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Tripartite evolutionary game study on decision-making behavior of cooperative development of agricultural operation subjects

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Abstract: How to give full play to the driving role of the new agricultural business entities to the small farmers, guide the small farmers into the modern agricultural development track, and realize the coordinated development of the agricultural business entities has become an urgent problem to be solved in the construction process of the new agricultural operation system. Therefore, based on evolutionary game theory, this paper constructed a three-party evolutionary game model of "government-new agricultural business entities - small farmers", and got the evolutionary and stable strategy of the three in different situations. And it studied how to promote the coordinated development of the three by Matlab numerical simulation. The results of the game show that: first of all, the decisions of the government, small farmers and new agricultural business entities are all influenced by the government itself and the other two parties, especially the government and small farmers' behavior choice is more sensitive. Second, if the three parties do not share the same direction of action, a series of guiding and supporting policies can still form a sound situation of common governance among the three parties. However, the decision-making of government guidance process has nothing to do with tax revenue and the rewards and punishments of the superior government. The guiding cost and loss of public credibility are the key factors that affect the choice of government behavior. Finally, as rational people, farmers will choose the strategy of "cooperation" only when they are satisfied that their income when participating in cooperation is higher than their own income when not participating in cooperation.

Keywords: Agricultural modernization, evolutionary stable strategy, replicator dynamics, new agricultural business entities, small farmers

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1. Introduction

Since the beginning of the new century, the central Committee of the Communist Party of China has arranged the rural revitalization as one of the important tasks to realize the national rejuvenation. In 2021, the "No. 1 Document" of the CPC Central Committee clearly stated that "by 2025, agricultural and rural modernization will make important progress, and areas with conditions will take the lead in basically realizing agricultural modernization." However, China's agriculture is mainly manifested by smallholder operation based on household contract responsibility system, which is generally small in scale and loosely organized, resulting in low land productivity and labor productivity [1]. For this situation, a new agricultural management intensive, large-scale, scientific business entity has become an important force in developing agriculture modernization [2], vigorously foster the subject of developing new type of agricultural business entities has become the inevitable requirement to carry out agricultural modernization, to become the solution quality is not high, the agricultural development in our country rural development slowly, farmers' income is slow the key breakthrough. Therefore, the CPC Central Committee and The State Council attach great importance to the development of modern

agriculture, and have made arrangements for the construction of agricultural modernization in important documents for many times: the construction and promotion of agricultural modernization cannot be separated from the driving and support of new agricultural business entities. The central committee of the communist party of China in 2014, no. 1 document "about comprehensively deepen rural reform to accelerate agricultural modernization of several opinions of the clear requirements for the first time" the support the development of agricultural management main body, encourage the development of various forms of rural cooperatives, mixed sector of the agricultural industrialization leading enterprises, actively carry out voluntary register family farm work"; In 2016, the CPC Central Committee listed "establishing and improving the policy system of new agricultural operating entities, supporting and developing various forms of new agricultural operating entities, promoting the development of new business models such as agri-business alliance" in the outline of the 13th Five-Year Plan. And in the "Several Opinions on The Implementation of the New Concept of Development to Speed up agricultural modernization and achieve the goal of all-round well-off" directly pointed out that "support the new agricultural business entities and the new agricultural service subjects to become the backbone of the construction of modern agriculture"; "Cultivating new agricultural business entities engaged in agricultural production and service is a major strategy related to China's agricultural modernization." Obviously, vigorously developing new agricultural business entities has become the only way of China's agricultural modernization process.

Under all guide incentive policies of the state, the new agricultural business entities in the process of industrialization and urbanization, the rapid development, in promoting China's agricultural production increase [3,4], the rural population employment, the improvement of the economic welfare of farm households [5] effect is remarkable, part of solve the low efficiency of small-scale peasant economy [6] and docking with the market's problems. New agricultural business entities in China since 2013, however, after ten years development period of explosive growth, advanced management system, in front of the "small farmers" power of the basic agricultural situation appeared over large, rigid cost and risk be innovated, farmers cooperatives falsified and alienation phenomenon is serious, agricultural enterprises from such outstanding problems as farmers tendency obvious [7]. More seriously, the emergence of a large number of new agricultural business entities has brought new problems to the production and development of small farmers and the construction of agricultural operating system: all kinds of new agricultural business entities are seriously "alienated", in the development of "large farmers eat small farmers", "elite capture" and other phenomena, squeezing the survival and profit space of small farmers; The rapid development of new agricultural business entities in the field of production has accelerated the transfer of agricultural land, intensified the differentiation of small-scale operation subjects, and produced obvious exclusion to small-scale farmers. The development of new agricultural business entities promotes the upgrading of agricultural value chain, raises the threshold of agricultural production, and makes it more difficult for small farmers to enter the market and a series of problems. How to solve the unbalanced and inadequate problems in the development of agricultural modernization has become the primary aspect that must be solved in the development process of agricultural business entities. To this end, the "No. 1 Document" of the CPC Central Committee in 2018 clearly pointed out that "we should promote the organic connection between the development of smallholder farmers and modern agriculture, give overall consideration to the cultivation of new agricultural business entities and support for smallholder farmers, and take targeted measures to bring smallholder production into the development track of modern agriculture". The High-quality Development Plan for New Agricultural Operating entities and Service Entities (2020-2022) emphasizes that "New agricultural business entities and service entities are closely related to small farmers and are the main force driving small farmers. We will accelerate the development of new types of agricultural business entities and service providers, and introduce small farmers into

the development of modern agriculture." In 2021, the No. 1 document of the CPC Central Committee pointed out that to promote the construction of a modern agricultural management system, "we should encourage the development of diversified and moderate scale operations. Develop and strengthen specialized and socialized agricultural service organizations, and introduce advanced and applicable varieties, inputs, technologies and equipment to small farmers ". Therefore, how to promote the coordinated development of new agricultural business entities and small farmers has become the focus of academic attention and a major research topic for the implementation of rural revitalization strategy in the new era.

