Evolutionary Game of Investment Strategy About Supply Chain for Quality Improvement of Agricultural Product with Government Subsidies

Xing Liu[1](✉) and Shengqiang Hu[2]

[1] School of Business Administration, Guangdong University of Finance and Economics, Guangzhou 510320, China
liuxing_7@163.com

[2] Research Institute of Innovation Competitiveness of Guangdong, Hongkong and Macao Bay Area, Guangdong University of Finance and Economics, Guangzhou 510320, China

Abstract. For the strategy choice of producers and transaction (or distribution) centers is whether to invest for quality improvement of agricultural products, the profits matrix and systematic evolutionary game models were built about the supply chain with or without government subsidies, the relationship between supply chain evolutionary stability strategy (ESS) and factors such as l investment return and investment cost without government subsidies was discussed, the influence of the government subsidy ratio for investment costs on the evolution process and results about strategies of the supply chain is analyzed, and the relevant conclusions were verified through simulation analysis. Finally, from the perspectives of producers, trading (or distribution) centers and the government, the optimization measures to improve the quality of agricultural products and the government supervision and subsidies mechanisms were proposed.

Keywords: Government subsidies · Agricultural product supply chain · Investment strategy for quality improvement · Evolutionary game

1 Introduction

During the "14th Five Year Plan" period, the overall qualification rate of major agricultural products in China reached 97.6% [1], but the safety incidents of agricultural products such as "poisonous bean sprouts" and "foot flavor pickled Chinese cabbage" continued to emerge one after another, which has seriously endangered the life and health of the public and social harmony and stability. China still has a long way to go to improve the quality of agricultural products and ensure their safety, stability, and efficient supply.

Scholars mainly approach improving the quality of agricultural products from two perspectives: one is the supply chain perspective that encompasses the production, circulation, sales, and consumption of agricultural products. On the production side, Dan et al. [2] designed a combination contract of "risk sharing +repurchase" related to weather

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indices to achieve high-quality and affordable agricultural products. On the circulation side, Zhang [3] and Han [4] pointed out that introducing advanced cold chain logistics technology and equipment by cold chain logistics enterprises is beneficial for improving the safety and quality of agricultural products. On the sales side, Tan [5] promotes retailers to improve the greenness and freshness of agricultural products by establishing a green investment cost sharing contract.

The second perspective is to consider the government as a direct participant or external influencing factor. Peng et al. [6] found that government regulatory strategies can encourage enterprises to choose to produce high-quality agricultural products. Yang et al. [7] found that a certain level of punishment given by the government is beneficial for relevant enterprises to invest in quality and safety. Lin et al. [8] found that government subsidy mechanisms can promote enterprises to control the quality and safety risks of agricultural products. Li et al. [9] and Chen et al. [10] found through evolutionary game theory that government subsidies are beneficial for improving the organic level of agricultural products.

In the context of rural revitalization, this article takes producers (responsible for the planting and breeding of agricultural products) and transaction distribution centers (responsible for the processing and distribution of agricultural products) as evolutionary game subjects, explores the investment balance strategy of enterprises with or without government subsidies, and proposes optimization strategies for improving the quality of agricultural product supply chains and government subsidy mechanisms. The innovation points of this article are as follows: 1) The existing literature does not involve quality improvement investment strategies and their interactions among multiple entities in the supply chain. 2) The existing literature does not consider government subsidies for enterprise investment costs. 3) This article proposes quality improvement and optimization strategies, government subsidy mechanisms, and a combination of micro and meso economies, as well as quantitative and qualitative analysis, based on the perspective of socialist political economy with Chinese characteristics. This reflects the innovation of the research perspective and the systematic nature of the research content.

2 Model Assumptions and Parameter Settings

Based on the spirit of relevant documents on rural revitalization and agricultural and rural modernization, the basic assumptions of the model are proposed:

1) The probabilities of producers (Abbreviated as M) investing and not investing are x, $1-x$ in order; The probabilities corresponding to the transaction distribution centers (Abbreviated as TDC) are y, $1-y$, $0 \leq x, y \leq 1$; **2)** The initial profit of the M and TDC is π_m, π_r, and the investment cost is C_m, C_r, respectively; **3)** When there is only investment from M in the supply chain, the profit is $\alpha_0\pi_m - C_m$, where α_0 represents the return rate of unilateral investment by M ($\alpha_0 \geq 1 + \frac{C_m}{\pi_m}$); TDC earn a "free ride" profit of $\beta_2\pi_r$, where β_2 ($\beta_2 \geq 1$) represents their "free ride" return rate; **4)** Similarly, when there is only investment in the TDC in the supply chain, the profit after investment is $\beta_0\pi_r - C_r$, where β_0 represents the return rate of unilateral investment in the TDC ($\beta_0 \geq 1 + \frac{C_r}{\pi_r}$); The M earns a "free ride" profit of $\alpha_2\pi_m$, with α_2 ($\alpha_2 \geq 1$) being its "free ride" return rate; **5)** When both M and TDC choose to invest in quality improvement,

