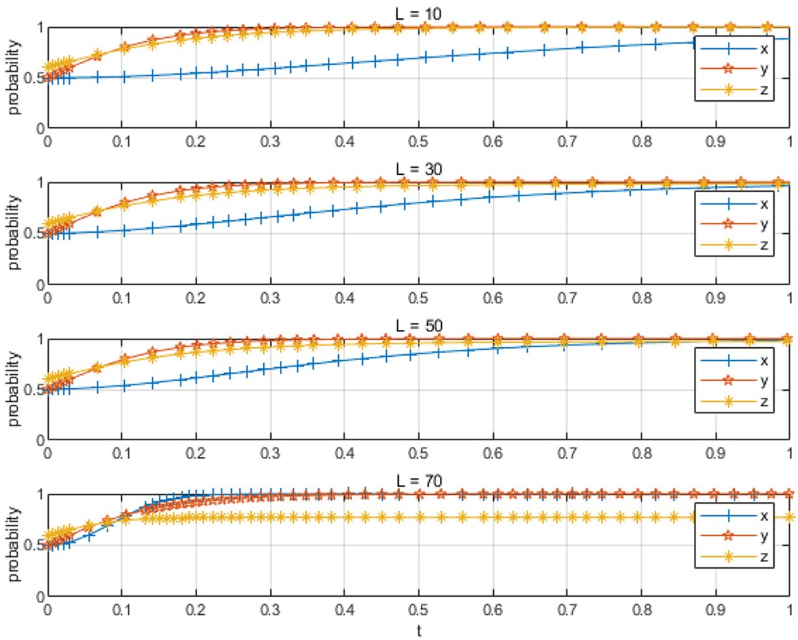

Figure 14. Each stakeholder's sensitivity to changes in *L*
Source: Authors' own creation

evolutionary stability analysis and numerical simulation experiments are carried out; and the following main conclusions are drawn:

The regulatory cost given by the government to guarantee farmers' GB. In reality, as the cost of government regulation increases, the convergence time for the government to choose regulation will decrease, but it should not exceed a certain limit; otherwise, it will force the government to choose not to regulate. To ensure the GB of farmers, the government should give appropriate supervision costs that are not too high or too low.

Reward and punishment mode on farmers' GB. In the actual situation, low reward and low punishment cannot make the three-party game system reach the ideal decision, and the other three reward and punishment modes can make the system maintain the ideal decision to a certain extent. Among them, high reward and high punishment are the fastest decisions for reaching the ideal state. The government adopts three reward and punishment modes of low reward and high punishment, high reward and low punishment and high reward and high punishment to gradually accelerate the convergence speed to the ideal state, and the time required for convergence to the ideal state is gradually shorter. Therefore, the government should choose a high reward and punishment mode for farmers' GB.

The investment cost of farmers adopting GB. Within a certain limit, reducing the investment cost of GB can accelerate the convergence of farmers to the ideal state. In comparison, the real simulation results are more sensitive to the change in investment cost, indicating that reducing the investment cost of farmers' GB is an effective way to promote farmers' GB.

Consumers' extra cost of purchasing green agricultural products is higher than that of purchasing ordinary agricultural products. Within a certain limit, when the extra cost of purchasing green agricultural products is lower than that of purchasing ordinary agricultural products, the evolution system of the three parties converges fastest, and the time required to converge to the ideal state is the shortest. At this point, consumers are more likely to buy green agricultural products. However, as additional costs increase, the rate at which consumers converge to their ideal state decreases. This indicates that there is a certain limit on the investment cost of farmers' GB, beyond which consumers can only maintain the current decision due to their own interests, and the price of green agricultural products should not be higher than that of ordinary agricultural products.

By analyzing the tripartite evolutionary game model of government, farmers and consumers, the most strategic combination of farmers' GB is obtained, which promotes the green transformation of agriculture from the perspective of multiple agents, provides a theoretical basis for countries to formulate agricultural emission reduction policies, encourages countries to achieve carbon neutrality and provides new emission reduction ideas for curbing global warming.