In general, some domestic scholars have studied how to introduce small farmers into the development track of agricultural modernization mainly from aspects of the convergence mode between new agricultural business entities and small farmers [8,99], institutional path [10-12] and convergence carrier [13,14], and most of them adopt case study methods [15-18]. However, as the indispensable backbone of modern agriculture in China, the research on the coordinated development of new agricultural business entities and small farmers in China is very limited. Most of them only put forward some broad suggestions from a macro perspective, with few theoretical analysis and empirical tests. It is the core to understand the relationship between the new agricultural business entities and small farmers to analyze their behavior choices. Their action strategies are not immutable, but constantly evolving in the game. At present, Chinese scholars construct theoretical analysis framework for behavioral choice between new agricultural business entities and small farmers mainly from the perspective of cooperation willingness analysis [19,20], interest game study in land transfer [21,22], relationship embedding problem [23,24], and make empirical analysis by using empirical data and cases. However, there are few game studies on the behavior choice of the two in the process of agricultural modernization, and the hypothesis of rational economic man in the traditional game theory can not fully explain the behavior choice of farmers because of the low level of education and organization of Chinese farmers. Therefore, based on evolutionary game theory of bounded rationality hypothesis will affect the game subject to factors into a model, in view of system analysis of the behavior selection and evolution of the group process, compared with the traditional game theory is more suitable for the analysis of the behavior choice and decision-making process of the government, the new agricultural business entities and small farmers.

Evolutionary game theory is based on the assumption of bounded rationality. Each game subject maximizes its own interests by constantly learning and adjusting strategies, so as to achieve system stability. From the perspective of research, scholars at home and abroad have conducted in-depth exploration on external regulation [25,26], collaborative innovation [27,28] and policy making [29,30] by using evolutionary game. From the perspective of research content, evolutionary game is regarded as one of the important analytical methods in environmental governance [31], public opinion communication [32] and quality safety [33]. Among them with respect to the application of agricultural management main body related field, Liu Yong et al. (2019) constructed an evolutionary game model between farmers and new agricultural business entities, and demonstrated that new agricultural business entities have demonstration effect and relatively low marginal cost in promoting low-carbon technologies [34]. Tang Yifu et al. (2022) investigated the game equilibrium state of new agricultural business entities and financial institutions respectively with or without incentive and constraint mechanisms, and the results showed that different initial states had a significant impact on the game equilibrium state of new agricultural business entities and financial institutions [35]. He Qilong et al. (2021) in fair contribution and altruistic preferences respectively under the two scenarios to build more farmers evolutionary game model, they analyze risk probability, the environment, the raise share on farmer participation in rural environment management, the influence of

bounded rationality is put forward to improve farmers environmental protection consciousness, regional environmental governance, policy suggestions such as construction of funds from the government [36]. From the above results, it is not difficult to see that current studies mainly focus on the interaction between new agricultural business entities and small farmers and between farmers, without taking the government into consideration. However, China's agricultural modernization is a process in which farmers, the government, the market and the society participate together. The government's policy and institutional guarantee is an important factor to maintain the stability of the contractual relationship between the new agricultural business entities and small farmers [23]. As the implementer and supervisor of policies, local governments, it also plays a key role in the behavior choice of farmers and new agricultural business entities Since the founding of New China, the relationship between farmers and the state has evolved from personal attachment to equal cooperation [37]. The government can benefit farmers' cooperation and provide them with resources such as organizational resources, material resources and reputation [38]. In the interactive influence, the new agricultural business entities and small farmers as game participants will have an impact on the final income, and the government as the national macro policy maker and market regulator, will also play a pivotal role in promoting the new agricultural business entities to bring small farmers into the agricultural modernization road.

To sum up, in this paper, the government, the new agricultural business entities and small farmers are incorporated into an overall model for consideration, and the choice and influence of the interaction between the government, the new agricultural business entities and small farmers are deeply explored. In order to study the interaction and long-term strategy evolution of small farmers driven by local government's guiding behavior in the process of cultivating new agricultural business entities, a tripartite evolutionary game model was used to characterize the interaction between local government, new agricultural business entities and small farmers. Evolutionary game in three participants in the group of bounded rationality as the research object, using the dynamic analysis method for the inclusion of the various factors of affecting the behavior of participants in the model, and the system theory point of view to examine evolution trend, group behavior of local governments, the new agricultural business entities and the behavior of the small farmers choose how evolution has high applicability. It can well analyze the decision-making process of relevant stakeholders, and finally provide corresponding suggestions and references for the tripartite collaborative development of local government, new agricultural business entities and small farmers. Compared with the existing literature, the innovation of this paper is as follows: (1) Under the background of rural revitalization, based on the evolutionary game theory, this paper analyzes the game principle of the three main bodies of agricultural modernization in the modernization construction, and provides practical support for the policy design of local government; (2) Second, the new agricultural business entities and the problem of small farmers more focus on the case study research, logic, the article using the evolutionary game model, based on system dynamics simulation with lyapunov theorem and the assumption of bounded rationality, to establish "the government, new agricultural business entities, small farmers" evolutionary game model, analysis of the evolution of the steady state and the convergence condition of equilibrium, to find the optimal strategy of each subject in the process of agricultural modernization, prove the effectiveness of government supervision and guidance to bring small farmers into the modernization track, and expand the game analysis model of agricultural modernization.

2. Three-party game model of "government-new agricultural business entities-farmers"

2.1. Problem description

Due to the urgency and complexity of agricultural modernization, it is necessary to coordinate the cooperation of local government, farmers and other relevant stakeholders, considering the effective play of new agricultural business entities to small farmers and the coordinated development of agricultural operation subjects. Therefore, this paper considers that there are mainly three groups of governments, new agricultural business entities and farmers in the construction of agricultural modernization in specific areas. The three groups are bounded rational and large in scale. After a long period of interaction and behavior learning, the behavior decisions of each group will be stable in the system. Among them, the new agricultural business entities include professional large households, family farms, farmers' cooperatives, agricultural industrialization leading enterprises and other forms of agricultural scale business entities; The government includes the people's governments of provinces, autonomous regions and municipalities directly under the Central Government. In this paper, the government refers to the above groups and there is an integrated cooperation mode between the new agricultural business entities and small farmers, that is, the enterprise rents land, invests and operates fixed assets in production activities, and employs local farmers for labor. The farmers obtain wages and rental income according to the quantity and quality of their labor, forming an integrated operation [20].

