Tea industry's sustainable development: based on participants' tripartite evolutionary game and numerical simulation

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Abstract: Based on the assumptions of bounded rationality and information asymmetry, this paper adopts the tripartite evolutionary game and the numerical simulation to analyse the evolutionary stable strategies and evolution process of the three participants in the sustainable development of the tea industry. Firstly, this paper makes reasonable assumptions based on reality and constructs the tripartite evolutionary game model that includes the government, the enterprises/farmers and consumers as the main participants. Secondly, this paper applies the Lyapunov stability discriminant equations to analyse the asymptotic stability of the equilibrium points in the tripartite evolutionary game model, and proves that when the constraints are met, there are four dynamic evolutionary stable strategies for the three participants. Thirdly, through further analysis and numerical simulation of each dynamic ESS, this paper confirms that under some constraints, it is more likely to achieve the sustainable development of the tea industry.

Keywords: tea industry; sustainable development; sustainable production technology; sustainable consumption behaviour; tripartite evolutionary game; numerical simulation; China; evolutionary stable strategies; ESS; equilibrium point.

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1 Introduction

Due to its good natural resource endowment, China has a wide variety of tea, and has become the world's largest tea producer (FAOSTAT, 2020; Liang et al., 2021) with 20 million rural labourers involved (Ahmed et al., 2018), most of which are used to satisfy the domestic market (Hung et al., 2019). According to the data from China Customs, China's tea exports reached 366,600 tons in 2019, of which green tea exports accounted for 82.90%; tea imports were only 43,400 tons, of which black tea imports accounted for 83.90%. Thus, the increasing demand and supply for tea have intensified competition on both the global and domestic tea markets (Xiao et al., 2018). In 2017, there were more than 20 provinces in China where tea was grown, mainly in Fujian, Yunnan, Hubei, Sichuan and Hunan. Generally, China's tea producing areas can be divided into four major tea areas: Southwest China, South China, Jiangnan (South Central) and Jiangbei (North Central) (Zhang et al., 2019). Although China's tea production has increased year by year, there are still many problems that hinder the sustainable development of the industry. In recent years, the supply of China's tea market has been much higher than the demand, and the phenomenon of weak demand and overcapacity has become relatively serious. Part of the tea produced every year becomes inventory because it cannot be sold on the market. Although the aforementioned tea can be made into beverages and other derivatives to reduce inventory, the inventory is still increasing. In addition, the abuse of pesticides and fertilisers has caused potential safety hazards in the quality of tea products, which has become another factor hindering the sustainable development of the tea industry. Specifically, the maximum residual limit of pesticides imposed by importing countries has significantly affected China's tea exports (Wei et al., 2012).

A large number of existing studies have shown that drinking tea can reduce the occurrence and deterioration of certain diseases. For instance, Jian et al. (2004) confirmed that green tea is protective against prostate cancer. Habitual tea consumption is associated with a lower likelihood of depressive symptoms (Feng et al., 2013; Li et al., 2016) and having hypertension (Yin et al., 2017) in older people. Also, tea drinking is beneficial toward the improvement of self-reported health for older adults (Wang et al., 2021a). However, there are still a small number of scholars who confirm that (excessive) drinking tea is not good for health. This is most likely caused by the unsustainable production and consumption of tea. For instance, the influence of environmental pollution on the heavy metal content in oolong teas may increase consumers' health risks (Gruszecka-Kosowska and Mazur-Kajta, 2016). Thus, the basic goal of industrial sustainable development is to realise the sustainable development of society, economy and environment, that is, to realise the balance and overall optimisation of social, economic and environmental benefits. The economic sustainable development of the tea industry is mainly related to the industrial foundation and economic benefits, the sustainable social development is mainly related to regional social welfare and cultural literacy, and the environmentally sustainable development is mainly related to the ecological environment and resource protection. Some scholars also believe that the basic goals of the sustainable development of the industry should include the sustainable development of the industry, the sustainable use of resources, the continuous improvement of the ecological environment, and the continuous optimisation of the humanistic environment. In addition, Katinas and Crisci (2018), Rao et al. (2019) and Koodsela et al. (2019) have conducted some researches on the sustainable development of the industry. In general, many scholars agree that the basic goal of sustainable industrial development should achieve the harmony and unity of society, economy and environment. Although the existing research has made some progress in the sustainable development of the tea industry, there is little research on the role, mutual influence and policy recommendations of the participants, so it needs to be supplemented and expanded appropriately.

Participants in the tea industry are concrete practitioners of achieving sustainable development, and they play an important role that cannot be ignored. Participants in the sustainable development of the industry are diverse, especially for agriculture. Restricting participants to the inside or outside of the industry is a relatively one-sided single perspective, and there are limitations. Therefore, in order to make agriculture embark on a benign sustainable development path, the key is to determine the main body of participation in the sustainable development of agriculture, namely the self-body, the main-body and the carrier. Small-scale sustainable agriculture should assume the self-body role, the new professional farmers should assume the self-body role, and the villages should assume the carrier role. That is, in the sustainable development of the tea industry, the villages that grow and produce tea should be the mainstay. The government continuously strengthens education and training for new-type professional farmers, and uses small-scale continuous agriculture as the main production method. However, limited by the special geographical environment and the particularity of tea, the scope of these participants is still slightly narrow. In addition to the government and farmers, multi-stakeholders including consumers, enterprises and industry organisations are also participants in the sustainable development of the industry. In the complex system of the sustainable development of the tea industry, the decisions made by all parties involved need to consider the decisions of other potential participants, not only the past and current status, but also the competition and cooperation behaviours of other participants, ultimately jointly promotes the sustainable development of the tea industry. Currently, many tea farmers have begun to adopt sustainable production methods and switch to organic tea production, especially under the impact of COVID-19 (Gerasimova et al., 2021). Additionally, the integration of tea and tourism has become another way to realise the sustainable development of the tea industry (Cheng et al., 2010; Yan et al., 2021).

The tripartite evolutionary game is currently an important method to study the game process between different participants, and the research belongs to the frontier field. Specifically, the tripartite evolutionary game was adopted to study areas including the sustainable development of the industry (Sheng et al., 2019; Liu et al., 2020; Wang et al., 2021b), health-related behaviour (Gao et al., 2017), environmental and energy policy (Yang and Yang, 2019; Zhao et al., 2019, 2020; Xu et al., 2019; Zhu et al., 2020; Chen et al., 2020), government behaviour (Zheng and Liao, 2019) and market behaviour (Pu et al., 2020; Wu et al., 2020; Han, 2020; Liu et al., 2021). In view of the advantages of the evolutionary game, the tripartite evolutionary game is used to analyse the stable strategy of the sustainable development of the tea industry.

Compared with existing researches, the innovations of this research are mainly reflected in the following three aspects. First, this research takes the sustainable development of the tea industry as the research object, avoids treating the macro-agricultural industry as a unified whole, and the research conclusions have clear pertinence. Second, this research included the government, enterprises, farmers, and consumers in the scope at the same time, so that the comprehensiveness of the participants in the sustainable development of the tea industry has been improved. Third, based on the tripartite evolutionary game, this research analyses the dynamic evolution of the tripartite entities, and carries out numerical simulations at the same time to expand the application of the evolutionary game model.

2 Theoretical model of the tripartite evolutionary game

2.1 *Definition of participants*

In terms of a single participant, the sustainable development of the tea industry is mainly affected by many factors from the government, enterprises, farmers, and consumers. For instance, the government's environmental regulations and financial support affect the sustainable development of the tea industry, and the enterprise's resource and environmental endowments are one of the main core factors to achieve the sustainable development of the tea industry. However, due to the irrationality and information asymmetry among the multi-participants in the sustainable development of the tea industry, that is, different participants show different interest demands; the ultimate realisation of the sustainable development of the tea industry depends on the game of behavioural strategies among the multi-participants. In addition, considering that there is no essential difference between tea enterprises and tea farmers in the ways of tea planting, production and sales, the two are regarded as the same participant. Therefore, the participants in the sustainable development of the tea industry are ultimately mainly summarised as the government, enterprises/farmers and consumers.

