 doi:10.20944/preprints202208.0471.v1

Article

Impact of Using Extension Services of Organic Fertilizers for Carbon Sequestration in China: Evolutionary Game Analysis on Local Governments and Farmers' Behavioral Strategies

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Abstract: The application of organic fertilizers plays a crucial role in achieving carbon sequestration in the agricultural sector. This paper discusses how farmers can more smoothly promote organic fertilizer extension services. An evolutionary game model is developed to describe the conflicting interests of Chinese farmers and local governments in organic fertilizer extension services, and the dynamic evolution of the game players and the influence of parameter adjustment on the strategic choices of both parties is presented. In this paper, the game model and the main results are validated with the help of simulation tools, and a sensitivity analysis of the selected parameters is performed. The results show that (1) the implementation of subsidy policy is less helpful for organic fertilizer extension services; (2) The ideal event probability of the game was found to be positively related to the cost of applying inorganic fertilizers, additional benefits to farmers, political returns to local governments, and penalties for not using organic fertilizers; (3) This is important for improving the performance of local governments, reducing government regulatory costs, improving policy support for organic fertilizer extension services, and reducing the cost of implementing organic fertilizer extension services.

Keywords: carbon sequestration; evolutionary game theory; organic fertilizer; food security

1. Introduction

As food security pressure improves, inorganic fertilizers have caused severe environmental problems such as water pollution, greenhouse gas emissions, and soil degradation [1,2]. Sustainable development can only be achieved if these problems are addressed; therefore, more organic fertilizers are used for agricultural cultivation. Organic fertilizers that are both safer for the environment and improve food quality are gaining popularity worldwide to meet the rapidly growing demand for food quality. Using organic fertilizers can reduce the inorganic fertilizers applied by farmers and provide better conditions for sustainable development [3]. The use of organic fertilizers as a percentage of total fertilizer use in China has decreased from 25% in 2003 to 8-10% in 2017. Empirical data from rural China also indicate that farmers in China are increasingly reluctant to apply organic fertilizers [4]. Although applying organic fertilizers is technically feasible [3], farmers seem unwilling to use organic fertilizers actively [5]. The gap between the ideal and the reality lies in the unsatisfactory organic fertilizer extension services [6].

Agriculture is one of the important sources of greenhouse gases, and after the ocean and geological reservoirs, the soil is the third-largest carbon reservoir in the world. Factors such as China's population and land area result in its agricultural soils having a massive impact on global atmospheric CO2 concentrations. The average level of organic carbon content in the EU is 30% higher than in China, and China's organic carbon content is even much lower than the global average. This suggests that the fragile ecological chain of Chinese farmland will have difficulty coping with and withstanding natural disasters brought about by climate change. However, it also strongly reflects considerable room for improvement in greenhouse gas emission reduction and carbon sequestration in Chinese agricultural soils [7].

Farmers have expressed aversion to the potential risks of organic fertilizer application, including the large financial investment and higher time costs. Without regulation, farmers are unlikely to forego short-term gains and apply organic fertilizers voluntarily [5]. Government intervention is non-negligible in farmers' production decisions [8]. Since applying organic fertilizers is indispensable for enhancing carbon sequestration [6], the government must explore organic fertilizer extension services [8]. Farmers have a choice of strategies (to apply organic fertilizer or not to apply organic fertilizer), and local governments have two strategies (to supervise or not to supervise). Considering the evolutionary mechanism and the assumption of finite rationality, evolutionary game theory can perfectly solve multiple equilibrium points by focusing on the evolutionary process of decision-making [9]. It is a standard theoretical tool for analyzing decision problems of firms and local governments [10]. According to evolutionary game theory, both sides of the game are rational for a given decision, but their choices change over time [11,12]. Therefore, we investigated unilateral evolutionary stabilization strategies for supervised and unsupervised systems using the analytical tools of evolutionary game theory. Then, based on the goal that local governments can promote organic fertilizers effectively over time, we will define an ideal event and analyze the influence of parameters on this ideal event.

This paper answers the following critical questions.

(1) Should farmers receive subsidies? If direct subsidies do not work well, in what form should they receive them?

Three key questions arise if local governments exercise intense supervision.

(2) How do local governments' penalties on farmers who do not use organic fertilizers affect the development of organic fertilizer extension services?

(3) Given local government oversight, how do farmers choose the best application strategy: organic or inorganic fertilizer?

(4) How can local governments take a practical approach to promote farmers' use of organic fertilizers when subsidy policies are challenging to implement?

Since there are few studies on organic fertilizer application from the perspective of evolutionary games, this study not only shows the dynamic game process of the game model under finite rationality but also provides a quantitative and qualitative simulation platform to analyze the complex dynamic evolution process between farmers and local governments, thus providing effective theoretical guidance for policymakers. The paper is organized as follows: Section 2 reviews the relevant literature and describes the innovative points of this paper. Section 3 describes the relationship between farmers and local governments and the assumptions required in the game. Section 4 analyzes the model's results and provides simulations and sensitivity analyses of the relevant parameters. Section 5 interprets these results in the context of previous studies and work. Finally, Section 6 reveals the conclusions, makes policy recommendations, and reveals future research directions.

2. Literature Review

Researchers are currently conducting pioneering work in organic fertilizer extension services. Li and Shen [4] explored guiding policies for organic fertilizer extension services. They suggested that improving the quality and speed of land transfer is a prerequisite for guaranteeing the large-scale application of organic fertilizers by farmers, including the implementation of an efficient land transfer system and ensuring the management rights of those farmers who obtain transferred land to lower the technical threshold for organic fertilizer application. Wang et al. [3] concluded that by long-term application of organic fertilizers, the organic matter content of dryland areas in China could be increased, the soil structure can be improved, the carbon sequestration capacity can be enhanced, and finally, the stability and sustainability of crop production can be guaranteed. Such findings could help policymakers effectively influence the strategies of those farmers who apply organic fertilizers. Luo et al. [8] investigated farmers' attitudes towards organic fertilizer application, and they identified higher time costs and technical uncertainty as the main barriers to the large-scale application of organic fertilizers. Since organic fertilizer extension services in China are at a standstill, Ju et al. [13] concluded from a large number of field trials with different nitrogen levels in the Taihu Lake region and the North China Plain that an inadequate government subsidy system, the absence of a nitrogen fertilizer tax mechanism, and the lack of farmers' awareness of environmental protection are the main barriers to the large-scale application of organic fertilizers in China. Wang et al. [5] found that large-scale application of organic fertilizers does not have purely technical barriers; the main obstacles were high time costs, failure of market mechanisms, insufficient incentives, lack of penalties for the application of inorganic fertilizers, and weak environmental awareness among farmers, and inadequate legal frameworks. To overcome these barriers, they collected data from Baota, Ansai, Luochuan, Baishui, and Changwu to measure farmers' risk preferences for organic fertilizer application for extension of organic fertilizer application.