2.2. Model assumptions

According to the actual situation, this paper makes the following assumptions for the evolutionary game model of "government-new agricultural business entities-farmers":

Hypothesis 1: Participants in the game are all bounded rational. The population size of the three groups in a specific region remained relatively stable, and the population size could be normalized to 1. At time t , the probability of local government group choosing guidance strategy is $x(t)$, and the probability of new agricultural business entities group and farmer group choosing cooperation strategy is $y(t)$ and $z(t)$ respectively, and meets $0 \le x(t) \le 1$, $0 \le y(t) \le 1$, $0 \le z(t) \le 1$.

Hypothesis 2: The local governments are participant 1, the new agricultural business entities are participant 2, and the farmers are participant 3. Local governments actively guide the coordinated development of new agricultural business entities and farmers by providing socialized services and punishing or encouraging them. The strategy set is $(g, \bar{g})$; The new type of agricultural business entities has two kinds of strategies: driving farmers or not. Driving farmers can be described as employing farmers and providing technical guidance services, etc., and their strategy set is $(e, \bar{e})$; In this paper, participation is defined as the cooperation of farmers through land transfer or employment by new agricultural business entities, while non-participation is defined as the self-sufficiency of small-scale farmers who do not participate in land transfer and agricultural division of labor, and their strategy is set as $(f, \bar{f})$.

Hypothesis 3: The local government taxes and fees charged in the part of new agricultural business entities T , provide social services and related guide will produce a certain implementation cost C_g , cultivating new type of agricultural business entities of local government and farmers into the agricultural modernization, the reward I_g will get from the superior government, on the contrary, will be a certain amount of fine P_g ($C_g < P_g$). If local governments choose not to guide cooperation between farmers and new agricultural business entities, they will lose credibility R . If all three choose cooperation, farmers of new agricultural business entities and small farmers will get incentives I_e and I_f from local government respectively.

Hypothesis 4: Assume that the land management proportions of new agricultural business entities and small farmers are α and $1-\alpha$ respectively.

Hypothesis 5: The unit land income of the new agricultural business entities is S_e, and the unit fixed cost is C_e. If the new agricultural business entities choose to drive farmers, they will invest in corresponding facilities and technologies, personnel training and other costs C_{ef}, and they are looking for farmers who are interested in cooperation with cost C_{es}. Meanwhile, if the local governments take strategy g and $\overline{f}$ farmers take strategy, the government will give a certain subsidy H to the new agricultural business entities, and the new agricultural business entities will carry out vicious competition on farmers in the market, and the loss caused to farmers is D.

Hypothesis 6: The unit land income of farmers for self-cultivation and self-sufficiency is S_f, and the corresponding cost C_f will be invested in cultivation. If you participate in the cooperation, you can not only get the income $Z(1-\alpha)$ of land transfer, but also get the wage W of labor, obviously $S_f < S_e$. The meanings of each parameter are shown in **Table 1**, and the value range of all parameters is greater than 0.

Table 1. Model Parameter Description

Parameter	Meaning of parameters
T	Taxes collected by local governments
C_g	The implementation cost of socialization services and related guidance.
I_g , P_g	Local governments are rewarded or punished ($C_g < P_g$)
R	Local governments do not guide farmers and the new agricultural business entities to lose credibility
α , $1-\alpha$	The area of land owned by the new agricultural business entities and farmers
S_e , C_e	Income and cost per unit area operation by new agricultural business entities
C_{ef}	The new agricultural business entities drives the cost of farmer's input
C_{es}	Cost of the new agricultural business entities looking for cooperative farmers
H	Subsidies given by local governments to the new agricultural business entities
S_f , C_f	Income and cost per unit area of farmers land management
D	Loss from the new agricultural business entities vicious competition
Z	Income per unit area of farmers land circulation
W	The wage of farmers
I_e , I_f	Incentives for new agricultural business entities and from local governments

2.3. Build an evolutionary game model

Under the guidance of the government, the new agricultural business entities and small farmers choose to participate in the cooperation of agricultural modernization, and the strategy is (g, e, f). The earnings of local government includes tax revenue T, superior government incentive I_g, minus guiding cost C_g and incentive to new agricultural business entities and small farmers $(I_e + I_f)$; The earnings of new agricultural business entities includes business profit $S_e - C_e$, local government incentive I_e, minus the technology cost and personnel training cost C_{ef} to drive the small farmers ; The earnings of smallholders is the sum of rental income $Z(1-\alpha)$, labor wage W and government incentives I_f. Similarly, in other strategies, the earnings of three-party game subjects are shown in **Table 2**.

Table 2. Payment matrix of three-party game

New agricultural business entities			Farmers	
			Cooperation	Noncooperation
			Z	$1-Z$
Local goverment	Cooperation X	Cooperation Y	(g, e, f)	$(g, e, \overline{f})$

Noncoopera-tion $1-X$		$T+I_g-C_g-I_e-I_f$ $S_e+I_e-C_e-C_{ef}$ $Z(1-\alpha)+W+I_f$	$T-C_g-H-P_g$ $(S_e-C_e)\alpha+H-C_{es}$ $(S_f-C_f)(1-\alpha)-D$
	Noncooperation $1-Y$	$(g,\bar{e},f)$ $T-C_g-P_g$ $(S_e-C_e)\alpha$ $(S_f-C_f)(1-\alpha)$	$(g,\bar{e},\bar{f})$ $T-C_g-P_g$ $(S_e-C_e)\alpha$ $(S_f-C_f)(1-\alpha)$
	Cooperation Y	$(\bar{g},e,f)$ $T+I_g-R$ $S_e-C_e-C_{ef}$ $Z(1-\alpha)+W$	$(\bar{g},e,\bar{f})$ $T-R-P_g$ $(S_e-C_e)\alpha-C_{es}$ $(S_f-C_f)(1-\alpha)-D$
	Noncooperation $1-Y$	$(\bar{g},\bar{e},f)$ $T-R-P_g$ $(S_e-C_e)\alpha$ $(S_f-C_f)(1-\alpha)$	$(\bar{g},\bar{e},\bar{f})$ $T-R-P_g$ $(S_e-C_e)\alpha$ $(S_f-C_f)(1-\alpha)$