Generally, the government is the main maker and supervisor of the sustainable development plan of the tea industry, and plays an important role in the development of the industry. Local industrial policies have played an important role when market failures occur in the development of agricultural clusters (Zhao et al., 2021). Specifically, the government guides enterprises/farmers to adopt sustainable production methods through the formulation of strict environmental regulations and sound financial subsidies, thereby realising the sustainable development of the tea industry. The strong financial support of the government also provides important material guarantee for the sustainable development of the tea industry. In addition, enterprises/farmers adopt appropriate production behaviours in accordance with government's mandatory measures and recommendations to effectively maximise economic benefits. When companies/farmers consider sustainable production behaviours, they need to weigh the relationship between production costs and benefits. The specific production behaviours of enterprises/farmers that violate the regulations may be restricted by the government. For instance, in Anxi County, Fujian Province, the main production area of Oolong tea in China, the local government issued a policy in 2018 to prohibit tea producers from using tea-moulding machine to produce tea products, because the machine had been confirmed to seriously affect the quality of tea. Specifically, the government stipulates that once the producer is found to have similar acts, the tea-moulding machine will be directly confiscated and destroyed in a centralised and unified manner. Consumers' influence on the sustainable development of the tea industry is mainly reflected in the influence of tea consumption behaviour. Consumers consume sustainable tea products by paying more economic costs. Therefore, in terms of the unit economic benefits of tea, enterprises/farmers can obtain more economic benefits than traditional tea from consumers' consumption behaviour. Driven by high economic benefits, enterprises/farmers are obviously more likely to adopt sustainable production methods. However, the economic cost acceptable to consumers is limited, that is, the price difference between sustainable tea products and traditional tea cannot exceed the range acceptable to most consumers. Specifically, although most consumers are concerned about the safety of tea, their willingness to pay for certified traceable tea is limited (Liu et al., 2015). These phenomena all indicate that there are characteristics of bounded rationality and information asymmetry among the government, enterprises/farmers, and consumers. Only after repeated imitating and learning from each other can the stability of the strategy be achieved. In short, the realisation of the sustainable development of the tea industry requires multiple parties to participate in the common standardisation of behaviour, and strengthen exchanges and cooperation while weighing the conflicts of interest of multiple parties.

2.2 *Application of the tripartite evolutionary game*

Compared with traditional game theory, the tripartite evolutionary game combines game theory and dynamic evolution process, and discards the assumption that the participants are completely rational. Based on the assumptions of bounded rationality, expected benefits and information asymmetry (Pu et al., 2020), the tripartite evolutionary game firstly analyses the decision-making behaviour of each subject, and believes that the participants of the game cannot reach a stable state in the initial stage, and need to learn and imitate each other to gradually realise the evolutionary stable strategies (ESS). Since the tripartite evolutionary game has certain advantages in the research of strategic equilibrium, this model is suitable for the analysis of the strategic equilibrium of the participants in the sustainable development of the tea industry.

3 Hypothesis and model construction

3.1 *Hypothesis*

In the sustainable development of the tea industry, the government, enterprises/farmers and consumers are a group of participants with a complex dynamic game relationship. The behaviours and decisions of one of the three participants will affect other participants, and at the same time will be affected by other participants. Therefore, in the process of behaviour and decision-making, participants continuously obtain the behaviour and decision-making information of other participants, and then adjust their own strategies, and finally make the evolutionary game relationship of the three-party participants reach a certain stable state. In order to effectively study the dynamic evolutionary game of the tripartite participants, without changing the essence of the research question, the following assumptions are made:

- Hypothesis 1: the government, enterprises/farmers and consumers are the three participants participating in the dynamic game, and the three participants are mainly based on the assumption of bounded rational economic man and information asymmetry. That is, the three participants do not have the ability to predict in advance, and in the initial stage they cannot obtain all the information about the behaviour and decision-making of other participants. However, in the process of behaviour and decision-making, the participants can use the continuous acquisition of information and learn to imitate, proceed from their own interests, and change their own strategies to achieve the optimisation of strategies.
- Hypothesis 2: the government's behaviour and decision-making strategies can be divided into support and non-support for the sustainable development of the tea industry, the probabilities of which are x and $1 - x$ respectively. It should be noted that the government's choice not to support the sustainable development of the tea industry mainly refers to passive support or neglect, and does not refer to the government's opposition to the sustainable development of the tea industry. Similarly, the probability of enterprises/farmers adopting sustainable tea production technology is y, and the probability of not adopting sustainable tea production technology is $1 - y$. The probability of consumers choosing the sustainable consumption behaviour of tea is z and the probability of not choosing the sustainable consumption behaviour of tea is $1 - z$. Therefore, the values of x, y and z are all between 0 and 1, that is, $x, y, z \in [0, 1]$.
- Hypothesis 3: the government supports the sustainable development of the tea industry, which is usually manifested by actively formulating reasonable development plans of the tea industry, taking reasonable regulatory measures to supervise the decision-making and behaviour norms of the relevant subjects of the tea industry, and carrying out appropriate financial subsidies and preferential tax policies for enterprises/farmers adopting sustainable production technologies. The government's support for the sustainable development of the tea industry and the benefits of improving government performance and credibility are R_g; the corresponding support cost paid by the government is C_g; the financial subsidies and tax preferential policies for sustainable production technology of enterprises/farmers are S_g. On the contrary, the government does not support the sustainable development of the tea industry, which usually means that the government lacks an overall plan for the development of the tea industry, lacks active supervision of the behaviour and strategic norms of enterprises/farmers, and even condones violations of enterprises/farmers. Under this circumstance, the basic income obtained by the government for the development of the tea industry is R_{gg}; the corresponding cost paid is C_{gg}; the loss of accountability and punishment of higher-level government departments, the reduction of credibility, and the reduction of social welfare is F_g. In addition, theoretical assumptions indicate that $R_g > R_{gg}$ and $C_g > C_{gg}$.
- Hypothesis 4: enterprises/farmers adopt sustainable tea production technology to promote the sustainable development of tea industry, which is usually manifested in the following aspects: optimisation of tea variety structure, green prevention and control technology of diseases and pests in tea garden, construction and management technology of ecological tea garden and organic tea garden, soil testing and formulated fertilisation technology in tea garden, interplanting and intercropping technology in tea garden. The income of enterprises/farmers using sustainable tea production technology to obtain corporate reputation and economic support is R_e; the production and operation costs of tea planting and production input and production mode conversion are C_e. On the contrary, if enterprises/farmers do not adopt sustainable tea production technology, the basic benefits of violations such as unqualified tea product quality are R_{ee}; the basic production and operation costs such as human, material and financial resources are C_{ee}. It should be pointed out that if the enterprises/farmers take opportunistic actions, such as excessive pesticide residues in tea products, and the government adopts the strategy of supporting sustainable development, the enterprises/farmers will be paid attention to and punished by the government regulatory department, and the punishment imposed for this is F_e. In addition, theoretical assumptions indicate that $R_e > R_{ee}$ and $C_e > C_{ee}$.
- Hypothesis 5: consumers choose sustainable tea consumption behaviour, which is usually manifested in environmental protection purchase, repeated use, recycling, resource conservation and species rescue. The benefits of product utility and physical and mental pleasure brought about by consumers choosing sustainable tea consumption behaviour are R_c; the cost of product purchase and information retrieval and identification for this is C_c. On the contrary, consumers do not choose sustainable tea consumption behaviour, which is usually manifested as buying traditional tea products or even not buying tea products, or ignoring the negative impact of consumer behaviour on the

environment and ecology during the tea consumption process. In this case, the basic benefits such as product utility received by consumers are R_{cc}; the corresponding cost for this is C_{cc}. Among them, the theoretical hypothesis shows that $R_c > R_{cc}$, $C_c > C_{cc}$. It needs to be noted that consumers can have a certain feedback effect on enterprises/farmers through their consumption behaviour. The mechanism of consumer feedback is that consumers indirectly reward enterprises/farmers that comply with the code of conduct, and indirectly punish those enterprises/farmers that violate the code of conduct. That is, when consumers choose sustainable consumption behaviours and enterprises/farmers adopt sustainable production technologies; the positive feedback benefit of consumer consumption behaviours to the enterprises/farmers is P_c. In comparison, when consumers choose sustainable consumption behaviours and enterprises/farmers do not adopt sustainable production technologies, the negative feedback benefits of consumer consumption behaviours to the enterprises/farmers are N_c. In summary, the main parameter settings and meanings of the tripartite evolutionary game are shown in Table 1. In addition, since the three participants in the sustainable development of the tea industry all use the benefits and utility of selected strategies as the criteria for behaviour and strategy selection, calculating the benefits and utility of each party's strategies has become the basis and key of the tripartite evolutionary game analysis. Accordingly, the payment matrix of the tripartite participants in the sustainable development of the tea industry is shown in Table 2.