As can be seen, these studies mainly explore the barriers to organic fertilizer extension services from a qualitative perspective and provide valuable policy recommendations. For quantitative analysis, various economic models are usually used. Huang et al. [14] used cost-benefit analysis to measure the costs associated with reducing nitrogen fertilizer use using different crop rotation patterns under other agricultural policy options. To analyze farmers' choices regarding prospective utility, risk, and environment, Wang et al. [5] used Kahneman's prospect theory and Levine's field theory to investigate their impact on organic fertilizer extension services in China, which proved robust and systematic. In addition, the Tobit regression model was introduced to explain farmers' choice between organic and inorganic fertilizers. According to the input-output model, large-scale application of organic fertilizers can also improve soil carbon sequestration capacity and protect soil [7].

However, little literature has focused on the extension services of organic fertilizers from a microeconomic perspective. There is a need to analyze the extension services of organic fertilizers from the micro level of the behavioral interactions between farmers and local governments. Game theory has been powerfully applied to study conflict coordination and interaction models between stakeholders with different objectives [15]. Game solutions allow stakeholders to realize their expectations of benefit maximization and determine the most beneficial strategy for themselves by predicting the behavior of others [16]. Contrary to reality, the full information static game assumes that the stakeholders are perfectly rational and have complete information [17]. Evolutionary game theory improves the traditional game theory by taking finite rationality as a premise and treating the strategy choice of the game players as a dynamic adjustment process [18]. Researchers have applied evolutionary game theory between governments and firms to conduct enlightening studies on low-carbon technologies.

Ji et al. [19] investigated the dynamic evolutionary mechanism of the complex behavior between local governments and automakers by modeling the evolutionary game between automakers and governments, including the phasing out of subsidy policies without consideration. They discussed how to stabilize the lifespan of new energy vehicles and alleviate the associated financial pressures governments face. Jiang et al. [20] established a three-way evolutionary game between the central government, local governments, and enterprises to promote the implementation of a multi-entity environmental regulation strategy to improve the deteriorating environmental quality. Numerical simulation results suggest that government regulation is essential but insufficient and that adopting environmental regulation strategies must depend on the synergy among the three stakeholders. Zhao and Liu [21] developed a government-firm evolutionary game framework to study the interaction between government and power plants to promote adopting CCS technology for cleaner production in power plants. The analysis showed that government subsidies, fines, and reduced CCS adoption costs would influence the strategy choice of power plants. Sheng et al. [22] developed a three-way evolutionary game model to theoretically analyze the evolutionary stable strategies of the central government, local governments, and firms in China to find the elements affecting each stakeholder's strategy and to test incentive-compatible environmental regulatory policies. The simulation results show that central government regulation is crucial to achieving environmental regulatory policy goals. In addition, increasing the penalties for non-compliance and incentives for compliance can encourage local governments to enforce environmental regulations more effectively, thereby alleviating the conflict of interests among stakeholders.

The above studies provide a firm basis for this study. However, no literature comprehensively analyzes organic fertilizers' extension services using evolutionary game models and simulation analysis. In addition, most of the existing literature studies the application behavior of organic fertilizers from an empirical perspective, with little insight into the behavioral strategies of stakeholders in applying organic fertilizers from a normative economics perspective. To fill the gap in the theoretical model, this study compares the existing literature from the following views.

(1) This study first analyzes organic fertilizer application behavior from a normative economics perspective and explores the conflict and interaction mechanisms between farmers and local governments in the organic fertilizer application process.

(2) An evolutionary game model between farmers and local governments is developed for the first time. A perfect information static game model is improved to discuss the application of organic fertilizer.

(3) Simulation analysis verifies the results and elucidates the dynamic evolutionary process of participants' strategies. Also, a sensitivity analysis of crucial parameters was conducted to reveal how to advance the evolutionary game to a perfectly stable state more quickly and smoothly.

3. Materials and Methods

3.1. The basis for model construction

In 2019, China was the largest user of inorganic fertilizers with 47.55 million tons, accounting for nearly 25.2% of the world's total use [23]. Meanwhile, China's share of organic fertilizer use has declined to 8-10% of total fertilizer use [4]. Data from a survey of 646 grain farmers in Shandong Province in 2014-2015 and 359 apple farmers in Shanxi Province in 2016 showed that the proportion of farmers applying organic fertilizers was 34.2% and 7.52% of the total sample, respectively [5,25]. Meanwhile, to increase soil organic carbon content, applying organic fertilizers is an efficient strategy [26]. Therefore, local governments in China must find methods to motivate farmers to use organic fertilizers instead of inorganic fertilizers to achieve sustainable development by increasing organic carbon sequestration [5,27]. For example, to ensure the large-scale application of organic fertilizers, local governments could subsidize organic fertilizers directly to farmers.

However, lagging extension services have become a bottleneck limiting the promotion of organic fertilizers in China: first, most farmers prefer to use inorganic fertilizers rather than organic fertilizers to maintain crop yields due to high costs and labor shortages [28]; second, there is currently insufficient government regulation and a lack of specific subsidy policies to support environmentally friendly agriculture [29]. Under such circumstances, farmers lack the incentive to use organic fertilizers; finally, even if organic fertilizers are used instead of inorganic fertilizers, there are potential reasons for China's rejection of organic food: higher prices and limited availability [30].

Farmers are stakeholders in applying organic fertilizers and are essential in the fight against climate change [31]. China is a country that values sustainable agricultural development [32]. Especially since the beginning of the COVID-19 pandemic, China needs to develop sustainable agriculture to ensure food security, meet its economic recovery goals, and mitigate the adverse effects of climate change on agriculture [33]. In this context, farmers need to consider using organic fertilizers to develop sustainable agriculture [4]. However, farmers are averse to the potential risks of organic fertilizer application, which requires local governments to enact policies to guide farmers to apply organic fertilizer without harming their interests. When local governments regulate negatively, farmers will not take the initiative to apply organic fertilizers. If local governments choose to regulate actively, farmers will consider applying more organic fertilizers.

Government regulation is one of the essential factors affecting organic fertilizer extension services [2,34]. China is facing severe climate problems, thus putting pressure on local governments to maintain economic development while achieving the goal of environmental protection [35–37]. However, local governments face regulatory challenges due to constraints in a regulatory capacity and human and material resources [38]. If farmers refuse to use organic fertilizers, local governments will also have to pay a huge price to deal with the negative impacts of excessive carbon emissions, which local governments would not have to pay if farmers used organic fertilizers.

In general, farmers need to consider whether to use organic fertilizers to develop sustainable agriculture [4,39]; local governments need to consider how they can incentivize farmers to use organic fertilizers [2,40]. These two actors are the most critical stakeholders of organic fertilizer extension services.