Table 1. Profit Matrix of Evolutionary Game between M and TDC

Participants	TDC			
		Proportion	y	$1 - y$
	Proportion	Strategy	Q_Y (Investment)	Q_N (No investment)
M	x	Q_Y	$(\alpha_1\pi_m - C_m, \beta_1\pi_r - C_r)$	$(\alpha_0\pi_m - C_m, \beta_2\pi_r)$
	$1 - x$	Q_N	$(\alpha_2\pi_m, \beta_0\pi_r - C_r)$	(π_m, π_r)

their profits are $\alpha_1\pi_m - C_m$ $(1 \leq \alpha_2 \leq \alpha_0 \leq \alpha_1)$ and $\beta_1\pi_r - C_r$ $(1 \leq \beta_2 \leq \beta_0 \leq \beta_1)$ respectively; **6)** When invest, the government provides subsidies of k_1C_m and k_2C_r to M and TDC, with k_1 and k_2 $(0 \leq k_1, k_2 \leq 1)$ being the subsidy ratio.

3 Evolutionary Game Analysis of Investment Strategies for Improving the Quality of Agricultural Product Supply Chain Without Government Subsidies

3.1 Analysis of Profit Matrix and Evolutionary Game Equilibrium Point

Based on the above assumptions and parameter settings, the profit matrix of the investment strategy evolution game for improving the quality of agricultural product supply chain without government subsidies is first constructed, as shown in Table 1.

Through mathematical calculations, Table 1 shows the two-dimensional power system (I) without government subsidies, namely:

$$\frac{dx}{dt} = x(1-x)\left[\alpha_0\pi_m - C_m - \pi_m - y(\alpha_0 - \alpha_1 - 1 + \alpha_2)\pi_m\right],$$
$$\frac{dy}{dt} = y(1-y)[\beta_0\pi_r - C_r - \pi_r - x(\beta_0 - \beta_1 - 1 + \beta_2)\pi_r].$$

For system (I), let $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$ respectively, obtain the following properties:

Corollary 1: The equilibrium points of system (I) are (0,0), (0,1), (1,0), (1,1) respectively. And when $1+\frac{C_m}{\pi_m} < \alpha_0 < \alpha_1, \alpha_1-\alpha_2 < \frac{C_m}{\pi_m}$ and $1+\frac{C_r}{\pi_r} < \beta_0 < \beta_1, \beta_1-\beta_2 < \frac{C_r}{\pi_r}$, (x^*,y^*) is also the equilibrium point of the system, where: $x^* = \frac{\beta_0\pi_r - C_r - \pi_r}{(\beta_0-\beta_1-1+\beta_2)\pi_r}$, $y^* = \frac{\alpha_0\pi_m - C_m - \pi_m}{(\alpha_0-\alpha_1-1+\alpha_2)\pi_m}$.

Proof: Let $\frac{dx}{dt} = 0$, $\frac{dy}{dt} = 0$, and under given conditions, it is evident that (0, 0), (0, 1), (1, 0), (1, 1) and (x^*, y^*) are the equilibrium points of the system.

3.2 Analysis of Evolutionary Stability Strategies for Supply Chain Systems

According to Friedman's method [11], the stability of each equilibrium point can be determined by analyzing the Jacobi matrix. If both conditions $Tr(J) < 0$ and $Det(J) > 0$ [12] are met, then the equilibrium point is the evolutionary stability strategy (ESS) of the system. Through relevant calculations, the following inference can be drawn:

Corollary 2: The Evolutionary Stability Strategy (ESS) changes with the value of $\alpha_0, \alpha_1, \alpha_2, \beta_0, \beta_1$ and β_2, and can be divided into the following 5 scenarios:

Scenario I: When $0 < \alpha_0 < 1 + \frac{C_m}{\pi_m}, \alpha_0 < \alpha_1, \alpha_1 - \alpha_2 < \frac{C_m}{\pi_m}$ and $0 < \beta_0 < 1 + \frac{C_r}{\pi_r}$, $\beta_0 < \beta_1, \beta_1 - \beta_2 < \frac{C_r}{\pi_r}$, the evolutionary stability strategy (ESS) of system (I) is (0, 0); Scenario II: When $0 < \alpha_0 < 1 + \frac{C_m}{\pi_m}, \alpha_0 < \alpha_1, \alpha_1 - \alpha_2 < \frac{C_m}{\pi_m}$ and $1 + \frac{C_r}{\pi_r} < \beta_0 < \beta_1$, $\beta_1 - \beta_2 < \frac{C_r}{\pi_r}$, the ESS of system (I) is (0,1); Scenario III: When $1 + \frac{C_m}{\pi_m} < \alpha_0 < \alpha_1$, $\alpha_1 - \alpha_2 < \frac{C_m}{\pi_m}$ and $0 < \beta_0 < 1 + \frac{C_r}{\pi_r}, \beta_0 < \beta_1, \beta_1 - \beta_2 < \frac{C_r}{\pi_r}$, the ESS of system (I) (1, 0); Scenario IV: When $1 + \frac{C_m}{\pi_m} < \alpha_0 < \alpha_1, \alpha_1 - \alpha_2 < \frac{C_m}{\pi_m}$ and $1 + \frac{C_r}{\pi_r} < \beta_0 < \beta_1$, $\beta_1 - \beta_2 < \frac{C_r}{\pi_r}$, the ESS of system (I) is (0,1) or (1,0); Scenario V: When $\frac{C_m}{\pi_m} + \alpha_2 < \alpha_0 < \alpha_1$ and $\frac{C_r}{\pi_r} + \beta_2 < \beta_0 < \beta_1$, the ESS of system (I) is (1,1).

Proof: Without government subsidies, when the values of each parameter are in different ranges, the sign of the Jacobi matrix trace and determinant of the system (I) will change, and thus the local stability of each equilibrium point can be determined.

Based on the above analysis, it is found that only when the investment profits obtained by M and TDC in the game are greater than their initial profits, it is possible to choose an investment strategy. However, whether the investment can be realized ultimately depends on factors such as investment costs and "free riding" returns.

4 Evolutionary Game Analysis of Investment Strategies for Improving the Quality of Agricultural Product Supply Chain Under Government Subsidies

In the context of rural revitalization and common prosperity, the government has repeatedly supported enterprises to improve the quality of agricultural products through investment in the form of subsidies in relevant central and local documents. Therefore, this article will explore the impact of government subsidies on the investment strategies of supply chain enterprises, in order to achieve mutual investment and improve the quality of agricultural products.

4.1 Analysis of Profit Matrix and Evolutionary Game Equilibrium Point

According to the model assumptions, the profit matrix with government subsidies is shown in Table 2.

According to Table 2, a two-dimensional power system (II) can be obtained, namely:

$$\frac{dx}{dt} = x(1-x)\left[\alpha_0\pi_m - C_m - \pi_m + k_1 C_m - y(\alpha_0 - \alpha_1 - 1 + \alpha_2)\pi_m\right]$$
$$\frac{dy}{dt} = y(1-y)[\beta_0\pi_r - C_r - \pi_r + k_2 C_r - x(\beta_0 - \beta_1 - 1 + \beta_2)\pi_r]$$

Corollary 3: The equilibrium point of system (II) is (0,0), (0,1), (1,0), (1,1). When $0 < k_1 < 1-(\alpha_1 - \alpha_2)\frac{\pi_m}{C_m}$ and $0 < k_2 < 1-(\beta_1 - \beta_2)\frac{\pi_r}{C_r}$, (x', y') is also the equilibrium point of the system. Among them, $x' = \frac{\beta_0\pi_r - C_r - \pi_r + k_2 C_r}{(\beta_0 - \beta_1 - 1 + \beta_2)\pi_r}$, $y' = \frac{\alpha_0\pi_m - C_m - \pi_m + k_1 C_m}{(\alpha_0 - \alpha_1 - 1 + \alpha_2)\pi_m}$.

Proof: Same as proof of Corollary 1.

Table 2. Profit Matrix of Evolutionary Game

Participants	TDC			
		Proportion	y	$1-y$
	Proportion	Strategy	Q_Y	Q_N
M	x	Q_Y	$(\alpha_1\pi_m - C_m + k_1 C_m,$ $\beta_1\pi_r - C_r + k_2 C_r)$	$(\alpha_0\pi_m - C_m + k_1 C_m,$ $\beta_2\pi_r)$
	$1-x$	Q_N	$(\alpha_2\pi_m,$ $\beta_0\pi_r - C_r + k_2 C_r)$	(π_m, π_r)

4.2 Analysis of Evolutionary Stability Strategies

Under government subsidies, the relationship between the evolutionary stability strategy of the supply chain system and the subsidy ratio can be analyzed.