3.2 Model construction

Assuming that the expected revenue of the government supporting the sustainable development of tea industry is U_g, the expected revenue of the government not supporting the sustainable development of tea industry is U_{gg} and the average expected revenue of the government is U_1, then:

$$\begin{aligned} U_g &= yz(R_g - C_g - S_g) + z(1-y)(R_g - C_g + F_e) \\ &\quad + y(1-z)(R_g - C_g - S_g) + (1-y)(1-z)(R_g - C_g + F_e) \end{aligned} \tag{1}$$

$$\begin{aligned} U_{gg} &= yz(R_{gg} - C_{gg} - F_g) + z(1-y)(R_{gg} - C_{gg} - F_g) \\ &\quad + y(1-z)(R_{gg} - C_{gg} - F_g) \\ &\quad + (1-y)(1-z)(R_{gg} - C_{gg} - F_g) \end{aligned} \tag{2}$$

$$U_1 = xU_g + (1-x)U_{gg} \tag{3}$$

Assuming that the expected revenue of enterprises/farmers adopting the sustainable production technology of the tea industry is U_e, the expected revenue of not adopting the sustainable production technology of the tea industry is U_{ee}, and the average expected revenue of enterprises/farmers is U_2, then:

$$\begin{aligned} U_e &= xz(R_e - C_e + S_g + P_c) + x(1-z)(R_e - C_e + S_g) \\ &\quad + z(1-x)(R_e - C_e + P_c) + (1-x)(1-z)(R_e - C_e) \end{aligned} \tag{4}$$

$$\begin{aligned} U_{ee} &= xz(R_{ee} - C_{ee} - F_e - N_c) + x(1-z)(R_{ee} - C_{ee} - F_e) \\ &\quad + z(1-x)(R_{ee} - C_{ee} - N_c) + (1-x)(1-z)(R_{ee} - C_{ee}) \end{aligned} \tag{5}$$

$$U_2 = yU_e + (1-y)U_{ee} \tag{6}$$

Assuming that the expected income of consumers who choose sustainable tea consumption behaviour is U_c, the expected income of not choosing sustainable tea consumption behaviour is U_{cc}, and the average expected income of consumers is U_3, then:

$$\begin{aligned} U_c &= xy(R_c - C_c - P_c) + x(1-y)(R_c - C_c + N_c) \\ &\quad + y(1-x)(R_c - C_c - P_c) + (1-x)(1-y)(R_c - C_c + N_c) \end{aligned} \tag{7}$$

$$\begin{aligned} U_{cc} &= xy(R_{cc} - C_{cc}) + x(1-y)(R_{cc} - C_{cc}) \\ &\quad + y(1-x)(R_{cc} - C_{cc}) + (1-x)(1-y)(R_{cc} - C_{cc}) \end{aligned} \tag{8}$$

$$U_3 = zU_c + (1-z)U_{cc} \tag{9}$$

Table 1 Setting and meaning of the main parameters of the model

Symbol	*The meaning of expression*	*Symbol*	*The meaning of expression*
x	Probability of government supporting sustainable development	R_{ee}	Benefits of enterprises/farmers not adopting sustainable production technologies.
y	Probability of enterprises/farmers adopting sustainable production technology.	C_e	Cost of enterprises/farmers adopting sustainable production technology
z	Probability of consumers choosing sustainable consumption behaviour	C_{ee}	Cost of enterprises/farmers not adopting sustainable production technology.
R_g	Benefits of government supporting sustainable development	F_e	Penalties for enterprises/farmers not adopting sustainable production technologies
R_{gg}	Benefits of government not supporting sustainable development	R_c	Benefits of consumers choosing sustainable consumption behaviours
C_g	Cost of government supporting sustainable development	R_{cc}	Benefits of consumers not choosing sustainable consumption behaviours
C_{gg}	Cost of government not supporting sustainable development	C_c	Cost of consumers choosing sustainable consumption behaviour

Table 1 Setting and meaning of the main parameters of the model (continued)

Symbol	*The meaning of expression*	*Symbol*	*The meaning of expression*
S_g	Government subsidies for sustainable production technology of enterprises/farmers.	C_{cc}	Cost of consumers not choosing sustainable consumption behaviour
F_g	Loss of government not supporting sustainable development	P_c	Positive feedback of consumer consumption behaviour to enterprises/farmers.
R_e	Benefits of enterprises/farmers adopting sustainable production technologies.	N_c	Negative feedback of consumer consumption behaviour to enterprises/farmers.

Table 2 Payment matrix of the tripartite evolutionary game

Government	*Enterprises/ farmers*	*Consumers: Choose (z)*	*Consumers: Not choose (1 – z)*
Support (x)	Adopt (y)	$R_g - C_g - S_g$	$R_g - C_g - S_g$
		$R_e - C_e + S_g + P_c$	$R_e - C_e + S_g$
		$R_c - C_c - P_c$	$R_{cc} - C_{cc}$
	Not adopt ($1 - y$)	$R_g - C_g + F_e$	$R_g - C_g + F_e$
		$R_{ee} - C_{ee} - F_e - N_c$	$R_{ee} - C_{ee} - F_e$
		$R_c - C_c + N_c$	$R_{cc} - C_{cc}$
Not support ($1 - x$)	Adopt (y)	$R_{gg} - C_{gg} - F_g$	$R_{gg} - C_{gg} - F_g$
		$R_e - C_e + P_c$	$R_e - C_e$
		$R_c - C_c - P_c$	$R_{cc} - C_{cc}$
	Not adopt ($1 - y$)	$R_{gg} - C_{gg} - F_g$	$R_{gg} - C_{gg} - F_g$
		$R_{ee} - C_{ee} - N_c$	$R_{ee} - C_{ee}$
		$R_c - C_c + N_c$	$R_{cc} - C_{cc}$

4 The tripartite evolutionary game analysis

4.1 Replicator dynamics and ESS of tripartite game

According to the Malthusian dynamic equation, the replicator dynamic differential equation of government supporting the sustainable development of tea industry is obtained as follows:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x\left(U_g - U_1\right) = x(1-x)\left(U_g - U_{gg}\right) \\ &= x(1-x)\left(R_g - C_g + F_e - yF_e - yS_g - R_{gg} + C_{gg} + F_g\right) \end{aligned} \tag{10}$$

Similarly, the replicator dynamic differential equation of tea sustainable production technology adopted by enterprises/ farmers is as follows:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y\left(U_e - U_2\right) = y(1-y)\left(U_e - U_{ee}\right) \\ &= y(1-y)\left(xS_g + R_e - C_e + zP_c + xF_e + zN_c - R_{ee} + C_{ee}\right) \end{aligned} \tag{11}$$

The replicator dynamic differential equation of consumers' sustainable consumption behaviour of tea is as follows:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z\left(U_c - U_3\right) = z(1-z)\left(U_c - U_{cc}\right) \\ &= z(1-z)\left(R_c - C_c + N_c - yP_c - yN_c - R_{cc} + C_{cc}\right) \end{aligned} \tag{12}$$

4.2 Government's ESS

The derivation of F(x) gives the following results:

$$\frac{\partial F(x)}{\partial x} = (1-2x)\left(R_g - C_g + F_e - yF_e - yS_g - R_{gg} + C_{gg} + F_g\right) \tag{13}$$

When $y = \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$, $F(x) \equiv 0$, no matter what strategy the government adopts for the sustainable development of tea industry, it is a stable strategy, and the strategy will not change with time. If $y \neq \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$, take $x = 0$ or $x = 1$ as two evolutionary stable points to make $F(x) = 0$. According to the stability theorem of differential equations, when a certain strategy adopted by the government is stable, $F(x) = 0$ and $\frac{\partial F(x)}{\partial x} < 0$ should be satisfied. Therefore, this research makes the following distinction:

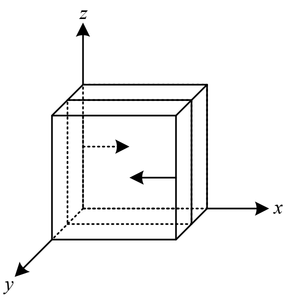
1 When $y > \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$, $\left.\frac{\partial F(x)}{\partial x}\right|_{x=0} < 0$, $\left.\frac{\partial F(x)}{\partial x}\right|_{x=1} > 0$, the equilibrium point of government strategy is $x = 0$.