3.2. Model Hypothesis and Parameters

H1. The evolutionary game theory emphasizes finite rational decision-making and believes that the game participants are finite rational parties whose behavioral choices will be in a constant process of adjustment and change and eventually tend to stability.

H2. The main game subjects are farmers and local governments. As finite rational subjects, the participants make mature strategies in the process.

H3. The farmers' decision to participate in applying organic fertilizer is "application" or "no application".

H4. The local governments' strategy choices for farmers' participation in organic fertilizer application are "supervision" and "no supervision".

The probability of farmers choosing to use organic fertilizers is x ($0 \leqslant x \leqslant 1$), the probability of farmers not using organic fertilizers is 1-x, and the probability of local governments supervising farmers to use organic fertilizers is y ($0 \leqslant y \leqslant 1$), and the probability of local governments not supervising farmers to use organic fertilizers is 1-y. When the local governments adopt a "supervision" strategy, C_1 represents the cost of government supervision. When farmers choose the "no application" strategy, C_2 represents the cost of additional carbon emissions to local governments, and C_3 represents the cost of inorganic fertilizer application to farmers. When the farmer chooses the "application" strategy, C_4 represents the total cost of organic fertilizer application, including the cost of purchasing organic fertilizers, additional time cost, labor, and capital investment.

R_1 denotes the return the farmers can obtain when they do not apply organic fertilizers, and R_2 denotes the additional return that the farmers can obtain when applying organic fertilizers. When the local governments adopt a "supervision" strategy, R_3 represents the political gains for the local governments. When the local governments adopt a "supervision" strategy, and the farmers adopt a "non-application" strategy, P represents the punishments to the farmers who do not apply organic fertilizers. When the local governments adopt a "supervision" strategy, and the farmers adopt an "application" strategy, S represents the subsidies to the farmers who apply organic fertilizers.

The parameters involved in the model of farmers' and local governments' behavior and their meanings are shown in Table 1 below.

Table 1. Parameters definitions.

Stakeholders	Parameters	Descriptions
Local governments	C_1	The cost of government supervision

Local governments	C_2	The cost of additional carbon emissions
Farmers	C_3	The cost of inorganic fertilizer application
Farmers	C_4	The cost of organic fertilizer application
Farmers	R_1	Returns gained by farmers if organic fertilizers are not adopted
Farmers	R_2	Additional returns gained by farmers if organic fertilizers are adopted
Local governments	R_3	Political gains for the local governments
Farmers and Local governments	P	The punishments to the farmers who do not apply organic fertilizers
Farmers and Local governments	S	The subsidies to the farmers who apply organic fertilizers

3.3. Jacobian matrix and evolutionary game modeling

Based on the method proposed by Friedman, the local stability of the Jacobian matrix can be used to verify whether the strategy combination formed by both sides of the game is an evolutionary stable strategy (ESS) and to analyze which factors influence the strategy choice of both sides [41].

Table 2. Jacobian matrix of the game between farmers and local governments.

		Local governments	
		supervision	No supervision
Farmers	application	$R_1 + R_2 + S - C_4$, $R_3 - C_1 - S$	$R_1 + R_2 - C_4$, 0
	No application	$R_1 - P - C_3$, $P - C_1 - C_2$	$R_1 - C_3$, $- C_2$

According to the model assumptions in Table 2, the expected and average returns for farmers adopting the "application" and "no application" strategies are U_{f1}, U_{f2} and U_f, respectively, are calculated as follows:

$$U_{f1} = y(R_1 + R_2 + S - C_4) + (1 - y)(R_1 + R_2 - C_4) \tag{1}$$

$$U_{f2} = y(R_1 - P - C_3) + (1 - y)(R_1 - C_3) \tag{2}$$

$$U_f = xU_{f1} + (1 - x)U_{f2} \tag{3}$$

The expected and average benefits of the "supervision" and "no supervision" strategies for local governments are U_{g1}, U_{g2} and U_g, respectively, and are calculated as follows:

$$U_{g1} = x(R_3 - C_1 - S) + (1 - x)(P - C_1 - C_2) \tag{4}$$

$$U_{g2} = - (1 - x)C_2 \tag{5}$$

$$U_g = yU_{g1} + (1 - y)U_{g2} \tag{6}$$

The replicator dynamic equation is a dynamic differential equation that describes the frequency of a group adopting a particular strategy [41]. The replicator dynamic equations for the probability x of farmers choosing the "application" strategy and the probability y of the local governments choosing the "supervision" strategy are:

$$F(x) = \frac{dx}{dt} = x(U_{f1} - U_f) = x(1 - x)[y(S + P) + R_2 + C_3 - C_4] \tag{7}$$

$$F(y) = \frac{dy}{dt} = y(U_{g1} - U_g) = y(1 - y)[x(R_3 - S - P) + P - C_1] \tag{8}$$

Letting equation (7) = 0 and equation (8) = 0, five equilibrium points are obtained as A(0, 0), B(0, 1), C(1, 0), D(1, 1), and E($\frac{P-C_1}{S+P-R_3}$, $\frac{C_4-C_3-R_2}{S+P}$).

The Jacobian matrix is obtained from equation (7) and equation (8) as follows:

$$J = \begin{bmatrix} \frac{\partial(\frac{dx}{dt})}{\partial x} & \frac{\partial(\frac{dx}{dt})}{\partial y} \\ \frac{\partial(\frac{dy}{dt})}{\partial x} & \frac{\partial(\frac{dy}{dt})}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[y(S+P)+R_2+C_3-C_4] & x(1-x)(S+P) \\ y(1-y)(R_3-S-P) & (1-2y)[x(R_3-S-P)+P-C_1] \end{bmatrix} \quad (9)$$

The determinant of the matrix is det(*J*), the trace of the matrix is tr(*J*), and the expressions for the five equilibrium points are shown in Table 3.

Table 3. The expression for the five equilibrium points.

