

Research Article

Evolutionary Game Analysis of Chinese Food Quality considering Effort Levels

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Received 14 June 2019; Revised 2 September 2019; Accepted 18 September 2019; Published 16 November 2019

Academic Editor: Michele Scarpiniti

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Food safety accidents occur frequently, which has caused great harm to people's health. With the consideration that food quality requires the joint efforts of all members of the food supply chain and that quality-improving efforts for food have a positive external effect, we focus on the quality-improving effort level, which is very important for food quality and safety. This paper builds an evolutionary game model and employs the replicated dynamic equation to study evolutionarily stable strategies of suppliers and producers. Furthermore, simulation experiments are conducted to verify the modeling analyses and demonstrate the influences of game parameters. The research results show that the behavioral strategies are closely related to the factors such as the ratios of the input to the output, the cost of quality-improving efforts, the hitchhiking benefits, and the initial strategy. Only when the punishing dynamics of the government exceeds a certain value, both participants can choose the quality-improving effort strategy. Based on the results, this paper has provided some inspiration for policy-making of government institutions.

1. Introduction

In recent years, because of the frequent occurrence of food safety accidents, great damage has occurred to the health of the people, causing widespread concern in the society. The No. 1 document of China's central government in 2019 once again stressed the importance of improving the food quality, improving the standard system of food quality, and effectively ensuring the quality of food. The food supply chain usually involves the source's supply of raw materials, production and processing, retail, and so on. Risk factors in any link may lead to unsafe food. Therefore, the joint efforts of all the participant bodies in the food supply chain are required to ensure the food safety [1]. However, China currently faces many food quality challenges such as inferior infant formula, toxic capsules, diseased or dead pig, hormone-tainted fruits, lean meat powder, ditch oil, and abuse of food additives [2–5]. Many scholars believed that information asymmetry was one of the main causes for the issue of food safety [6, 7]. Information asymmetry, on the

one hand, leads to moral hazard; that is, food producers reduce their quality by making shoddy food and even produce fake and inferior food. On the other hand, it leads to adverse selection; that is, consumers choose low-quality products to avoid risks because they cannot effectively distinguish product quality [8, 9]. The market failure caused by asymmetric information needs the participation of government regulation [10]. But a series of important food safety accidents have shaken the public confidence in the government's ability to manage food safety risks [11, 12]. According to the public governance theory, the third party must be introduced to participate in governance in the case of "market failure" and "government failure". Therefore, cogovernance was proposed, the subjects of which include the government, nongovernmental organizations (social organizations and social media), market entities, and social individuals [13]. However, cogovernance is to coordinate the social, economic, and cultural environment and coordinate the interest conflicts of different groups [14]. If the conditions are not met,

cogovernance is difficult to construct, the substance of which belongs to external governance. The fundamental solution to food safety problems is that all participants in the food supply chain make efforts to invest in quality. However, the quality effort input in the food supply chain has a positive external effect, which provides a strong incentive for the participants in the supply chain to hitchhike. Therefore, the government needs to take measures to encourage participants to take the initiative in quality input. In response to this, this paper studies the quality input behavior of food supply chain members from the perspective of quality effort.

The relationship between the effort behavior of members and the operation efficiency of the supply chain has always been a hot topic among scholars. He et al. [15] review the operation management research on food quality and safety and classify the related articles into four categories, that is, storage problems, distribution problems, marketing problems, and food traceability and safety problems. Roels et al. [16] discusses the impact of non-contractual arrangements on bilateral efforts and profits, and the results show that fixed-fee contracts are optimal when the service output is more sensitive to the vendor's effort, that time-and-materials contracts are optimal when the output is more sensitive to the buyer's effort, and that performance-based contracts are optimal when the output is sensitive to both the buyer's and the vendor's inputs. Kaya [17] finds that a linear contract, a quantity discount contract, and a simultaneous revenue and cost-sharing contract can coordinate the supply chain in the manufacturers' effort model. However, when the supplier is the one exerting the effort, only a simultaneous revenue and cost-sharing contract can coordinate the supply chain. Tsao and Sheen [18] consider a two-echelon multiple-retailer distribution channel with retailers' promotional efforts and the sales learning curve. The model shows that keeping the fraction of promotion cost sharing within an appropriate range increases profits for all parties. Taylor [19] shows that a properly designed target rebate and returns contract achieves coordination and a win-win outcome when demand is impacted by retailer sales effort. He et al. [20] explore a variety of contracts to coordinate the supply chain when the demand is influenced by both retail price and retailer sales effort. They find that only the properly designed returns policy with the SRP contract can achieve channel coordination and lead to Pareto improving the win-win situation for supply chain members.