2 When $y < \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$, $\left.\frac{\partial F(x)}{\partial x}\right|_{x=0} > 0$, $\left.\frac{\partial F(x)}{\partial x}\right|_{x=1} < 0$, the equilibrium point of government strategy is $x = 1$.

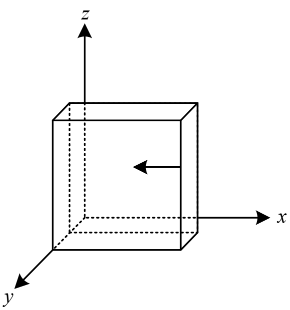
In summary, the evolutionary dynamic replication phase diagram of government strategy selection is shown in Figure 1.

As shown in Figure 1, when the net benefits, (i.e., the difference between benefits and costs) obtained by the government supporting the sustainable development of tea industry are much higher than those obtained by the government not supporting the sustainable development of tea industry, the government is more likely to support the sustainable development of tea industry based on the consideration of interests. In addition, the greater the loss of reputation and credibility suffered by the government for not supporting the sustainable development of the tea industry, the more likely it is that the government will support the sustainable development of the tea industry, which is consistent with reality observation. Meanwhile, the smaller the financial subsidies and tax incentives provided by the government to the compliance behaviour of enterprises/farmers, the more likely the government is to support the sustainable development of tea industry. One possible explanation is that the government's financial support to enterprises/farmers will become part of the government's fiscal expenditure, that is, one of the costs of its operation.

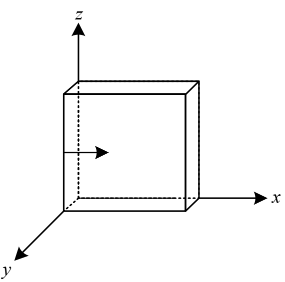
Figure 1 The evolutionary dynamic replication phase diagram of the government's strategic choice,
(a) $y = \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$,
(b) $y > \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$,
(c) $y < \frac{R_g - C_g + F_e - R_{gg} + C_{gg} + F_g}{F_e + S_g}$



(a)



(b)



(c)

4.3 *Enterprises/farmers' ESS*

The derivation of $F(y)$ gives the following results:

$$\frac{\partial F(y)}{\partial y} = (1-2y)\left(xS_g + R_e - C_e + zP_c + xF_e + zN_c - R_{ee} + C_{ee}\right) \quad (14)$$

When $z = -\frac{x\left(S_g + F_e\right) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, $F(y) \equiv 0$, no matter what strategy enterprises/farmers take for sustainable tea production technology, it is a stable strategy, and the strategy will not change with time. If $z \neq -\frac{x\left(S_g + F_e\right) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, take $y = 0$ or $y = 1$ as two evolutionary stable points to make $F(y) = 0$. As mentioned above, when the strategy adopted by enterprises/farmers is stable, $F(y) = 0$ and $\frac{\partial F(y)}{\partial y} < 0$ should be satisfied. Therefore, this research makes the following distinction:

1 When $z > -\frac{x\left(S_g + F_e\right) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, $\left.\frac{\partial F(y)}{\partial y}\right|_{y=0} > 0$, $\left.\frac{\partial F(y)}{\partial y}\right|_{y=1} < 0$, the equilibrium point of enterprises/farmers' strategy is $y = 1$.

2 When $z < -\frac{x\left(S_g + F_e\right) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, $\left.\frac{\partial F(y)}{\partial y}\right|_{y=0} < 0$, $\left.\frac{\partial F(y)}{\partial y}\right|_{y=1} > 0$, the equilibrium point of enterprises/farmers' strategy is $y = 0$.

In summary, the evolutionary dynamic replication phase diagram of enterprises/farmers' strategy selection is shown in Figure 2.

As shown in Figure 2, when the benefits obtained by enterprises/farmers adopting sustainable tea production technology are much higher than those obtained by not adopting sustainable tea production technology, enterprises/farmers are more likely to adopt sustainable tea production technology based on interest considerations. In addition, the higher the government's financial subsidies and tax incentives for enterprises/farmers' sustainable production technology, and the higher the penalty for not using sustainable production technology, under the dual guidance of incentive mechanism and punishment mechanism, enterprises/farmers are more likely to adopt sustainable production technology. The intensity of positive and negative feedback of consumers' sustainable consumption behaviour to enterprises/farmers will restrict enterprises/farmers to adopt sustainable tea production technology. One possible explanation is that in the tea market, the tea planted and produced in the traditional way still accounts for the main proportion, while the consumer feedback is very strong, that means the fluctuation of the tea market faced by enterprises/farmers is relatively large. Because sustainable production technology needs to bear many additional fixed costs and the price of this type of tea is high, enterprises/

farmers are usually afraid to adopt tea sustainable production technology on a large scale.

4.4 Consumers' ESS

The derivation of $F(z)$ gives the following results:

$$\frac{\partial F(z)}{\partial z} = (1-2z)\left(R_c - C_c + N_c - yP_c - yN_c - R_{cc} + C_{cc}\right) \quad (15)$$

When $y = \frac{R_c - C_c + N_c - R_{cc} + C_{cc}}{P_c + N_c}$, $F(z) \equiv 0$ no matter what strategy consumers take for sustainable consumption behaviour, it is a stable strategy, and the strategy will not change with time. If $y \neq \frac{R_c - C_c + N_c - R_{cc} + C_{cc}}{P_c + N_c}$, take $z = 0$ or $z = 1$ as two evolutionary stable points to make $F(z) = 0$. As mentioned above, when the strategy adopted by consumers is stable, $F(z) = 0$ and $\frac{\partial F(x)}{\partial z} < 0$ should be satisfied. Therefore, this research makes the following distinction:

1 When $y > \frac{R_c - C_c + N_c - R_{cc} + C_{cc}}{P_c + N_c}, \left.\frac{\partial F(z)}{\partial z}\right|_{z=0} < 0$, $\left.\frac{\partial F(z)}{\partial z}\right|_{z=1} > 0$, the equilibrium point of consumers' strategy is $z = 0$.

2 When $y < \frac{R_c - C_c + N_c - R_{cc} + C_{cc}}{P_c + N_c}, \left.\frac{\partial F(z)}{\partial z}\right|_{z=0} > 0$, $\left.\frac{\partial F(z)}{\partial z}\right|_{z=1} < 0$, the equilibrium point of consumers' strategy is $z = 1$.

In summary, the evolutionary dynamic replication phase diagram of consumers' strategy selection is shown in Figure 3.

4.5 Analysis of the asymptotic stability of the model

In order to effectively analyse the asymptotic stability of the equilibrium point of the tripartite evolutionary game, we make the replicator dynamic equation (10), equation (11) and equation (12) of the government, enterprises/farmers and consumers equal to 0, that is, let $\frac{dx}{dt} = \frac{dy}{dt} = \frac{dz}{dt} = 0$, and obtain multiple equilibrium points of the replicator dynamic. Meanwhile, according to the research of Ritzberger and Weibull (1995), the ESS of multi group evolutionary game must be strict Nash equilibrium, and the strict Nash equilibrium is pure strategy equilibrium, that is, in asymmetric game, the mixed strategy equilibrium must not be evolutionary stability equilibrium. Therefore, we only need to consider the asymptotic stability of pure strategy equilibrium, that is, we only need to discuss the asymptotic stability of 8 pure strategy Nash equilibrium points, which are $E_1(0, 0, 0)$, $E_2(0, 1, 0)$, $E_3(1, 0, 0)$, $E_4(0, 0, 1)$, $E_5(0, 1, 1)$, $E_6(1, 0, 1)$, $E_7(1, 1, 0)$ and $E_8(1, 1, 1)$.

As shown in Figure 3, consumers are more likely to choose sustainable consumption behaviour of tea when they choose sustainable consumption behaviour of tea to get more benefits than they do not. In addition, the smaller the positive feedback of consumers' sustainable consumption behaviour to enterprises/farmers, the more likely consumers are to choose sustainable consumption behaviour of tea. This shows that there is a close relationship between the dynamic game evolution strategy between consumers and enterprises/farmers.