Equilibrium points	Det(*J*)	Tr(*J*)
A(0, 0)	$(R_2+C_3-C_4)(P-C_1)$	$R_2+C_3-C_4+P-C_1$
B(0, 1)	$-(R_2+C_3-C_4)(R_3-S-C_1)$	$R_2+C_3-C_4+R_3-S-R_1$
C(1, 0)	$-(S+P+R_2+C_3-C_4)(P-C_1)$	$S+R_2+C_3-C_4+C_1$
D(1, 1)	$(S+P+R_2+C_3-C_4)(R_3-S-C_1)$	$C_1-P-R_2-C_3+C_4-R_3$
E($\frac{P-C_1}{S+P-R_3}$, $\frac{C_4-C_3-R_2}{S+P}$)	$[P-C_1-\frac{(P-C_1)^2}{S+P-R_3}][C_4-C_3-R_2-\frac{(C_4-C_3-R_2)^2}{S+P}]$	0

To determine the symbols of the det(*J*) and tr(*J*) at different equilibrium points, the following hypotheses are made: (1) According to Wang et al. [5], $C_4 > R_2 + C_3$, because the biggest challenge that prevents farmers from applying organic fertilizers is that the extra benefit from applying organic fertilizers in the short run is less than the extra cost from applying organic fertilizers. (2) According to Zhao et al. [21], $R_3 > C_1 + S$, because the political gains for local governments need to be greater than the sum of the cost of government supervision and the subsidies to farmers. Otherwise, local governments will have no incentive to supervise. (3) According to the model hypothesis, any initial point and its evolved point are meaningful only in the two-dimensional space V = {(x, y)|$0 \leqslant x \leqslant 1$, $0 \leqslant y \leqslant 1$}, so $S+P-R_3 < P-C_1 < 0$ and $0 < C_4-C_3-R_2 < S+P$. The evolutionary stability of the five equilibrium points is shown in Table 4.

Table 4. The evolutionary stability of the five equilibrium points.

Equilibrium points	Det(*J*)	Tr(*J*)	State
A(0, 0)	+	-	ESS
B(0, 1)	+	+	Unstable
C(1, 0)	+	+	Unstable
D(1, 1)	+	-	ESS
E($\frac{P-C_1}{S+P-R_3}$, $\frac{C_4-C_3-R_2}{S+P}$)	-	0	Saddle point

According to the results of evolutionary stability points, the equilibrium points A(0, 0) and D(1, 1) show two ESS equilibrium points. The equilibrium point A(0, 0) indicates that the farmers choose the "no application" strategy and the local governments choose the "no supervision" strategy. The equilibrium point D(1, 1) indicates that the farmers choose the "application" strategy and the local governments choose the "supervision" strategy. B(0, 1) and C(1, 0) are two instability points, where B(0, 1) means that farmers choose the "no application" strategy and local governments choose the "supervision" strategy. E($\frac{P-C_1}{S+P-R_3}$, $\frac{C_4-C_3-R_2}{S+P}$) is a saddle point. The evolutionary process of farmers' and local governments' strategies is shown in Figure 1.

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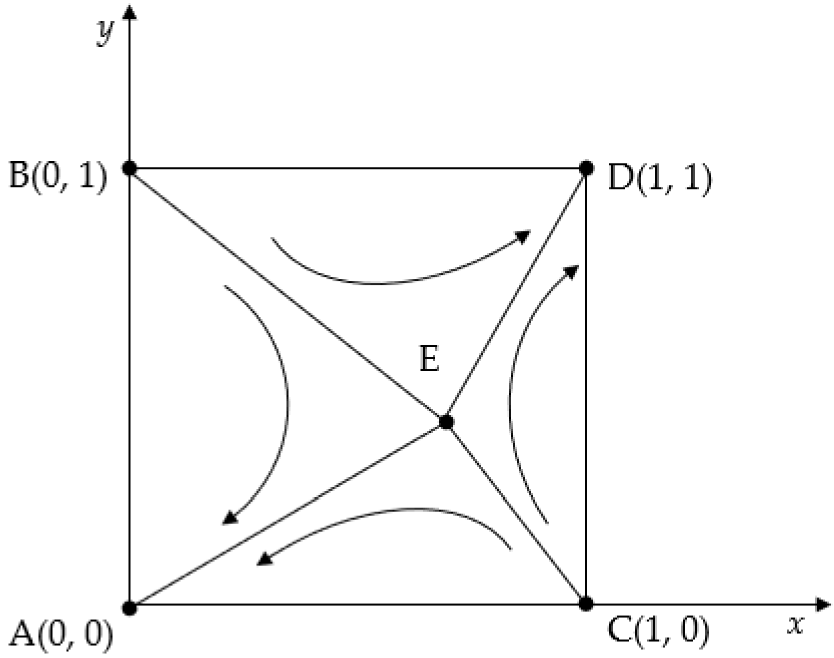

Figure 1. The replicated dynamic diagram of farmers and local governments.

A(0, 0) and D(1, 1) are equilibrium points, indicating that the replicated dynamic curves of farmers and local governments tend to converge to these two points. When both replicated dynamic curves converge at A(0, 0), farmers choose the "no application" strategy, and local governments choose the "no supervision" strategy. When both replicated dynamic curves converge at D(1, 1), farmers choose the "application" strategy, and local governments choose the "supervision" strategy. Where E($\frac{P-C_1}{S+P-R_3}$, $\frac{C_4-C_3-R_2}{S+P}$) is the crucial point to determine the probability of convergence of the two replicated dynamic curves to A and D. As shown in Figure 1, if the initial state of farmers and local governments is near point E, subtle changes will change the dynamic evolution results of both sides. The participants' final trend depends on comparing the area of regional ABCE and the area of regional BCDE. When $S_{BCDE} > S_{ABCE}$, farmers tend to apply organic fertilizers, and local governments tend to supervise. On the contrary, when $S_{BCDE} < S_{ABCE}$, farmers tend not to use organic fertilizers, and local governments tend not to supervise. To analyze which factors influence the stability state of both strategies, it is necessary to analyze the parameters that influence S_{BCDE}. Among them:

$$S_{BCDE} = 1 - \frac{1}{2}\left[\frac{P-C_1}{S+P-R_3} + \frac{C_4-C_3-R_2}{S+P}\right] \quad (10)$$

It can be seen from the formula of S_{BCDE} that the parameters affecting S_{BCDE} are C_1, C_3, C_4, R_2, R_3, S, and P. Calculate the partial derivatives of these parameters, respectively, and use "+" to indicate that the parameters are positively correlated with S_{BCDE}, "-" to indicate negative correlation, and "/" to indicate that the correlation cannot be distinguished. The results are shown in Table 5.

Table 5. Analysis of parameters influencing farmers' and local governments' strategies.

Parameters	Partial derivatives	Impact on S_{BCDE}
C_1	< 0	-
C_3	> 0	+
C_4	< 0	-
R_2	> 0	+
R_3	> 0	+

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P	/	/
S	/	/

As shown in Table 5, C_1 for farmers to choose the "application" strategy and C_4 for local governments to choose the "supervision" strategy are negatively correlated with S_{BCDE}. When C_1 and C_4 increase, S_{BCDE} decreases. In other words, as the cost increases, the benefit to both parties decreases, and the likelihood of changing strategies increases.