Corollary 4: The Evolutionary Stability Strategy (ESS) changes with the value of subsidy ratio and can be divided into the following four scenarios:

Scenario VI: When $k_1 < 1 - (\alpha_0 - 1)\frac{\pi_m}{C_m}$ and $k_2 < 1 - (\beta_0 - 1)\frac{\pi_r}{C_r}$, the equilibrium point (0,0) is the only ESS of system (II); Scenario VII: When $k_1 < 1 - (\alpha_1 - \alpha_2)\frac{\pi_m}{C_m}$ and $k_2 > 1 - (\beta_0 - 1)\frac{\pi_r}{C_r}$, (0,1) is the only ESS of system (II); Scenario VIII: When $k_1 > 1 - (\alpha_0 - 1)\frac{\pi_m}{C_m}$ and $k_2 < 1 - (\beta_1 - \beta_2)\frac{\pi_r}{C_r}$, (1,0) is the only ESS of system (II); Scenario IX: When $k_1 > 1 - (\alpha_1 - \alpha_2)\frac{\pi_m}{C_m}$ and $k_2 > 1 - (\beta_1 - \beta_2)\frac{\pi_r}{C_r}$, (1,1) is the only ESS of system (II).

Proof: With government subsidies, when the subsidy ratio values are in different ranges, the sign of the Jacobi matrix trace and determinant in system (II) will change, and thus the local stability of each equilibrium point can be determined.

According to Corollary 4, when the subsidy ratio is set in different ranges, the equilibrium points of the supply chain system may be of four types, that is, the subsidy is ineffective, it promotes unilateral investment in improving agricultural product quality, or both parties invest.

Corollary 4 indicates that when factors such as returns are taken within different ranges, the ESS of the supply chain system exhibits significant differences. When the subsidy ratio meets certain conditions, the investment strategies of each enterprise will change. Therefore, the government should provide certain subsidies to both parties based on the actual situation to encourage them to abandon the "free riding" behavior that is not conducive to improving the quality of agricultural products and increase investment enthusiasm.

5 Evolutionary Game Simulation Analysis

This article simulates the dynamic evolution process of investment strategies between producers and TDC using Matlab based on the changes in government subsidy ratios. Taking scenario I as an example, it discusses the government subsidy mechanism and its role in improving investment in agricultural product supply chain quality.

Assuming that the initial value is: $C_m = 1$, $\pi_m = 2$, $k_1 = 0$, $\alpha_0 = 1.4$, $\alpha_1 = 1.6$, $\alpha_2 = 1.3$, $C_r = 0.8$, $\pi_r = 2.4$, $k_2 = 0$, $\beta_0 = 1.2$, $\beta_1 = 1.3$, $\beta_2 = 1.1$, initial investment ratio (x_0, y_0) between the M and the TDC as (0.4,0.5). From corollary 2, without government subsidies, the system's evolutionary stability strategy is (0,0), that is, Neither party invests. The evolution result is shown in Fig. 1(a);

When only subsidize the M, take $k_1 = 0.1$, $k_2 = 0$ (scenario VI), and at this point, subsidies have no effect; Take $k_1 = 0.3$, $k_2 = 0$ (scenario VIII). At this point, government subsidies encourage producers to invest, and the evolution result is shown in Fig. 1(b);

In the case of only subsidizing the TDC, take $k_1 = 0$, $k_2 = 0.3$ (scenario VI), and the government subsidy has no effect; Take $k_1 = 0$, $k_2 = 0.5$ (scenario VII), the government subsidy will encourage the trading and distribution center to choose investment. The evolution result is shown in Fig. 1c);

If both parties are subsidized at the same time, take $k_1 = 0.1$, $k_2 = 0.3$ (scenario VI), and the subsidy has no effect; Take $k_1 = 0.3$, $k_2 = 0.5$ (scenario VII), the government subsidy only promotes unilateral investment in the TDC; Take $k_1 = 0.4$, $k_2 = 0.3$ (scenario VIII), in which case the government subsidy only promotes unilateral investment by the producer; Take $k_1 = 0.5$, $k_2 = 0.5$ (scenario IX). At this point, subsidies encourage both producers and TDC to invest. The evolution result is shown in Fig. 1(d).