Figure 2 The evolutionary dynamic replication phase diagram of the enterprises/farmers' strategic choice, (a) $z = -\frac{x(S_g + F_e) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, (b) $z > -\frac{x(S_g + F_e) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$, (c) $z < -\frac{x(S_g + F_e) + R_e - C_e - R_{ee} + C_{ee}}{P_c + N_c}$

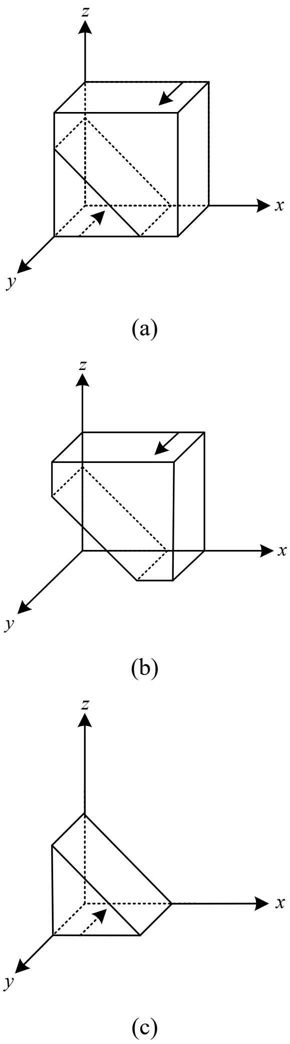
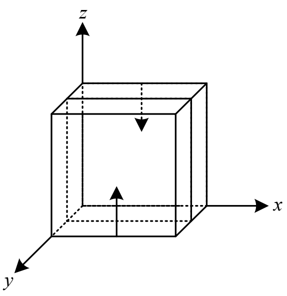
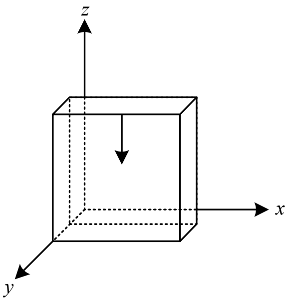


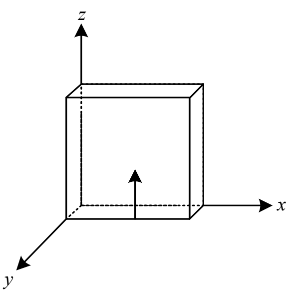
Figure 3 The evolutionary dynamic replication phase diagram of the consumers' strategic choice, (a) $y=\frac{R_c-C_c+N_c-R_{cc}+C_{cc}}{P_c+N_c}$, (b) $y>\frac{R_c-C_c+N_c-R_{cc}+C_{cc}}{P_c+N_c}$, (c) $y<\frac{R_c-C_c+N_c-R_{cc}+C_{cc}}{P_c+N_c}$



(a)



(b)



(c)

Generally, the asymptotic stability of equilibrium point can be judged by the positive and negative of determinant *det*(*J*) and trace *tr*(*J*) of Jacobian matrix *J* of equilibrium point. However, this method is not suitable for analysing the asymptotic stability of the tripartite evolutionary game, so Lyapunov stability theory (indirect method) is mainly used to determine the asymptotic stability of the equilibrium point. Lyapunov discriminant method is mainly used to judge the eigenvalue symbols of Jacobian matrix. That is, when all the eigenvalues of Jacobian matrix *J* are negative, the corresponding equilibrium point is the ESS of the system (Friedman, 1991). After calculation, the Jacobian matrix of the system is as follows: $J=\begin{bmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z}\\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z}\end{bmatrix}$. Among them:

$$\frac{\partial F(x)}{\partial x}=(1-2x)\left(R_g-C_g+F_e-yF_e-yS_g-R_{gg}+C_{gg}+F_g\right) \quad (13)$$

$$\frac{\partial F(y)}{\partial y}=(1-2y)\left(xS_g+R_e-C_e+zP_c+xF_e+zN_c-R_{ee}+C_{ee}\right) \quad (14)$$

$$\frac{\partial F(z)}{\partial z}=(1-2z)\left(R_c-C_c+N_c-yP_c-yN_c-R_{cc}+C_{cc}\right) \quad (15)$$

$$\frac{\partial F(x)}{\partial y}=\text{-}x(1-x)\left(F_e+S_g\right) \quad (16)$$

$$\frac{\partial F(x)}{\partial z}=0 \quad (17)$$

$$\frac{\partial F(y)}{\partial x}=y(1-y)\left(S_g+F_e\right) \quad (18)$$

$$\frac{\partial F(y)}{\partial z}=y(1-y)\left(P_c+N_c\right) \quad (19)$$

$$\frac{\partial F(z)}{\partial x}=0 \quad (20)$$

$$\frac{\partial F(z)}{\partial y}=\text{-}z(1-z)\left(P_c+N_c\right) \quad (21)$$

We bring the value of each equilibrium point into the Jacobian matrix *J*, obtain the corresponding eigenvalue of each equilibrium point, and judge the asymptotic stability of each equilibrium point according to the positive and negative signs of its signs, see Table 3 and Table 4 for details.

According to the rule of judging the asymptotic stability of equilibrium point, it can be seen from Table 4 that the eigenvalues of equilibrium point $E_1(0, 0, 0)$ are greater than 0, indicating that the equilibrium point is an unstable point. The eigenvalue symbols of equilibrium points $E_3(1, 0, 0)$, $E_4(0, 0, 1)$ and $E_6(1, 0, 1)$ have both positive and negative directions, indicating that these equilibrium points are saddle points. In addition, the positive and negative of the eigenvalues of equilibrium points $E_2(0, 1, 0)$, $E_5(0, 1, 1)$, $E_7(1, 1, 0)$ and $E_8(1, 1, 1)$ are uncertain and need to be classified and discussed.

Table 3 Corresponding eigenvalues of each equilibrium point

Equilibrium point	*Eigenvalue 1*	*Eigenvalue 2*	*Eigenvalue 3*
$E_1(0, 0, 0)$	$R_g - C_g + F_e - R_{gg} + C_{gg} + F_g$	$R_e - C_e - R_{ee} + C_{ee}$	$R_c - C_c + N_c - R_{cc} + C_{cc}$
$E_2(0, 1, 0)$	$R_g - C_g - S_g - R_{gg} + C_{gg} + F_g$	$-R_e + C_e - R_{ee} - C_{ee}$	$R_c - C_c - P_c - R_{cc} + C_{cc}$
$E_3(1, 0, 0)$	$-R_g + C_g - F_e + R_{gg} - C_{gg} - F_g$	$S_g + R_e - C_e + F_e - R_{ee} + C_{ee}$	$R_c - C_c + N_c - R_{cc} + C_{cc}$
$E_4(0, 0, 1)$	$R_g - C_g + F_e - R_{gg} + C_{gg} + F_g$	$R_e - C_e + P_c + N_c - R_{ee} + C_{ee}$	$-R_c + C_c - N_c + R_{cc} - C_{cc}$
$E_5(0, 1, 1)$	$R_g - C_g - S_g - R_{gg} + C_{gg} + F_g$	$-R_e + C_e - P_c - N_c + R_{ee} - C_{ee}$	$-R_c + C_c + P_c + R_{cc} - C_{cc}$
$E_6(1, 0, 1)$	$-R_g + C_g - F_e + R_{gg} - C_{gg} - F_g$	$S_g + R_e - C_e + P_c + F_e + N_c - R_{ee} + C_{ee}$	$-R_c + C_c - N_c + R_{cc} - C_{cc}$
$E_7(1, 1, 0)$	$-R_g + C_g - S_g + R_{gg} - C_{gg} - F_g$	$-S_g - R_e + C_e - F_e + R_{ee} - C_{ee}$	$R_c - C_c - P_c - R_{cc} + C_{cc}$
$E_8(1, 1, 1)$	$-R_g + C_g + S_g + R_{gg} - C_{gg} - F_g$	$-S_g - R_e + C_e - P_c - F_e + N_c + R_{ee} - C_{ee}$	$-R_c + C_c + P_c + R_{cc} - C_{cc}$