C_3, R_2, and R_3 are positively correlated with S_{BCDE}. When C_3, R_2, and R_3 increase, S_{BCDE} increases. C_3 is the cost of applying inorganic fertilizers, and when C_3 increases, people will increase their consumption of organic fertilizer as a substitute [42–44]. R_2 and R_3 are the additional benefits farmers and local governments receive when choosing {application, supervision}, respectively. The increase in these two additional benefits motivates both parties to choose {application, supervision}.

However, the effect of S and P on S_{BCDE} could not be determined. Therefore, to facilitate the analysis, it would be helpful to use numerical simulations to explore how changes in the initial percentage of participants selected and changes in various parameters affect the evolutionary trajectory [45,46].

4. Results

4.1. Sensitivity analysis of initial value of participants

In this paper, MATLAB R2021a is applied to conduct numerical simulation to further demonstrate the evolutionary trajectory of each equilibrium point mentioned above and the different initial value points of the game subjects toward the equilibrium point to verify the accuracy of the model results and make the dynamic evolutionary trend more clear and vivid. Let $R_2 = 300$, $R_3 = 400$, $C_1 = 40$, $C_3 = 150$, $C_4 = 600$, $P = 5$, and $S = 350$. Taking the initial values of numerical simulation (x, y) as (0.1, 0.6), (0.5, 0.5), (0.6, 0.2), (0.2, 0.9), (0.6, 0.7) and (0.9, 0.5). The dynamic evolutionary process of strategy choice of participating subjects over time is shown in Figure 2.

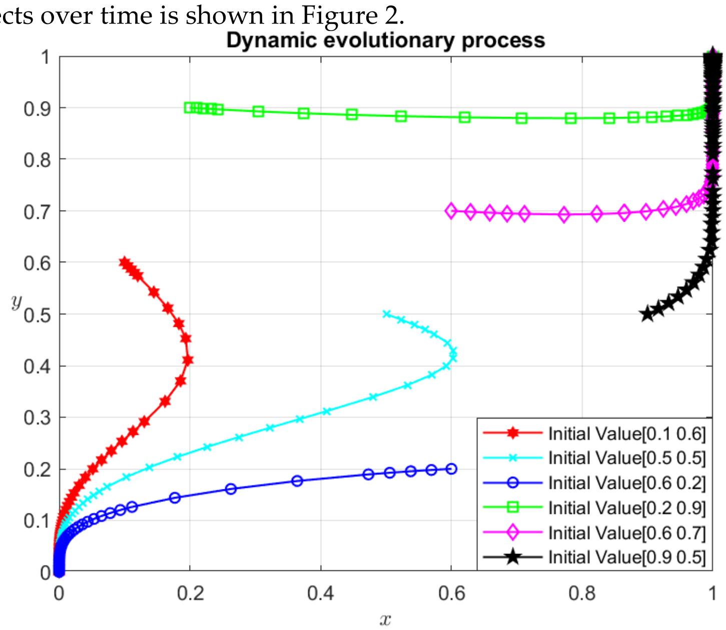

Figure 2. The dynamic evolutionary process of strategy choice of participating subjects.

As can be seen from Figure 2, when the probabilities (x, y) of the two sides of the game take different initial values, the final game evolution results also converge to different points. In the initial value set state, the value of the saddle point E can be calculated roughly (0.78, 0.42), in connection with Figure 1, it can be seen that when the initial value of (x, y) falls in the ABCE region, the initial value converges to (0, 0), farmers will choose

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the "no application" strategy and local governments will choose the "no supervision" strategy. When the initial value of (x, y) falls in the BCDE region, the initial value converges to (1, 1), farmers will choose the "application" strategy, and local governments will choose the "supervision" strategy. It is verified that the evolution of both strategies depends on the initial value of (x, y). Therefore, it is necessary to develop guidelines to improve the possibility of the initial choice of supervision by local governments and initial choice of organic fertilizer application by farmers, which is of great importance for the extension services of organic fertilizer.

4.2. Sensitivity analysis of parameters

In this subsection, the sensitivity of the participants to the parameters, namely, the cost of supervision by local governments (C_1), the cost of inorganic fertilizer application by farmers (C_3), the cost of organic fertilizer application by farmers (C_4), the additional benefit of organic fertilizer application by farmers (R_2), the political gains of local governments (R_3), the punishments for farmers who do not apply organic fertilizers (P) and the subsidies for farmers who apply organic fertilizers (S), is investigated. We assume that the sensitivity of one parameter is simulated with the initial choice probability of stakeholders (x, y) = (0.5, 0.5), while the values of the other parameters remain constant [47].

(1) Figure 3 shows the sensitivity of stakeholders to the cost of supervision by local governments (C_1), with C_1 taking values of 40, 45, and 49. Farmers and local governments will move in the direction of {no application, no supervision} and will move faster as C_1 increases. This suggests that the high cost of supervision not only discourages farmers from applying organic fertilizer, but also reduces the willingness of local governments to supervise. Further measures should be taken to reduce the cost of government supervision and increase the willingness of both parties to promote organic fertilizers.

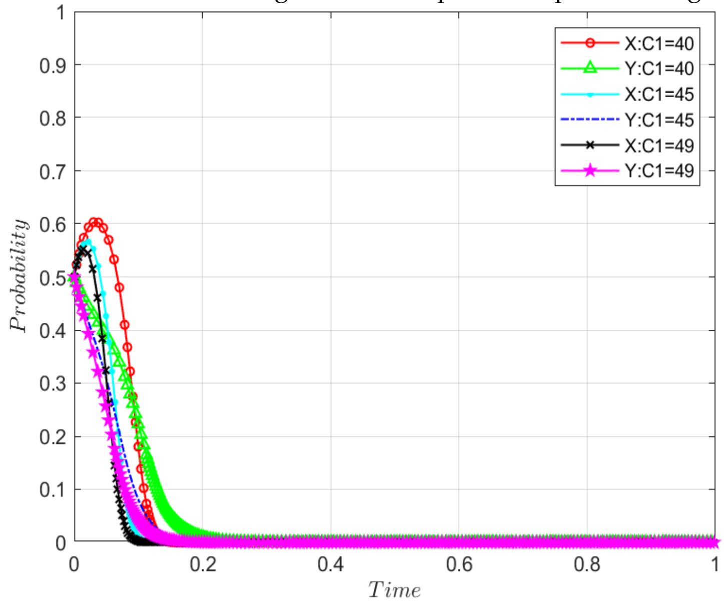

Figure 3. The sensitivity of stakeholders to the cost of supervision by local governments (C_1).

(2) Figure 4 shows the sensitivity of stakeholders to the cost of inorganic fertilizer application by farmers (C_3), with C_3 values of 150, 155, and 160. When farmers pay low costs for applying inorganic fertilizers (C_3 = 150, 155), ESS will tend to {no application, no supervision}. When C_3 equals 150, the system evolves faster than when C_3 equals 155. When C_3 increases to 160, the ESS will tend to {application, supervision} and the farmers evolve faster than local governments. This suggests that farmers will prefer to apply organic fertilizers when the cost of applying inorganic fertilizers increases to a certain level.