3. Analysis of equilibrium results of tripartite evolutionary game

3.1. Equilibrium point of evolutionary process

The expected income of the government choosing to guide the new agricultural business entities is:

$$U_g = yz(H+P_g+I_g-I_e-I_f)-yH+T-C_g-P_g$$

The expected income of the government choosing not to guide the new agricultural business entities is:

$$U_{\bar{g}} = yz(P_g+I_g)+T-P_g-R$$

The average expected return for the government is:

$$\overline{U}_g = xyz(H-I_e-I_f)+yz(P_g+I_g)-xyH-x(C_g-R)+T-R-P_g$$

Similarly, a 3d copy dynamic equation system (I) can be obtained:

$$\begin{cases} F(x)=\dot{x}=x(1-x)[yz(H-I_e-I_f)-yH+R-C_g]=0 \\ F(y)=\dot{y}=y(1-y)\{z[(S_e-C_e)(1-\alpha)+C_{es}-C_{ef}]+xz(I_e-H)+xH-C_{es}\}=0 \\ F(z)=\dot{z}=z(1-z)y\{[Z-(S_f-C_f)](1-\alpha)+D+W+xI_f\}=0 \end{cases}$$

To simplify the above equation, let $A=H-I_e-I_f$, $B=(S_e-C_e)(1-\alpha)+C_{es}-C_{ef}$, $C=[Z-(S_f-C_f)](1-\alpha)$.

The equilibrium point of the 3d replication dynamic equation system (I) is divided into three population pure strategy, two population pure strategy, single population pure strategy and mixed strategy. When $x=0$ or 1, $y=0$ or 1, $z=0$ or 1, there are always $\dot{x}=\dot{y}=\dot{z}=0$. Therefore, there are eight three-population pure strategy equilibrium points in the system, which are $E_1=(0,0,0)$, $E_2=(0,1,0)$, $E_3=(0,0,1)$, $E_4=(1,0,0)$, $E_5=(1,1,0)$, $E_6=(1,1,1)$, $E_7=(0,1,1)$, $E_8=(1,0,1)$ respectively; When $x=0$ or 1, $y=0$ and $0<z<1$ there are two equilibrium points $E_9=(0,0,z_9)$ and $E_{10}=(0,0,z_{10})$ of the pure strategy adopted by the two populations make $\dot{x}=\dot{y}=\dot{z}=0$; In the case of single population adopting pure strategy, when $y=1$, $0<x<1$ and $0<z<1$, if $yz(H-I_e-I_f)-yH+R-C_g=0$ and $yz(H-I_e-I_f)-yH+R-C_g=0$, also have

$\dot{x} = \dot{y} = \dot{z} = 0$. Then it can be seen that if $0 < \frac{-I_f}{[Z-(S_f - C_f)](1-\alpha)+D+W} < 1$ and $0 < \frac{H + C_g + R}{H - I_e - I_f} < 1$ are satisfied, $E_{11} = (\frac{-I_f}{[Z-(S_f - C_f)](1-\alpha)+D+W}, 1, \frac{H + C_g + R}{H - I_e - I_f})$ is the equilibrium point. Similarly, there are two single population pure strategy equilibrium points $E_{12} = (\frac{C_{es}}{H}, \frac{R - C_g}{H}, 0)$ and $E_{13} = (\frac{-I_e}{(S_e - C_e)(1-\alpha) - C_{ef}}, \frac{R - C_g}{I_e + I_f}, 1)$. In addition, there may be mixed strategy points where all three populations do not adopt pure strategy $E_{14} = (x^*, y^*, z^*)$.

When $yz(H - I_e - I_f) - yH + R - C_g = 0$, $z(S_e - C_e)(1-\alpha) + C_{es} - C_{ef} + xz(I_e - H) + xH - C_{es} = 0$, and $[Z-(S_f - C_f)]\ (1-\alpha) + D + W + xI_f = 0$ are satisfied, $\dot{x} = \dot{y} = \dot{z} = 0$. Therefore, $E_{14} = (x^*, y^*, z^*)$ is the equilibrium point of the system, where,

$$x^* = \frac{(S_f - C_f - Z)(1-\alpha) - D - W}{I_f},$$

$$y^* = \frac{[B \cdot I_f + (C + D + W) \cdot (I_e - H)] \cdot (C_g - R)}{[C_{ef} - D - W - (S_e - C_e)(1-\alpha)] I_f \cdot H - C_{es} \cdot I_f \cdot (I_e + I_f)},$$

$$z^* = \frac{C_{es} \cdot I_f + (C + D + W)H}{B \cdot I_f - (C + D + W)(I_e - H)} . \ E_{14} = (x^*, y^*, z^*)$$

is the equilibrium point of the system (I) under conditions $0 < x^*, y^*, z^* < 1$, $x^* \neq \frac{C_{ef} - C_{es} - (S_e - C_e)(1-\alpha)}{I_e - H}$ and $z^* \neq \frac{H}{H - I_e - I_f}$.