Government regulation is the main way to solve food safety problems. Some scholars have studied the necessity of government regulation, and the results show that food safety is the basic responsibility of the government [21–23]. Other scholars have also discussed some problems in the China food regulatory system and proposed suggestions for the current situation. For example, Liu [24] thinks that China's food safety supervision has many problems, such as imperfect supervision system and mechanism, weak supervision capacity, decentralized supervision power allocation structure, and insufficient supervision independence. Ren et al. [25] explore the

operational problems of traditional supervision, advocate to convert government functions, and change enterprises from "reactive" supervision to "autonomous" supervision. Cao et al. [26] suggest that the government should increase the inspection frequency of enterprises, reduce the cost of enterprise self-discipline, and increase the punishment of enterprises. Zhang [27] points out that government supervision should adopt scientific food safety supervision methods, and it has become an inevitable trend to use information means to realize fast and effective food safety management. The above studies emphasize that government regulation is very important in food safety. However, they neglect the impact of changes in the intensity of government regulation on food enterprises.

Because of the limitation of information, knowledge, environment, and so on, it is difficult for some members in the supply chain to know whether other members exert effort to improve product quality. Therefore, members in the supply chain cannot make a completely rational decision. In order to overcome the defect of traditional game theory, which assumes that supply chain members are completely rational, the evolutionary game theory is developed as a means to predict the expected distribution of individual behaviors in a biological system with a single species that evolves under natural selection [28]. Smith and Price [29] first put forward an evolutionary stable strategy (ESS), which is defined as a strategy S^* satisfying the following two conditions: (1) $E(S^*, S^*) \geq E(S, S^*)$ for all $S \neq S^*$ and (2) $E(S^*, S) > E(S, S)$ when equality in the first condition holds, where E is the payoff function [30]. The replicator dynamics is proposed by Taylor and Jonker [31], the basic idea of which is that if one strategy gains more than the average income of other strategies during the game process, then it indicates that the strategy is suitable for the evolution of the group [32]. Some researchers have applied evolutionary game theory to study low-carbon scenarios [33, 34], pollution regulation [35, 36], enterprises' cooperation and competition in the supply chain [37–39], and so on. For example, He et al. [32] study an effective green incentive mechanism for the government to promote green tourism development by establishing a three-party dynamic evolutionary game model. So far, few researchers have employed the evolutionary game theory to study food quality. Ma [40] researches the quality control issue in the food supply chain by establishing a dynamic evolutionary game model. Xu et al. [41] analyze the investment decisions of suppliers and manufacturers in food safety based on an evolutionary game. Cao et al. [42] analyze the influence and authenticity of new media on the decision-making results of the government and food enterprises by establishing an asymmetric evolutionary game. Su et al. [43] discuss the influence of the trilateral evolutionary game on the quality of agrifood under the farmer-supermarket direct purchase mode. However, the above studies ignored the quality effort level of supply chain members. Compared with the previous studies mentioned above, the possible innovations of our research include the following three points: First, the payment matrix is constructed by introducing two kinds of ratios of the input to the output. Second, this paper studies the quality-improving

input from the perspective of quality effort levels, which is the key innovation. Third, we analyze the evolutionary stable strategy (ESS) of the system under a punishment mechanism, and numerical simulation is presented under different degrees of punishment.

The rest of this paper is organized as follows: Section 2 introduces the basic assumptions, parameters, and variables. Section 3 constructs a model and analyzes the decision-making strategies of suppliers and producers. Section 4 analyzes the evolutionary behaviors of players under a penalty mechanism. A numerical simulation is presented in Section 5. Finally, conclusions and future work are presented.

2. Research Assumptions

Assume that there are only two kinds of participants in the food supply chain: The first group is the suppliers who are engaged in the production of food raw materials. Quality-improving efforts of suppliers include actively developing quality management and supervision systems, strictly implementing production safety standards, introducing more advanced production equipment, and investing refrigeration facilities. The second group is the producers who are engaged in the production of food. Quality-improving efforts of producers include the purchase of food testing equipment, traceability system software, and hardware and safety production training. The pure strategy set of the supplier and producer consists of two alternative strategies: quality-improving effort (QE) and no effort (NE). The supplier adopts the QE strategy with the probability of x ($0 \leq x \leq 1$) and the NE strategy with $1 - x$. Similarly, the probability of the producer choosing the QE strategy is y ($0 \leq y \leq 1$), and the probability of NE is $1 - y$.

Hypothesis 1. When neither supplier nor producer makes quality-improving efforts, the food supply chain can only provide products that meet the basic qualification requirements. R_1 and R_2 ($R_1 > 0$ and $R_2 > 0$), respectively, represent the supplier's profit and producer's profit without effort input.