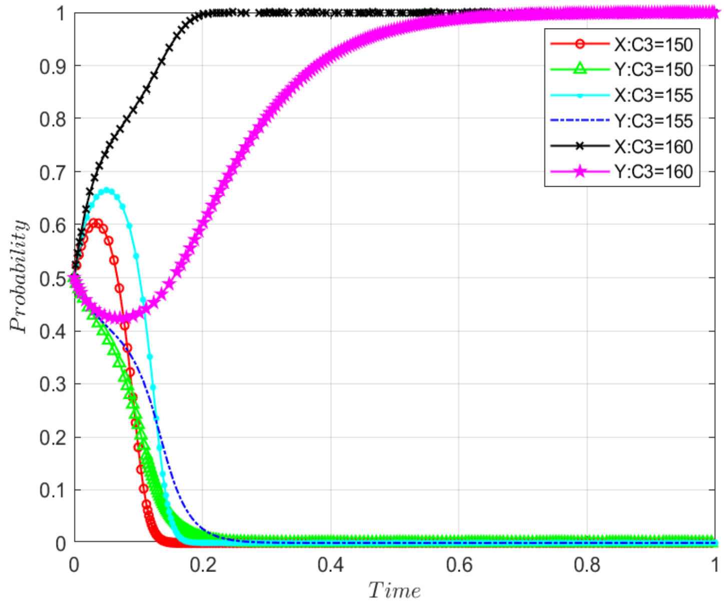

Figure 4. The sensitivity of stakeholders to the cost of inorganic fertilizer application by farmers (C_3).

(3) Figure 5 shows the sensitivity of stakeholders to the cost of organic fertilizer application by farmers (C_4), with C_4 taking values of 600, 605, and 610. Farmers and local governments will evolve towards {no application, no supervision} and move faster as C_4 increases. This suggests that further measures should be taken to reduce the cost of organic fertilizer application by farmers and to promote more active participation of both parties in the process of organic fertilizer application.

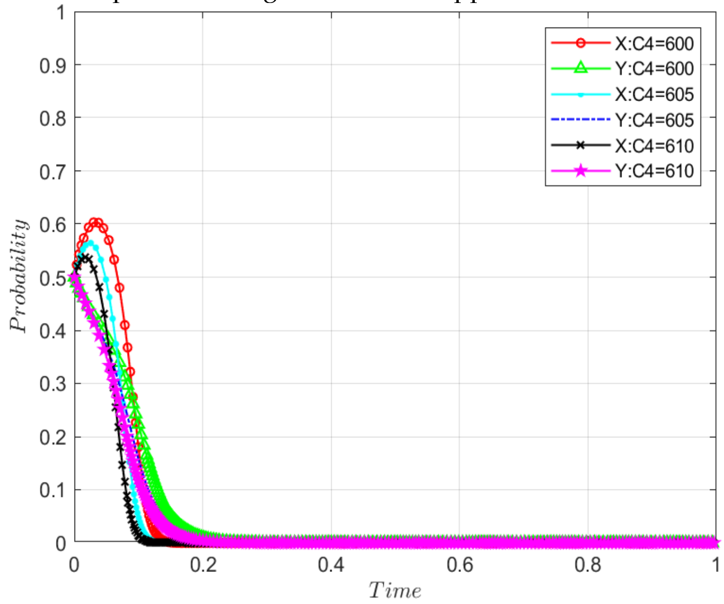

Figure 5. The sensitivity of stakeholders to the cost of organic fertilizer application by farmers (C_4).

(4) Figure 6 shows the sensitivity of stakeholders to the additional benefits of organic fertilizer application by farmers (R_2), with R_2 taking values of 300, 310, and 320. When R_2 equals 300, the ESS will tend to {no application, no supervision}. When farmers get high returns from organic fertilizer application (R_2 = 310, 320), ESS will tend to {application, supervision}. When R_2 equals 320, the system evolves faster than R_2 equals 310, and the farmers evolve faster than local governments. This suggests that farmers will be more willing to apply organic fertilizers when the benefits of applying organic fertilizers increase to a certain level.

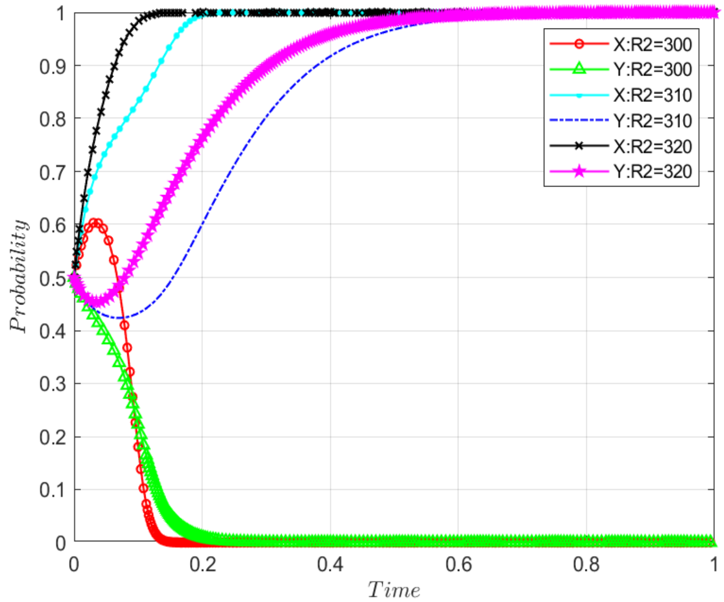

Figure 6. The sensitivity of stakeholders to the additional benefits of organic fertilizer application by farmers (R_2).

(5) Figure 7 shows the sensitivity of stakeholders to the political gains of local governments (R_3), with R_3 taking values of 400, 405, and 410. When R_3 equals 400, ESS will tend to {no application, no supervision}. When local governments receive high political returns for their regulatory actions (R_3 = 405, 410), the ESS will tend to {application, supervision}. When R_3 equals 410, the system evolves faster than when R_3 equals 405. Therefore, local governments should use the power of news media, the Internet, and non-governmental organizations (NGOs) to supervise farmers. This can increase the motivation for governmental supervision and create more social public benefits and political gains for local governments [48–50].