3.2. Stability analysis of equilibrium point

By solving the replicating dynamics equation, the equilibrium point of the system is not necessarily stable, so according to the lyapunov's stability theory, the system is asymptotically stable at equilibrium characteristics can be through the analysis of the local stability of the Jacobian matrix of judgment, namely the jacobian matrix eigenvalues are all less than zero is the sufficient and necessary conditions for the asymptotically stable system. The Jacobian matrix of the 3d dynamical system is shown below.

$$\begin{pmatrix} (1-2x)(yzA - yH + R - C_g) & x(1-x)(zA - H) & x(1-x)yA \\ y(1-y)[H + z(I_e - H)] & (1-2y)[zB + xz(I_e - H) + xH - C_{es}] & y(1-y)[B + x(I_e - H)] \\ z(1-z)yI_f & z(1-z)(C + D + W + xI_f) & (1-2z)y(C + D + W + xI_f) \end{pmatrix}$$

By substituting 14 local equilibrium points into the Jacobian matrix, three eigenvalues λ_1, λ_2 and λ_3 corresponding to each equilibrium point can be obtained, according to which the asymptotic stability of each equilibrium point can be judged.

According to Lyaplov stability condition, if all eigenvalues in the Jacobian matrix satisfying the equilibrium point have negative real parts, then the equilibrium point is a stable point, and the behavior choice of the game subject at this point will be stable after a long period of learning and influence. If the eigenvalues are all negative under certain conditions, the equilibrium point finally reaches a stable state under certain conditions. Taking $E_2 = (0,1,0)$ as an example, the jacobian matrix J of the 3d dynamic system at the equilibrium point $E_2 = (0,1,0)$ is discussed as follows.

$$J=\begin{pmatrix} R-H-C_{\mathrm{g}} & 0 & 0 \\ 0 & C_{es} & 0 \\ 0 & 0 & C+D+W \end{pmatrix}$$

At this point, the eigenvalue of J is $\lambda_1=R-H-C_{\mathrm{g}}$, $\lambda_2=C_{es}$ and $\lambda_3=C+D+W$. If λ_1, λ_2, and λ_3 are all less than 0, then $E_2=(0,1,0)$ is asymptotically stable. Obviously, the eigenvalue $\lambda_2=C_{es}>0$ of $E_2=(0,1,0)$ does not meet the Lyaplov stability condition, so $E_2=(0,1,0)$ is not a stable point. Similarly, the asymptotic stability conditions of the 3d dynamic system at the remaining 13 equilibrium points can be obtained, as shown in **Table 3** and **Table 4**. The eigenvalues of jacobian matrix corresponding to E_5, E_6 and E_7 equilibria may be positive or negative, that is, under certain conditions, the three eigenvalues are negative, and E_5, E_6 and E_7 meet the stability conditions ①, ② and ③ respectively, then the equilibrium point is stable. In addition, the eigenvalues of other equilibrium points are all positive or zero. Therefore, only E_5, E_6 and E_7, which may be stable points, exist in the 3d replica dynamic equation system, and the other 11 equilibrium points are unstable.

Table 3. Equilibrium point and eigenvalue of evolutionary game

Equilibrium point	λ_1	λ_2	λ_3	Asymptotic stability
E_1	$R-C_g$	$-C_{es}$	0	Instability
E_2	$R-C_g-H$	C_{es}	$C+D+W$	Instability
E_3	$R-C_g$	$B-C_{es}$	0	Instability
E_4	C_g-R	$H-C_{es}$	0	Instability
E_5	C_g+H-R	$C_{es}-H$	$C+D+W+I_f$	Condition①
E_6	$C_g+H-R-A$	$C_{es}-B-I_e$	$-(C+D+W+I_f)$	Condition②
E_7	$-(C_g+H-R-A)$	$C_{es}-B$	$-(C+D+W)$	Condition③
E_8	C_g-R	$B+I_e-C_{es}$	0	Instability
E_9	$R-C_g$	$z_9\cdot B-C_{es}$	0	Instability
E_{10}	C_g-R	$z_{10}\cdot(B+I_e-H)-H-C_{es}$	0	Instability
E_{11}	Δ_1	Δ_2	$-\Delta_2$	Instability
E_{12}	Δ_3	Δ_4	$-\Delta_4$	Instability
E_{13}	0	Δ_5	Δ_6	Instability
E_{14}	0	Δ_7	Δ_8	Instability

Table 4. Equilibrium stability conditions

Equilibrium point	Stability condition	Number
E_5	$C_g+H-R<0, C_{es}-H<0, C+D+W+I_f<0$	①
E_6	$C_g+H-R-A<0, C_{es}-B-I_e<0, -(C+D+W+I_f)<0$	②
E_7	$-(C_g+H-R-A)<0, C_{es}-B<0, -(C+D+W)<0$	③

4. Scenario analysis of evolution results

According to the equilibrium point analysis and local stability analysis of the above evolutionary model, we can know the set of strategies owned by the government, the new agricultural business entities and the farmers and the possible evolutionary equilibrium and stability strategies in the coordinated development of agricultural modernization. In this evolutionary game model, only when the following conditions are met at the same time can the evolutionary stability strategies of the government, new agricultural business entities and small farmers be obtained: $\begin{cases} F(x)=0 \\ F'(x)<0 \end{cases}$, $\begin{cases} F(y)=0 \\ F'(y)<0 \end{cases}$, $\begin{cases} F(z)=0 \\ F'(z)<0 \end{cases}$.

For the government, when $yz(H-I_e-I_f)-yH+R-C_g<0$, ESS will stabilize at $x=0$ due to $F(x)=0$ and $F'(x)<0$; when $yz(H-I_e-I_f)-yH+R-C_g>0$, ESS stabilizes at $x=1$; Similarly, the conditional inequality of the final stable strategy set of the new agricultural business entities and the small farmers can be obtained. Considering that the system evolution has multiple and complex paths, this paper discusses the evolution process of the three-party game respectively based on the set of strategies with three possible stable points, namely, the three parties jointly promote cooperation, farmers not participating in cooperation, and the government not participating in cooperation. It points out whether the equilibrium point exists and is stable in the system under different conditions. Furthermore, the deterministic and uncertain factors affecting the selection of the subjects of the game are analyzed, and the process of the evolutionary equilibrium of the subjects of the game and the final equilibrium result are deduced by using the phase diagram and MATLAB software.