Table 4 The symbols and asymptotic stability of the eigenvalues of each equilibrium point

Equilibrium point	*Eigenvalue 1*	*Eigenvalue 2*	*Eigenvalue 3*	*Asymptotic stability*
$E_1(0, 0, 0)$	Positive	Positive	Positive	Unstable point
$E_2(0, 1, 0)$	Uncertain	Negative	Uncertain	Uncertain
$E_3(1, 0, 0)$	Negative	Positive	Positive	Saddle point
$E_4(0, 0, 1)$	Positive	Positive	Negative	Saddle point
$E_5(0, 1, 1)$	Uncertain	Negative	Uncertain	Uncertain
$E_6(1, 0, 1)$	Negative	Positive	Negative	Saddle point
$E_7(1, 1, 0)$	Uncertain	Negative	Uncertain	Uncertain
$E_8(1, 1, 1)$	Uncertain	Negative	Uncertain	Uncertain

4.5.1 Equilibrium point $E_2(0, 1, 0)$

While $R_g - C_g - (R_{gg} - C_{gg}) < S_g - F_g$ and $R_c - C_c - (R_{cc} - C_{cc}) < P_c$, the equilibrium $E_2(0, 1, 0)$ is asymptotically stable. In other cases, the equilibrium point is unstable. When the difference between the benefits and costs of government support for sustainable development and that of non-support is less than that of government subsidies and government losses, the government will eventually tend not to support the sustainable development of tea industry. When the difference of benefits and costs between enterprises and farmers using sustainable production technology is greater than that without using sustainable production technology, enterprises and farmers will eventually adopt sustainable production technology of tea. When the difference between benefits and costs of consumers choosing sustainable consumption behaviour and that of consumers not choosing sustainable consumption behaviour is less than the positive feedback of consumption behaviour to enterprises/farmers, consumers will eventually tend not to adopt sustainable consumption behaviour of tea.

4.5.2 Equilibrium point $E_5(0, 1, 1)$

While $R_g - C_g - (R_{gg} - C_{gg}) < S_g - F_g$ and $R_c - C_c - (R_{cc} - C_{cc}) < P_c$, the equilibrium $E_5(0, 1, 1)$ is asymptotically stable. In other cases, the equilibrium point is unstable. As mentioned above, when the government's conditions are consistent with equilibrium point $E_2(0, 1, 0)$, the government will not support the sustainable development of tea industry. When the consumer's condition is opposite to the equilibrium point $E_2(0, 1, 0)$, enterprises/farmers will adopt sustainable tea production technology. However, when the difference between benefits and costs obtained by enterprises/farmers without using sustainable production technology and the profit and cost obtained by using sustainable production technology is less than the sum of positive and negative feedback of consumption behaviour to enterprises/farmers, consumers will eventually tend to adopt sustainable consumption behaviour of tea.

4.5.3 Equilibrium point $E_7(1, 1, 0)$

While $R_g - C_g - (R_{gg} - C_{gg}) > S_g - F_g$ and $R_c - C_c - (R_{cc} - C_{cc}) < P_c$, the equilibrium $E_7(1, 1, 0)$ is asymptotically stable. In other cases, the equilibrium point is unstable. When the difference between benefits and costs of the government's support for sustainable development and that of the government's non-support is greater than that of the government's external subsidies and government losses, the government will eventually tend to support the sustainable development of tea industry. When the difference between benefits and costs obtained by the enterprises/farmers without using the sustainable production technology is less than the sum of the government subsidies and the punishment of the enterprises, the enterprises/farmers will eventually adopt the sustainable production technology. Similarly, when the difference between benefits and costs of consumers choosing sustainable consumption behaviour and that of consumers not choosing sustainable consumption behaviour is less than the positive feedback of consumption behaviour to enterprises/farmers, consumers will eventually tend not to adopt sustainable consumption behaviour of tea.

4.5.4 Equilibrium point $E_8(1, 1, 1)$

While $R_g - C_g - (R_{gg} - C_{gg}) > S_g - F_g$ and $R_c - C_c - (R_{cc} - C_{cc}) > P_c$, the equilibrium $E_8(1, 1, 1)$ is asymptotically stable. In other cases, the equilibrium point is unstable. When the government's conditions are consistent with the equilibrium point $E_7(1, 1, 0)$, the government will eventually tend to support sustainable development. When the consumer's condition is opposite to the equilibrium point $E_7(1, 1, 0)$, the consumer will eventually tend to adopt sustainable consumption behaviour. When the difference between benefits and costs obtained by the enterprise/farmer is less than the sum of the government subsidies, the punishment of the enterprise/farmer, the positive and negative feedback from the consumers to the enterprise/farmer, the enterprise/farmer will eventually tend to adopt the sustainable production technology.

5 Numerical simulation

In order to analyse the ESS of government, enterprises/farmers and consumers in the sustainable development of tea industry in more detail, based on the previous investigation in Fujian, China, parameter assignment was set, and the evolutionary game models of unilateral and tripartite participants were simulated respectively. According to the research conclusions of the replicator dynamic equation of the participants and the constraints of the asymptotic stability of the equilibrium point, as well as the investigation of the main tea producing areas in Fujian, the parameters and assignment of each equilibrium point are shown in Table 5. The numerical simulation process of the tripartite evolutionary game is implemented by the *R* package *deSolve* of RStudio 1.2 software.

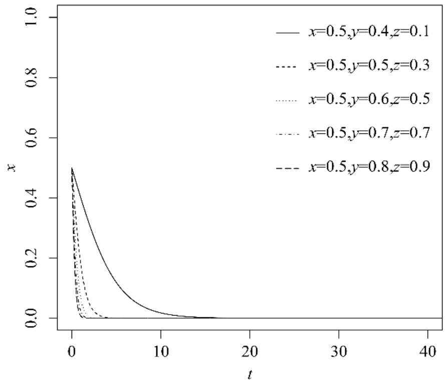
Table 5 Parameters and assignment of equilibrium points

Equilibrium point	*Parameters and assignment*								
	R_g	R_{gg}	C_g	C_{gg}	S_g	F_g	R_e	R_{ee}	C_e
$E_2(0, 1, 0)$	12	8	7	5	10	1	15	12	9
$E_5(0, 1, 1)$	12	8	7	5	10	1	15	12	9
$E_7(1, 1, 0)$	12	8	7	5	5	5	15	12	9
$E_8(1, 1, 1)$	12	8	7	5	5	5	15	12	9
Equilibrium point	*Parameters and assignment*								
	C_{ee}	F_e	R_c	R_{cc}	C_c	C_{cc}	P_c	N_c	
$E_2(0, 1, 0)$	8	1	15	11	10	8	7	1	
$E_5(0, 1, 1)$	8	1	15	11	10	8	1	7	
$E_7(1, 1, 0)$	8	1	15	11	10	8	7	1	
$E_8(1, 1, 1)$	8	1	15	11	10	8	1	7	

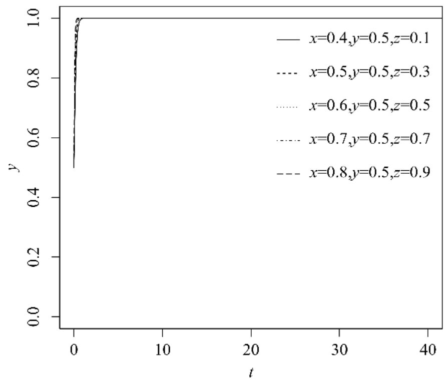
5.1 Equilibrium point $E_2(0, 1, 0)$

We fixed the initial value of the probability of government, enterprise/farmer and consumer supporting the sustainable development of tea industry respectively, and then generated the initial strategy value of the other two participants. As shown in Figure 4, the dynamic evolution game of the three participants at equilibrium point $E_2(0, 1, 0)$ will finally reach a stable state, that is, the government does not support the sustainable development of tea industry, and the enterprises/farmers adopt the technology of tea sustainable production, and consumers do not choose the sustainable consumption behaviour of tea. In this state, when the probability of government supporting the sustainable development of tea industry remains unchanged, the speed of government evolutionary game tends to be stable varies with the different probability of enterprises/farmers and consumers supporting the sustainable development of tea industry. When consumers choose the sustainable consumption behaviour of tea, the speed of the evolutionary game tends to be stable also varies with the probability of the government and enterprises/farmers supporting the sustainable development of tea industry. Compared with the above conclusions, the evolutionary game strategy of enterprises/farmers tends to be stable faster, and the difference is not significant. In addition, when $x = 0.5$, $y = 0.5$ and $z = 0.5$, the evolutionary game strategy tends to be stable faster than the government and consumers.