Hypothesis 2. When only the supplier in the supply chain exerts effort, his/her effort improves the quality of raw materials, which will help to improve food quality. It is assumed that market demands are related to the quality of the product and consumers buy high-quality food at a high price. With the improvement of product quality, market demands will increase. The supplier's profit is $R_1 + \alpha_0 e_1 - C_1$, where e_1 represents the supplier's effort input, α_0 ($0 < \alpha_0 < 1$) represents the ratio of the input to the output of the supplier, and C_1 represents the cost of the supplier's efforts. Because of the effort of the supplier, the producer can obtain a supernormal benefit T_2 ($T_2 > R_2$) by free-riding.

Hypothesis 3. When only the producer in the supply chain exerts quality-improving effort, his/her effort improves the quality of production and processing which will help to

improve the food quality. Similarly, the producer's profit is $R_2 + \beta_0 e_2 - C_2$, where e_2 represents the producer's effort input, β_0 ($0 < \beta_0 < 1$) represents the ratio of the input to the output of the producer, and C_2 represents the cost of the producer's effort. Because of the effort of the producer, the supplier can obtain a supernormal benefit T_1 ($T_1 > R_1$) by free-riding.

Hypothesis 4. When both sides exert effort together to improve the quality of products, the quality of products has been greatly improved. With the further improvement of product quality, the market demands will increase even more. Consumers will buy high-quality food products at a higher price. Their earnings are expressed as $R_1 + \alpha_1 e_1 - C_1$ and $R_2 + \beta_1 e_2 - C_2$, respectively, where α_1 ($\alpha_1 \geq \alpha_0$) represents the ratio of the input to the output of the supplier when both sides exert effort together and β_1 ($\beta_1 \geq \beta_0$) represents the ratio of the input to the output of the producer when both sides exert effort together.

3. Game Model

3.1. The Model. Regarding the above assumption, the payoff of the supplier and the producer is presented in Table 1.

In terms of the parameters in Table 1, the expected return of the supplier choosing the QE and NE strategies is

$$\begin{aligned} U_{11} &= y(R_1 + \alpha_1 e_1 - C_1) + (1 - y)(R_1 + \alpha_0 e_1 - C_1), \\ U_{12} &= yT_1 + (1 - y)R_1, \end{aligned} \quad (1)$$

where U_{11} represents the expected return of the supplier for the QE strategy and U_{12} represents the expected return of the supplier for the NE strategy. Thus, the average expected return of the supplier is

$$\bar{U}_1 = xU_{11} + (1 - x)U_{12}. \quad (2)$$

Thus, the replicated dynamic equation of the supplier's evolutionary strategy is

$$\begin{aligned} \dot{x} &= \frac{dx}{dt} = x(U_{11} - \bar{U}_1) = x(1 - x)(\alpha_0 e_1 - C_1 \\ &\quad + y(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)). \end{aligned} \quad (3)$$

Similarly, the expected return of the producer choosing the QE and NE strategies is

$$\begin{aligned} U_{21} &= x(R_2 + \beta_1 e_2 - C_2) + (1 - x)(R_2 + \beta_0 e_2 - C_2), \\ U_{22} &= xT_2 + (1 - x)R_2, \end{aligned} \quad (4)$$

where U_{21} represents the expected return of the producer for the QE strategy and U_{22} represents the expected return of the producer for the NE strategy. Thus, the average expected return of the producer is

$$\bar{U}_2 = yU_{21} + (1 - y)U_{22}. \quad (5)$$

Thus, the replicated dynamic equation of the producer's evolutionary strategy is

TABLE 1: Payoff matrix.

| Supplier | Producer | |
|----------|---|---------------------------------|
| | QE | NE |
| QE | $R_1 + \alpha_1 e_1 - C_1, R_2 + \beta_1 e_2 - C_2$ | $R_1 + \alpha_0 e_1 - C_1, T_2$ |
| NE | $T_1, R_2 + \beta_0 e_2 - C_2$ | R_1, R_2 |

$$\dot{y} = \frac{dy}{dt} = y(U_{21} - \bar{U}_2) = y(1-y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 - (\beta_0 - \beta_1)e_2)). \quad (6)$$

The two-dimensional dynamic autonomy system I consisting of formulas (3) and (6) can be expressed as

$$\begin{cases} \frac{dx}{dt} = x(1-x)(\alpha_0 e_1 - C_1 + y(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)), \\ \frac{dy}{dt} = y(1-y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 - (\beta_0 - \beta_1)e_2)). \end{cases} \quad (7)$$