4.1. Scenario 1: The three parties jointly promote cooperation

It can be seen from **Table 4** that in order to achieve the ideal state of three-party coordinated development of the system, the system needs to be stable at the equilibrium point $E_6=(1,1,1)$, and condition ②,

$$\begin{aligned}&C_g+I_e+I_f-R<0,\\&(C_{ef}-I_e)-(S_e-C_e)(1-\alpha)<0,\\&[(S_f-C_f)(1-\alpha)-D]-[W+I_f+Z(1-\alpha)]<0\end{aligned}$$

At this point, the reputation loss of the local government is greater than the sum of the guiding cost, the new agricultural business entities and the incentive expenditure of small farmers, so the local government will choose to guide the new agricultural business entities and small farmers to participate in agricultural modernization. Secondly, for the new agricultural business entities, the cost of guiding small farmers to participate in agricultural modernization is less than the earnings and government reward, so the new agricultural business entities will make the strategic choice of "cooperation". Finally, the sum of land transfer rental income, wages and local material rewards obtained by small farmers is greater than the earnings of self-sufficiency. After long-term selection game, small farmers will eventually choose to "cooperate" with new agricultural business entities.

The following phase diagram is used to verify the stability of evolution trajectory of government, new agricultural business entities and farmers. Based on existing research and the actual situation, the parameters are set to $C_g=4$, $R=8$, $\alpha=0.15$, $S_e=15$, $C_e=5$, $C_{ef}=4$, $I_e=2$, $S_f=6$, $C_f=2$, $D=3$, $Z=2$, $W=4$, $I_f=1$, $C_{es}=1$, $H=2$.

This moment, $F'(x)=(1-2x)(-yz-2y+4)$, $F'(y)=(1-2y)(5.5z+2xH-1)$, $F'(z)=(1-2z)y(5.3+x)$.

According to the rules, we can characterize the phase diagrams of government, new agricultural business entities and small farmers respectively, as shown in **Figure 1**(a), (b) and (c). Among them, due to $x,y,z\in[0,1]$, there are obviously $-yz-2y+4>0$.

And $5.3+x>0$, so the final evolutionary stability strategies of the government and small farmers are $x=1$ and $z=1$ respectively. For the new agricultural business entities, when the government and small farmers choose the cooperation strategy with a small probability, the equilibrium points are below the plane $5.5z+2x-1=0$, and $y=0$ is the stable strategy of the new agricultural business entities. However, when the equilibrium points move above the plane, $y=1$ is the ultimate evolutionarily stable strategy. Because the government and small farmers will continue to cooperate in a long time ($x\to1, z\to1$), the points under the plane will continue to move outward along the *x* axis and upward along the *z* axis, and eventually the equilibrium point will be stabilized above the plane.

Therefore, after long-term learning and repeated selection, the new agricultural business entities will stabilize at $y=1$, that is, the strategy of participating in cooperation. Thus, we have obtained the optimal evolution state pursued in this paper, that is, the set of strategies in which the government, new agricultural business entities and farmers all participate in the cooperation (g,e,f).

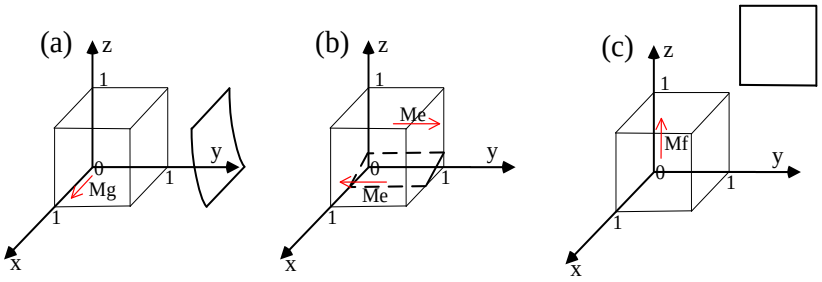

Figure 1. Scenario 1: Phase diagram of government, new agricultural business entities and small farmers

Matlab simulation tool is used to conduct numerical experimental analysis on the above evolutionary game model, and the numerical analysis results are shown in **Figure 2**. $E_6=(1,1,1)$ is the ESS of system (I), and E_5 and E_7 are not stable points according to ESS determination rules and stability conditions in **Table 4**. This suggests that, in the government, the new agricultural business entities, farmers to participate in the act of modernization of the coordinated development of agricultural modernization, as long as effective constraint mechanism, makes the government, the new agricultural business entities, small farmers can gain real benefits in their own game, then choose three positive participation in agricultural modernization strategy set will reach a stable equilibrium, then it will improve the quality of agricultural modernization, accelerate the process of agricultural modernization, and the system will enter a stable and virtuous cycle stage.

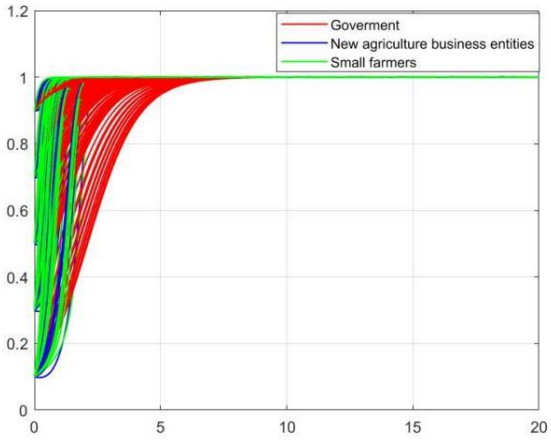

Figure 2. Two-dimensional equilibrium diagram of E6 equilibrium point

4.2. Scenario 2: Farmers do not participate in cooperation

Similarly, if farmers do not participate in the cooperation and the government and new agricultural business entities choose to participate in agricultural modernization, that is, $E_5(1,1,0)$ is the stable point when condition ① is met. Since farmers do not participate in the cooperation while the new agricultural business entities are willing to participate in the cooperation, there are government subsidies and search costs of the new agricultural business entities, and parameter values $H=2$ and $C_{es}=1$ are set. At the same time, to reduce farmers' land rental income, wage, government incentives, vicious competition

from new agricultural business entities, and increase farmers' earnings from independent operation, the parameter values are respectively adjusted to $D=0.5$, $Z=0.5$, $W=0.3$, $I_f=0.2$, $S_f=8$, and the values of other parameters are the same as scenario 1.