Figure 4 The evolutionary path of equilibrium point $E_2(0, 1, 0)$, (a) the evolutionary game of government, (b) the evolutionary game of enterprises/farmers, (c) The evolutionary game of consumers, (d) the evolution of the tripartite game strategy



(a)



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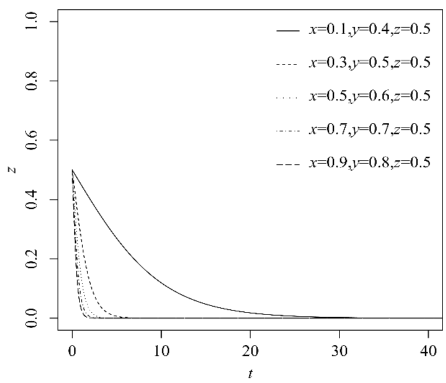
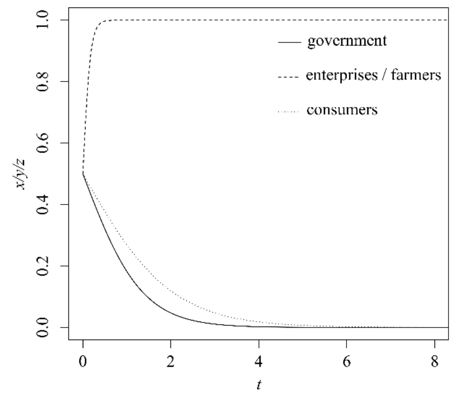


(c)

Figure 4 The evolutionary path of equilibrium point $E_2(0, 1, 0)$, (a) the evolutionary game of government, (b) the evolutionary game of enterprises/farmers, (c) The evolutionary game of consumers, (d) the evolution of the tripartite game strategy (continued)



(d)

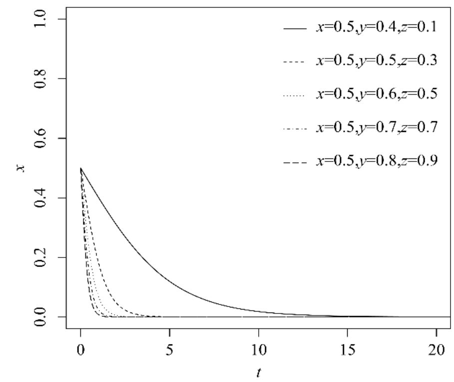
5.2 Equilibrium point $E_5(0, 1, 1)$

The dynamic evolution path of the tripartite evolutionary game of the government, enterprises/farmers and consumers at the equilibrium point $E_5(0, 1, 1)$ is shown in Figure 5. In the long run, the government will tend not to support the sustainable development of tea industry, the evolutionary game strategy of enterprises/farmers will tend to adopt the sustainable production technology of tea, and consumers will tend to choose the sustainable consumption behaviour of tea. The speed of the government dynamic evolution tends to be stable is related to the choice of game strategies of enterprises/farmers and consumers. In addition, taking $x = 0.5$, $y = 0.5$ and $z = 0.5$, the research shows that the rate of enterprises/farmers and consumers tending to stable state is faster than that of the government tending to stable state, followed by the dynamic evolution speed of consumers, and the dynamic evolution speed of the government is the slowest.

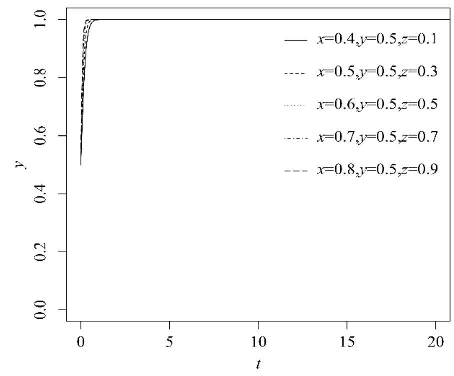
5.3 Equilibrium point $E_7(1, 1, 0)$

As shown in Figure 6, the dynamic evolutionary game between government and enterprises/farmers at equilibrium point $E_7(1, 1, 0)$ will tend to support the sustainable development of tea industry in the long run, that is, the former tends to support the sustainable development of tea industry in the long run, while the latter tends to adopt the sustainable production technology of tea in the long run, and both of them can quickly reach a stable state in a short time. Compared with the game, the dynamic evolution game process of consumers is relatively slow, and it tends to choose no sustainable consumption behaviour of tea for a long time. The dynamic evolution of the game strategy of the three participants in Figure 6 can also confirm the above conclusion. When $x = 0.5$, $y = 0.5$ and $z = 0.5$, the dynamic evolutionary game between enterprises/farmers and government tends to be stable faster than that of consumers.

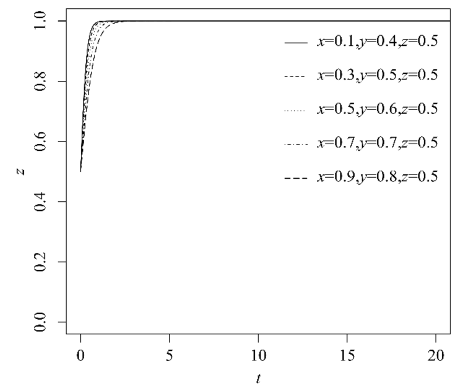
Figure 5 The evolutionary path of equilibrium point $E_5(0, 1, 1)$, (a) the evolutionary game of government, (b) the evolutionary game of enterprises/farmers, (c) The evolutionary game of consumers, (d) the evolution of the tripartite game strategy



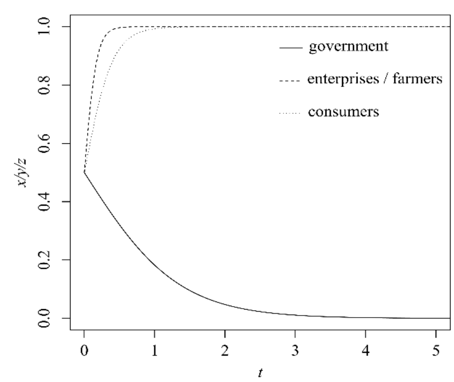
(a)



(b)



(c)



(d)

Figure 6 The evolutionary path of equilibrium point $E_7(1, 1, 0)$, (a) the evolutionary game of government, (b) the evolutionary game of enterprises/farmers, (c) the evolutionary game of consumers, (d) the evolution of the tripartite game strategy