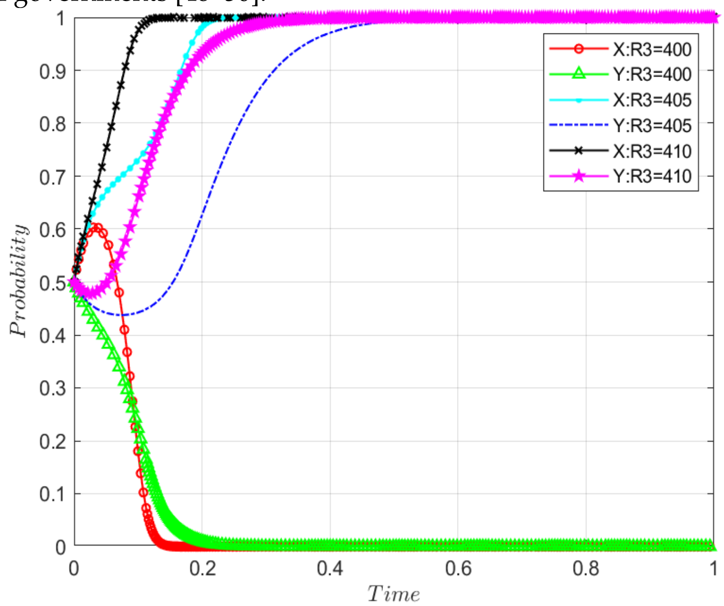

Figure 7. The sensitivity of stakeholders to the political gains of local governments (R_3).

(6) Figure 8 shows the sensitivity of stakeholders to penalties for farmers not applying organic fertilizer (P), with P taking values of 5, 20, and 35. When P equals 5, ESS will tend to {no application, no supervision}. When farmers receive high penalties for not applying organic fertilizers (P = 20, 35), the ESS will tend to {application, supervision}. When P equals 35, the system evolves faster than when P equals 20, and the farmers evolve faster

than the local governments. This suggests that farmers will be more willing to apply organic fertilizer when the punishments for not applying organic fertilizers increase to a certain level.

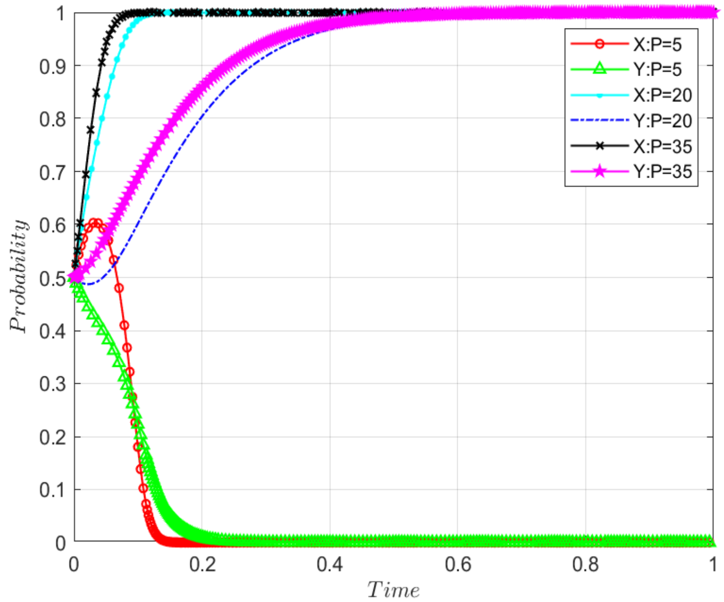

Figure 8. The sensitivity of stakeholders to penalties for farmers not applying organic fertilizer (*P*).

(7) Figure 9 shows the sensitivity of stakeholders to subsidies for farmers to apply organic fertilizer (*S*), with *S* values of 350, 355, and 359. Farmers and local governments will evolve in the direction of {no application, no supervision}, indicating that direct subsidies may not be an effective policy to promote organic fertilizer extension services. Direct subsidies make it challenging to attract farmers to use organic fertilizers, and the tendency of local governments to choose the "no supervision" strategy increases resource mismatch. Further measures should be taken to change the form of subsidies, such as direct distribution of organic fertilizer to farmers [29,51], to promote more active participation in the process of organic fertilizer application.

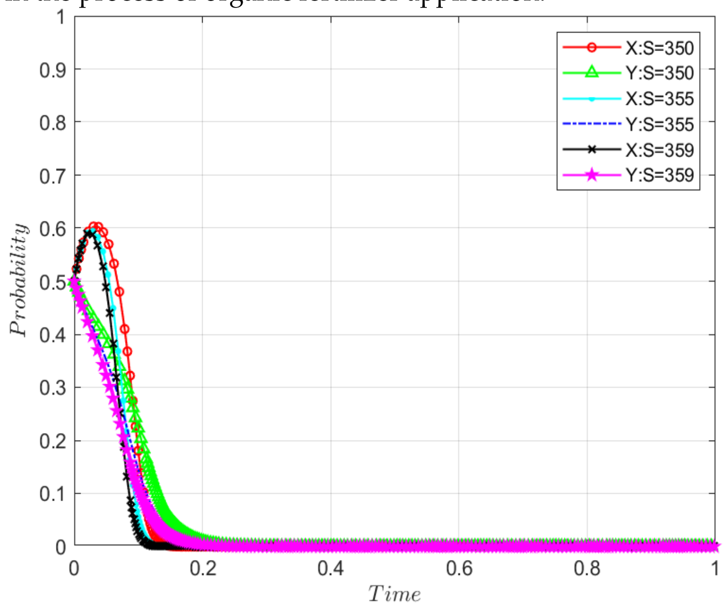

Figure 9. The sensitivity of stakeholders to subsidies for farmers to apply organic fertilizer (S).

5. Discussion

The above simulations reveal the influence of the main parameters on the evolution of the behavioral strategies of both parties. Local governments play a crucial role in promoting farmers' widespread use of organic fertilizers. Local governments need not only to improve regulatory efficiency and implement effective penalties, but also to help farmers increase their income and develop their environmental awareness [52,53].

If local governments spend much money on monitoring and low penalties for farmers who refuse to use organic fertilizers, then ESS will be {no application, no supervision}. Therefore, local governments can use NGOs, the media, and the Internet to help with monitoring, reduce the cost of supervision, and gain a good reputation. In the case of farmers, their strategies depending on the level of government supervision and penalties, the cost of applying inorganic fertilizers, and the additional returns of using organic fertilizers. Therefore, there is a need for local governments to increase the penalties for farmers who refuse to apply organic fertilizers according to local conditions.

Currently, many Southern Hemisphere countries provide subsidies to promote the application of mineral fertilizers by farmers, but there are fewer incentives to use organic fertilizers [54]. A study by Marenya et al. [55] showed that using carbon credits for farmers can promote fertilizer use and sustainable agriculture more effectively than subsidies. Empirical cases in five Chinese counties, Baota, Ansai, Luochuan, Baishui, and Changwu, showed that 91% of farmers believed that abandoning inorganic fertilizers and applying organic fertilizers was not good for yield [5]. Therefore, local governments need to change the form of subsidies, such as in-kind subsidies, to increase farmers' willingness to use organic fertilizers.