We can depict the phase diagram of the evolutionary equilibrium of government, new agricultural operating subjects and small farmers in scenario 2: when farmers do not participate in cooperation, as shown in **Figure 3**(a), **Figure 3** (b) and **Figure 3** (c) respectively. By comparing the phase diagram of the three-party game subjects in scenario 1, it can be seen that the government's equilibrium strategy is still $x=1$, while the phase diagram of small farmers has changed significantly, and $z=0$ is the final equilibrium strategy of small farmers now. For the new agricultural business entities, when the government or small farmers choose the cooperation strategy with a small probability, the equilibrium points are under the plane $5.5z+2x-1=0$, and $y=0$ is the equilibrium strategy of the new agricultural operation subjects. However, when the equilibrium points move above the plane, $y=1$ is the final evolutionarily stable strategy. As the government continues to follow the cooperative strategy and small farmers continue to follow the non-cooperative strategy $(x\to 1,\ z\to 0)$, although the equilibrium points always move downward along the z axis, it will continue to move outward along the x axis and eventually remain above the plane. Therefore, the new agricultural business entities will eventually stabilize at $y=1$, that is, the strategy of participating in cooperation. Thus, a stable strategy (guidance, cooperation, non- cooperation) is formed.

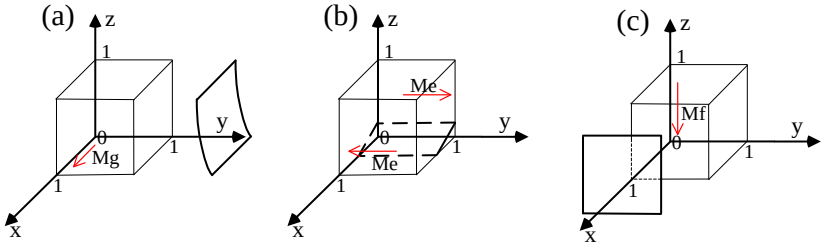

Figure 3. Phase diagram of government, new agricultural business entities and small farmers

The numerical analysis results of each game subject in scenario 2 are shown in **Figure 4**.

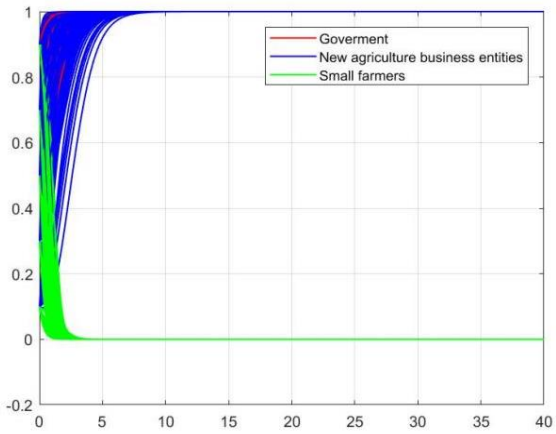

Figure 4. Two-dimensional equilibrium diagram of E5 equilibrium point

At this time, there is only one ESS, namely $E_5(1,1,0)$, in system (I). By comparing condition ②, it can be seen that although the choice decision judgment inequalities of the

government and the new agricultural business entities have changed, both the government and the new agricultural business entities will choose the behavior mode of guiding cooperation as long as the government's subsidies to the new agricultural business entities is increased in a certain proportion to make up for the search cost of the new agricultural business entities. From the perspective of farmers, the reduction of wages, rental income, competition losses and government incentives will reduce the profits of farmers participating in agricultural modernization. If the comprehensive impact is not as good as the benefits brought by independent operation, farmers will choose not to participate in agricultural modernization and continue to maintain the agricultural production mode of independent operation.

4.3. Scenario 3: Government does not participate in cooperation

The government does not participate in the cooperation, that is, the equilibrium point $E_7 = (0,1,1)$ is required to be the *ESS* of the system under certain conditions. According to the stability conditions in **Table 4**, the government's guidance cost and material incentive expenditure are increased, while the government's reputation loss is reduced. The parameter values are respectively adjusted to $C_g = 6$, $R = 4$, $I_e = 4$ and $I_f = 2$, and the values of other parameters are the same as scenario 1.

By comparing the phase diagram of three-party cooperation with scenario 1, it can be seen that in scenario 3, only the phase diagram of small farmers does not change significantly, and the phase diagram of government, new agricultural operation subjects and small farmers are **Figure 5** (a), **Figure 5** (b), **Figure 5** (c) respectively. Among them, obviously, $z = 1$ is the ultimate evolutionary stability strategy of small farmers. For the new agricultural business entities, the equilibrium points will move along the z axis and eventually be above the surface $5.5z + 2xz + 2x - 1 = 0$, as the small farmers tend to cooperate with each other ($z \to 1$). Therefore, $y = 1$ is the evolutionary stable strategy of the new agricultural business entities. According to phase diagram in the government, as a result of new agricultural business entities and small farmers tend to be cooperative strategy ($y \to 1, z \to 1$), the equilibrium points will continue to move upward with the z axis, y axis to the right. Therefore, stable equilibrium will finally, on the right side surface $4yz + 2y - 2 = 0$. After a long period of study, namely, the government will choose to "no guidance" strategy, and form a stable set of policies -- (No guidance, Cooperate, Cooperate).