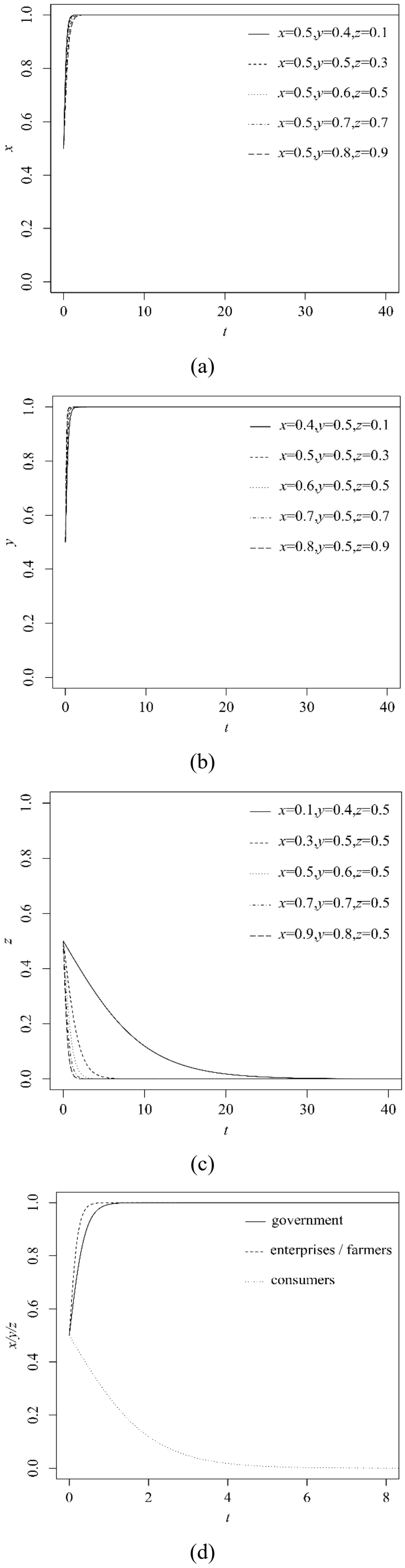
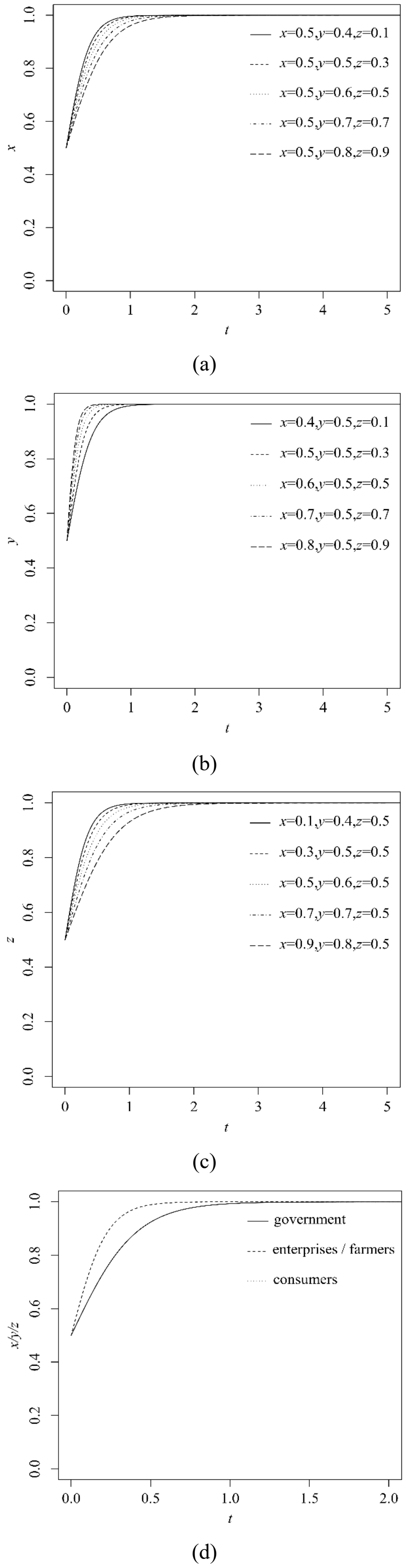


Figure 7 The evolutionary path of equilibrium point $E_8(1, 1, 1)$, (a) the evolutionary game of government, (b) the evolutionary game of enterprises/farmers, (c) the evolutionary game of consumers, (d) the evolution of the tripartite game strategy



5.4 Equilibrium point $E_8(1, 1, 1)$

As shown in Figure 7, in the long run, the dynamic evolutionary game among government, enterprises/farmers and consumers at equilibrium point $E_8(1, 1, 1)$ tends to support the sustainable development of tea industry, that is, the government supports the sustainable development of tea industry, enterprises/farmers adopt the sustainable production technology of tea, and consumers choose the sustainable consumption behaviour of tea. In general, the dynamic evolutionary game of enterprises/farmers tends to be stable faster than that of government and consumers, that is, the dynamic evolutionary game curve of the former is steeper. In addition, when $x = 0.5$, $y = 0.5$ and $z = 0.5$, the dynamic evolutionary game speed of enterprises/farmers is the fastest, and the dynamic evolutionary game curves of government and consumers almost coincide.

In conclusion, the dynamic evolution game of the government, enterprise/farmer and consumer participants tends to be stable at equilibrium points $E_2(0, 1, 0)$, $E_5(0,1,1)$, $E_7(1, 1, 0)$ and $E_8(1, 1, 1)$ and the dynamic evolution speed is different. As the sustainable development of tea industry is closely related to the complex strategy choice of the government, enterprises/farmers and consumers, and sustainable development has become an important path for the development of tea industry, we mainly consider the constraints of equilibrium point $E_8(1, 1, 1)$.

As mentioned above, if the dynamic evolutionary game of three participants wants to be stable in the long run at the equilibrium $E_8(1, 1, 1)$, that is, if the equilibrium $E_8(1, 1, 1)$ wants to be asymptotically stable, it needs to satisfy $R_g - C_g - (R_{gg} - C_{gg}) > S_g - F_g$, $R_{ee} - C_{ee} - (R_e - C_e) < S_g + P_c + F_e + N_c$ and $R_c - C_c - (R_{cc} - C_{cc}) > P_c$ at the same time. That is, the difference of benefits and costs of government support for sustainable development of tea industry is usually higher than that of non-support. The potential loss that the government chooses not to support the sustainable development of tea industry is usually greater than the government's subsidy to the compliance behaviour of enterprises/farmers. The difference between benefits and costs of consumers choosing sustainable consumption behaviour of tea is usually higher than that of not choosing, and the difference between the above two differences is usually greater than the positive feedback of consumers to enterprises/farmers. Under the above constraints, the government, enterprises/farmers and consumers will tend to support the sustainable development of tea industry. Therefore, the conclusion can provide a theoretical basis for the policy formulation and implementation of tea industry related participants, and then effectively promote the sustainable development of tea industry.

6 Conclusions and discussion

Through the derivation and numerical simulation of the tripartite evolutionary game of the government, enterprises/farmers and consumers in the sustainable development of tea industry, this research analyses the gradual stability of the strategy in the dynamic evolution. The conclusion shows that the evolutionary strategies of the government, enterprises/farmers and consumers are closely related and interact with each other, that is, the strategies of any participant will be affected by other participants at the same time. In addition, in each equilibrium point, when the corresponding constraints are satisfied, there are four ESS: $E_2(0, 1, 0)$, $E_5(0, 1, 1)$, $E_7(1, 1, 0)$ and $E_8(1, 1, 1)$. Therefore, in order to support the sustainable development of tea industry by the government, enterprises/farmers and consumers at the same time, it is necessary to enhance the credibility loss of the government not supporting the sustainable development of tea industry, appropriately enhance the government's financial subsidies and tax incentives for enterprises/farmers to adopt sustainable production technologies, and increase the punishment for enterprises/farmers' violations.

The above conclusions are closely related to the hypothesis of this paper. Specifically, in the sustainable development of the tea industry, each participant will be affected by other participants in the behavioural decision-making process, which reflects the contents of Hypothesis 1 and Hypothesis 2. Additionally, if the government does not support the sustainable development of the tea industry, its credibility will be severely compromised, which reflects the content of Hypothesis 3. Furthermore, adopting encouraging policies or restrictive measures on the tea production behaviour of enterprises/farmers by the government and consumers can effectively improve the sustainable development of the tea industry, which is closely linked to Hypothesis 4 and Hypothesis 5. In short, these conclusions are crucial to the sustainable development of China's tea industry, especially the regulators of the development of the tea industry, as well as those who overuse pesticides and fertilisers. These conclusions also provide some references for international tea trade. In addition, consumers can also find some connections in the conclusions. For instance, consumers should pay more attention to the safety and health attributes of tea in the process of tea consumption, and effectively use economic benefits to guide and restrict the behaviours of producers.

Combined with the current situation of sustainable development of China's tea industry, the following targeted policy suggestions are put forward. First, the government should guide the situation and adjust measures to local conditions, develop the tea industry scientifically, promote the research and development of infrastructure construction and public technology of tea production, provide public service products and formulate relevant institutional measures for the sustainable development of the tea industry, increase the policy support for the investment in the tea industry, and promote the effective cooperation and optimal allocation of various resources. Second, enterprises and farmers should make full use of various internal resources and technologies, increase the ecological management of tea planting environment and the monitoring of agricultural environment by internet of things, master systematic tea planting and production knowledge, replace traditional experience production with scientific theoretical knowledge, strengthen the study and use of modern production technology, change the mode of tea planting and production management, and change the backward face of tea production. Third, because consumers can make positive and negative feedback to enterprises and farmers in the competitive tea market through specific consumption behaviour, enterprises and farmers need to adjust tea production according to the situation of consumer market and provide tea products to meet the needs of consumers.

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