In addition, as the income level of Chinese urban and rural residents increases and the consumption structure is upgraded, consumers have higher food safety and quality demands. Organic fertilizers meet consumers' demand for healthy food by improving the quality of agricultural products. On the other hand, organic food in China can increase farmers' income because consumers are willing to pay higher prices for organic food [51]. Therefore, increasing the local publicity of organic fertilizers is also helpful in raising public awareness of sustainable development and green food.

6. Conclusions and prospects

6.1. Conclusions

By establishing the Jacobian matrix of farmers and local governments, the replicated dynamic equations of both parties are derived, and the sign of the determinant of the Jacobian matrix and the sign of the trace are derived from the replicated dynamic equations. Based on MATLAB R2021a operations, it is concluded that the dynamic evolution of farmers' and local governments' strategies is related to the initial values of both sides, which determine the final convergence of both sides of the game at two different ESS equilibrium points. Further studies show that the equilibrium point at which farmers and local governments choose {application, supervision} or choose {no application, no supervision} is the evolutionary stable strategy (ESS), which has long-term stability. The stability of the strategy chosen by both sides of the game is related to the change in the parameters of the replicated dynamic equation, and the stability of the choice of {application, supervision} is positively related to C_3, R_2, R_3, and P. That is, the choice of {application, supervision} is more stable in the long run when the cost and punishments of not applying organic fertilizers are higher for farmers, the additional benefits of applying organic fertilizers are higher for farmers, and the political returns from supervision are higher for local governments, have long-term stability.

Since farmers and local governments are rational people [56–58], they will choose the strategy that is beneficial to each of them, and this determines that both sides of the game will put their individual interests at stake when making decisions, ignoring the real purpose of using organic fertilizers to improve the environment, and weakening the efforts to improve carbon sequestration capacity and reduce the efficiency of meeting carbon sequestration targets. This is reflected in the inefficient implementation of applying organic fertilizers by farmers, who seek subsidies and other social resources to participate in organic fertilizer application activities and may shirk their responsibilities in the process of organic fertilizer application. Local governments may be prone to pressuring farmers to apply organic fertilizers, asking them to contribute money and effort without caring about their difficulties in using organic fertilizers, and some local government officials even resort to deception for personal gain [59,60].

Based on the above analysis, and taking into account the regional differences in rural China, this paper proposes the following recommendations in order to maintain the long-term stability of farmers' and local governments' choice of {application, supervision} strategies, to make both sides of the game choose a more benign way of cooperation, and to improve the carbon sequestration capacity of China.

6.2. Policy implications

(1) Build an effective mechanism for farmers' participation in public decision-making. Chinese farmers have improved the level of national governance by utilizing grassroots democratic self-governance [61]. However, in the practice of organic fertilizer application, farmers have limited expertise. Local governments can gather farmers and experts to establish a sound democratic decision-making mechanism; establish a system for farmers and experts to monitor the implementation of decisions before, during, and afterward to improve scientific, democratic, and transparent decision-making.

(2) To improve the realistic path for rural cooperatives and other types of grassroots self-governance organizations to participate in organic fertilizer extension services, because farmers are more willing to use organic fertilizers after joining progressive social groups [62]. Local governments should pave the way for direct and long-term participation of these social groups, improve the system of grassroots self-governance, formulate rules for organic fertilizer application, and provide institutional guarantees for the participation of social groups in organic fertilizer extension services. Local governments can also promote the benefits of organic fertilizer through websites, radio, and newspapers to gain public support for organic fertilizer extension services. More importantly, by mobilizing the enthusiasm of the Internet, the media, and NGOs, the power of social monitoring can be brought into play, reducing the pressure on local governments to supervise.

(3) Assist farmers in establishing a stable and effective self-monitoring body. This self-monitoring body is a semi-formal social organization consisting of a chairman, several vice chairmen, and several members for effective self-monitoring. The local government can help appoint a respected farmer with a good public base to the position of chairman; to promote the extension of organic fertilizer services, the appointment of a strong and capable farmer to the position of vice chairman can make the function of the self-monitoring body in practice. The members at the top of the self-monitoring body should have made great contributions to the countryside and be loved by the public. The middle-tier members are the backbone of the self-monitoring body. They are mainly young and middle-aged people who have made outstanding achievements in their respective fields and can provide financial, technical, and knowledge resources for the extension of organic fertilizer services. The bottom section consists of a large number of farmers who are enthusiastic about supporting the application of organic fertilizers. Their contribution should not be underestimated, and they are the main body of organic fertilizer extension services and should receive more attention and publicity.

(4) Introduce means to effectively reduce the cost of organic fertilizer application by farmers. Daily supervision can be conducted using wireless and portable devices for network supervision and video supervision, reducing time and transportation costs. Improve the internal structure of self-monitoring bodies, divide farmers according to their places of residence and work, and participate in organic fertilizer extension services in small groups to reduce the costs arising from formalism. Treat farmers' demands rationally, seek professional help for professional matters, and reduce the possible sunk costs. For China's underdeveloped rural areas, we should develop a channel for farmers to participate

simply, effectively, and cost-effectively. Secondly, local governments should take the initiative to unite with farmers and strengthen internal unity in rural areas to stimulate farmers' feelings for their hometowns and farmers' understanding and trust in local governments so that the extension of organic fertilizer services can be more reasonable. Finally, local governments should be more flexible in their approach, learn from the experience of organic fertilizer application in developed regions, combine with actual research and establish the most suitable system for organic fertilizer application in the local region.

(5) Establishing an organic food certification system to increase farmers' incomes, as Chinese citizens are willing to pay higher prices for organic food out of a desire for health [63]. Different types of solutions should be sought for different problems that arise in the process of applying organic fertilizers, such as political participation, economic development, culture, and moral construction. For example, helping poor farmers through individual donations, fundraising, and establishing an organic fertilizer extension service foundation. Technical personnel can provide farmers with the skills to apply organic fertilizers through intensive training and one-on-one support. Local governments can also offer lecture classes and select model farmers to motivate farmers to develop proper fertilization concepts and foster safe food concepts among Chinese citizens.

6.3. Limitations and Further Research

We acknowledge some strict limitations due to the model assumptions. However, this may provide alternative ideas for future research. Like most of the literature, we assume that farmers and local governments make purely strategic choices based on model derivations and simulations, and our work is somewhat removed from reality and needs to be further analyzed with the help of actual data. Moreover, this paper only deals with the evolutionary game between farmers and local governments, but in reality, there are many stakeholders in the process of using organic fertilizer extension services. We believe that modeling the strategic interactions of all possible stakeholders is a worthwhile attempt to address this issue and can be studied.

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