5.2 Policy recommendations

To mitigate the trend of climate warming and achieve sustainable agriculture in addressing climate change, it is necessary to reduce agricultural carbon emissions and achieve the goal of agricultural carbon neutrality in all countries around the world. It is very important to promote the joint participation of the government, farmers and consumers to achieve a balanced state of green agricultural development and to build an institutional environment that is suitable for green production and green consumption on the whole. To change the original institutional evolution process, it is necessary for an "innovator" to take the lead in deviating from established rules and achieving higher returns, and the government can play this role. The establishment of multiple co-governance mechanisms is the only way to realize the evolution from farmers' passive behaviour to their active behaviour in green production. The government, as an "innovator", can proceed from the following perspectives:

Establish a reward and punishment mechanism with high rewards and punishments. According to the characteristics of local farmers, a reward and punishment mechanism is formulated. Rewards and subsidies can improve the material income of farmers, reduce their burden of capital investment and enhance their confidence in development, while punishment can constrain their production behaviour.

Green production publicity and promotion. Professionals should be recruited to popularize green concepts and teach new technologies to farmers, popularize green agricultural knowledge and agricultural technology to farmers and improve their value awareness of ecological benefits. When leading enterprises of green production are supported, and demonstration areas of agricultural green production and large green production households are established, farmers can see successful models of green production and change their previous cognition.

Establish an effective supervision system and testing standards. This should be done to supervise farmers' GBs and supervise and test agricultural products, promote standardized production of green agricultural products and provide direction and guidance for farmers' transformation of production mode.

Formulating standards for agricultural products. Unified and credible standards for green agricultural products should be established, powerful signals for the identification of green agricultural products should be provided and farmers' production motivation and consumers' purchasing motivation should be stimulated.

Promoting green civilization. This can be accomplished through knowledge dissemination, natural education, agriculture and tourism culture and other means to improve the overall public

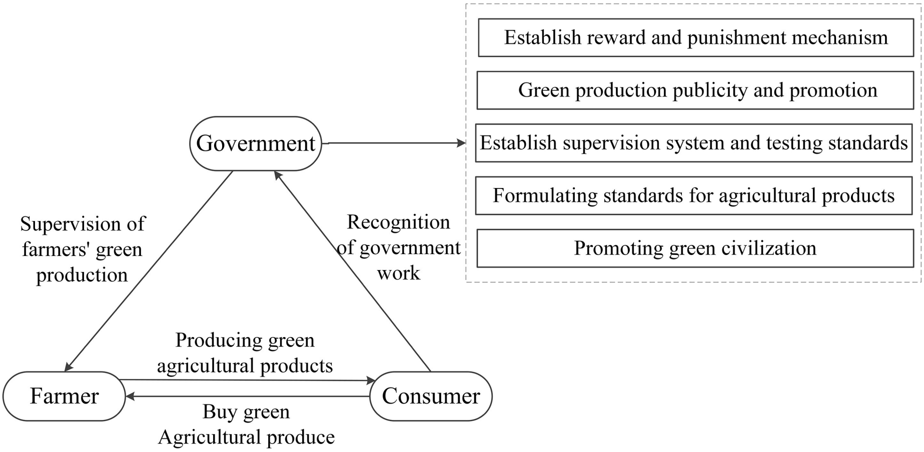

Figure 15. Optimal strategy operation mechanism of government, farmers and consumers
Source: Authors' own creation

awareness of green agriculture and encourage the whole society to consciously observe and practice the civilized fashion of green production and consumption.

Finally, the government, farmers and consumers will participate in the construction of green agriculture development, effectively build the development mechanism of green agriculture and achieve the path of green agriculture efficiency. The optimal strategy operation mechanism of the government, farmers and consumers is shown in Figure 15.

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Further reading

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