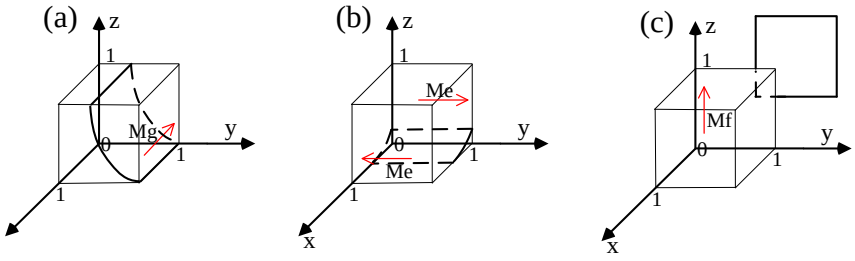

Figure 5. Scenario 3: Phase diagram of government, new agricultural business entities and small farmers

The numerical analysis results of the progressive stable evolution trajectory of the policy set (No guidance, Cooperation, Cooperation) are shown in **Figure 6**, where the *ESS* of system (I) is $E_7(0,1,1)$. This indicates that reducing the government's reputation loss while increasing the government's guiding cost and incentive expenditure, the evolution scenario will change from tripartite cooperation to government not guiding agricultural modernization, and both new agricultural business entities and small farmers will choose the cooperative strategy.

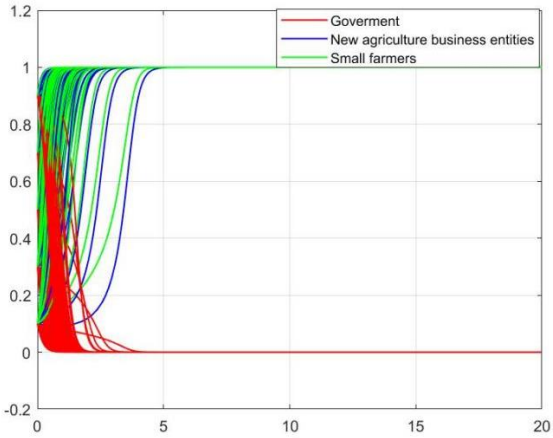

Figure 6. Two-dimensional equilibrium diagram of E7 equilibrium point

4.4. Scenario synthesis analysis

According to the result of evolutionary game of the tripartite equilibrium analysis, the system exists $E_5(1,1,0)$, $E_6(1,1,1)$ and $E_7(0,1,1)$ three balance, when meet certain conditions, the evolution of the corresponding to three different scenarios, each situation there is only a stable point, finally evolved result depends largely on the initial state of three kinds of species and their incentive and constraint relation. It can be seen from the change of scenario from tripartite cooperation to non-participation of farmers in cooperation that if the market squeeze of new agricultural business entities on non-participation of farmers is increased and the wages, rental income and government incentives of farmers are increased, farmers' participation in agricultural modernization will be better promoted. Similarly, it can be seen that reducing the cost of government guidance, subsidies and government reward and increasing the loss of credibility of government, and the degree of improvement is much higher than the sum of government guidance cost and reward expenditure, which is conducive to improving the enthusiasm of government to participate in guiding agricultural modernization. However, in the model, there is no situation in which the new agricultural business entities do not participate in the cooperation when the system may be stable. According to the judgement inequality in Tab.4, we found that as long as the guarantee of new agricultural business entities itself operating earnings higher than the cost of drive small farmers or government subsidies to make up for the search cost, at this point, whether the government or the small farmers to participate in agricultural modernization, the new agricultural business entities constantly adjust their own decision-making behavior, the final balance in the "cooperation" strategy. It can be seen that the government and small farmers are more sensitive in adjusting their own behaviors according to the choices of game subjects other than themselves. Therefore, when formulating a series of measures for the government and small farmers, the principle of caution should be adopted, and the response degree of the government and small farmers to the policy should be fully considered.

5. Research conclusions

Based on the evolutionary game theory, this paper constructs a coordinated development model of agricultural modernization of local government, new agricultural business entities and small farmers based on the premise of bounded rationality, and analyzes three different evolutionary scenarios that may be formed by the three-party game subject through long-term repetition, learning and adjustment strategies. Through comparative analysis of adjustment parameters of three different evolution scenarios and numerical simulation by MATLAB, there are four main conclusions:

(1) In the system composed of the government, the new agricultural business entities and the small farmers, the decision-making of any party will be affected by its own decision-making factors and the behavior of the other two parties; Moreover, compared with the new agricultural business entities, the government and small farmers have a higher degree of acute behavior choice;

(2) By studying the influence factors of the strategy change the sensitivity of the result of the evolution, found that the local government and farmers are existing and new agricultural business entities of action that are not consistent, but as long as the guidance and support through a series of policy guarantee of local government, farmers, get real benefits from participation in rural modernization, it can still form a good situation of three-party joint governance (guidance, cooperation, cooperation), which is conducive to promoting the improvement of agricultural modernization level, solving the problem of farmers' income, and promoting China's agricultural modernization.

(3) Significantly different from our daily understanding, in the process of deciding whether to form tripartite coordination, local government's decision has nothing to do with taxation and the rewards and punishments of the superior government, but is significantly related to its guidance cost and credibility loss. Participate in the cooperation of the boot cost, not the size of the loss of credibility, cooperation is the key factors influencing the behavior of local government, local government subsidies and incentives spending only exist when the government choice to cooperate, and not conducive to improve the government to participate in the enthusiasm of agricultural modernization, but will improve the small farmers and new agricultural business entities participation willingness to agricultural modernization;

(4) Farmers' decision-making choices mainly depend on their own benefits when they do not participate in cooperation, the loss of vicious competition in the market, rental income and wages when they participate in cooperation, and possible local government incentives. Farmers will choose the strategy of "cooperation" only when the income of farmers participating in cooperation is higher than their own income when they do not participate. However, farmers are limited by their own culture, knowledge and technical level, resulting in low income. If vicious competition is blindly increased for farmers, the rights and interests of small farmers will be even more insecure, which also shows that vicious market competition has a negative effect on farmers' participation in agricultural modernization. From the analysis of the influencing factors of farmers' willingness to participate in agricultural modernization, it can be seen that rent income, wages and material rewards can increase farmers' income in actual production, which will also improve farmers' enthusiasm to participate in agricultural modernization.

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Competing interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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