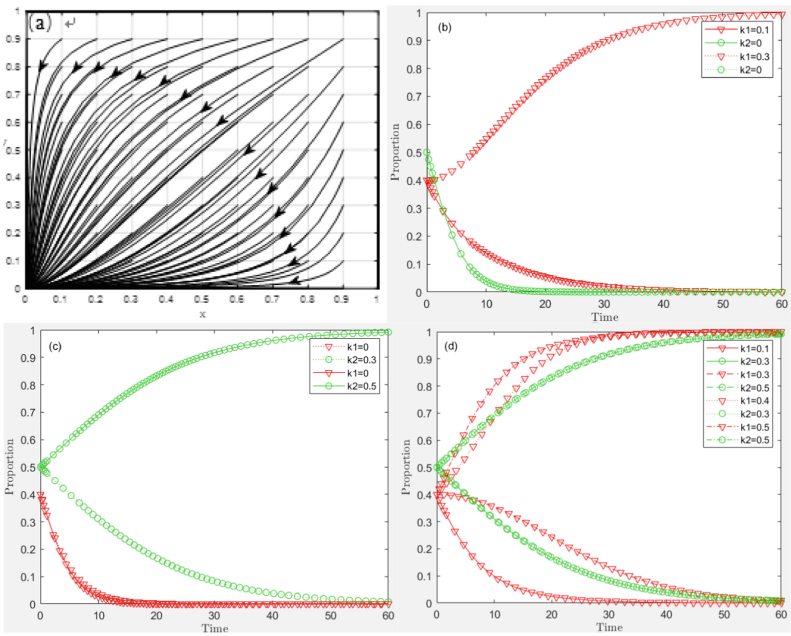

Fig. 1. Evolution Path of Quality Improvement Investment between M and TDC Based on Different Subsidies in Scenario I

6 Conclusions and Recommendations

This article constructs an evolutionary game model of investment strategies for improving the quality of agricultural product supply chain with or without government subsidies, focusing on analyzing the range of government subsidy ratios when ESS is (0,0), (0,1), (1,0) and (1,1), and the following conclusions are drawn:

(1) Without government subsidies, only when the investment profits of both parties are greater than initial profits, can they possibly invest. However, whether the investment can be realized ultimately depends on factors such as investment costs and "free riding" returns.
(2) Under government subsidies, only by providing subsidies to both parties can investment be promoted, but the specific impact depends on the level of government subsidies. Appropriate subsidy intensity can effectively suppress their speculative behavior and make them willing to pay investment costs.

This article proposes the following suggestions and measures:

The investment measures for agricultural product supply chain enterprises are as follows:

(1) For producers, they should minimize the risks of agricultural product output, such as natural disasters and pests, and improve breeding technology and agricultural machinery and equipment; At the same time, strengthen cooperation with downstream enterprises in quality traceability and other aspects, and strengthen communication to eliminate "free riding" behavior; Actively communicate with the government, comply with laws and regulations, and strive to improve quality levels to meet the quality standards required by the government.
(2) For TDC, strict management should be implemented on the input and output of agricultural products at each node of the supply chain; Strengthen contact and communication with upstream and downstream enterprises, establish information sharing mechanisms, and form a win-win or multi win situation; Strengthen cooperation and communication with the government, implement relevant government policies, and seek government assistance when facing financial difficulties.

The design of government regulation and subsidy mechanisms is as follows:

On the one hand, in order to meet the social demand for organic and green agricultural products, the government should actively create local "vegetable basket" brands, establish information sharing mechanisms and information hub platforms, strengthen market supervision of green and high-quality agricultural products, and improve laws and regulations on agricultural product quality and safety.

On the other hand, in order to promote enterprises to actively invest in improving the quality of agricultural products, the government should design a government subsidy mechanism for agricultural product supply chain that includes subsidy targets, subsidy conditions, subsidy methods, etc., and improve the accuracy, stability, and timeliness of subsidy policies.

In addition, the article has certain limitations: firstly, it does not consider the supervisory feedback effect of consumers on the quality of agricultural products from a demand perspective. Secondly, the possible negative externality of government subsidies and other measures on investment behavior are not considered. Finally, the interaction between the output risk of producers and the quality of agricultural products was not considered. Therefore, considering the negative externality brought about by government subsidies, introducing consumer feedback and supervision mechanisms, studying the interaction effects of enterprises' optimal strategies, and then establishing a multi-party game model is the direction of future research.

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