Proposition 1. The equilibrium points of system I are $O(0, 0)$, $A(0, 1)$, $B(1, 0)$, and $C(1, 1)$. When $(C_1/e_1) < \alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$ and $(C_2/e_2) < \beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, $D(x^*, y^*)$ is the equilibrium point.

$$\begin{aligned} x^* &= \frac{\beta_0 e_2 - C_2}{T_2 + (\beta_0 - \beta_1)e_2 - R_2}, \\ y^* &= \frac{\alpha_0 e_1 - C_1}{T_1 + (\alpha_0 - \alpha_1)e_1 - R_1}. \end{aligned} \quad (8)$$

$$J = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} (1-2x)(\alpha_0 e_1 - C_1 + y(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)) & x(1-x)(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1) \\ y(1-y)(R_2 - T_2 - (\beta_0 - \beta_1)e_2) & (1-2y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 - (\beta_0 - \beta_1)e_2)) \end{bmatrix}. \quad (10)$$

The value of the matrix determinant J is

$$\begin{aligned} \det J &= (1-2x)(\alpha_0 e_1 - C_1 + y(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)) \\ &\quad \cdot (1-2y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 - (\beta_0 - \beta_1)e_2)) \\ &\quad - x(1-x)(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)y(1-y) \\ &\quad \cdot (R_2 - T_2 - (\beta_0 - \beta_1)e_2). \end{aligned} \quad (11)$$

The trace of the matrix J is

$$\begin{aligned} \text{tr} J &= (1-2x)(\alpha_0 e_1 - C_1 + y(R_1 - T_1 - (\alpha_0 - \alpha_1)e_1)) \\ &\quad + (1-2y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 - (\beta_0 - \beta_1)e_2)). \end{aligned} \quad (12)$$

3.2. Model Discussion. According to different conditions, we study the local stability of different equilibrium points. There

Proof. Let equation (3) = 0 and equation (6) = 0, then we can get the equilibrium points $O(0, 0)$, $A(0, 1)$, $B(1, 0)$, and $C(1, 1)$. When $(C_1/e_1) < \alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$ and $(C_2/e_2) < \beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, we obtain $0 < (\beta_0 e_2 - C_2)/(T_2 + (\beta_0 - \beta_1)e_2 - R_2) < 1$ and $0 < (\alpha_0 e_1 - C_1)/(T_1 + (\alpha_0 - \alpha_1)e_1 - R_1) < 1$. Therefore, $D(x^*, y^*)$ is the equilibrium point.

According to Friedman's research method [44], the evolutionary stable strategy (ESS) can be judged by the following criteria:

$$\begin{aligned} \det(J) &= \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22} - a_{12}a_{21} > 0, \\ \text{tr}(J) &= a_{11} + a_{22} < 0. \end{aligned} \quad (9)$$

The Jacobian matrix of system I is as follows:

would be five scenarios in the game, which are analyzed as follows.

3.2.1. Scenario I

Proposition 2. When $0 < \alpha_0 < (C_1/e_1)$, $\alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$, $0 < \beta_0 < (C_2/e_1)$, and $\beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, $O(0, 0)$ is the ESS point. The behavior strategy is (NE, NE).

Proof. According to the above method, we can calculate the value of $\det J$ and $\text{tr} J$ for each equilibrium point. The results of four local equilibrium points are shown in Table 2.

Although the quality-improving effort is high, the supplier and producer all get less revenue because ratios of the input to the output α_0 , α_1 , β_0 , and β_1 are relatively small. Therefore, $O(0, 0)$ is an ESS point, $A(0, 1)$ and $B(1, 0)$ are two

saddle points, and $C(1, 1)$ is an unstable point. The evolutionary path is shown in Figure 1(a).

3.2.2. Scenario II

Proposition 3. When $0 < \alpha_0 < (C_1/e_1)$, $\alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$, and $(C_2/e_2) < \beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, $A(0, 1)$ is the ESS point. The behavior strategy is (NE, QE).

Proof. The method is similar to the proof of Proposition 2. The results of four local equilibrium points are shown in Table 3.

The revenue of the producer's quality-improving effort is greater than the cost but less than the free-riding revenue. The revenue of the supplier's effort is less than the cost, so the supplier is reluctant to improve quality. Therefore, $A(0, 1)$ is an ESS point, $O(0, 0)$ and $B(1, 0)$ are two saddle points, and $C(1, 1)$ is an unstable point. The evolutionary path is shown in Figure 1(b).

3.2.3. Scenario III

Proposition 4. When $(C_1/e_1) < \alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$, $0 < \beta_0 < (C_2/e_2)$, and $\beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, $B(1, 0)$ is the ESS point. The behavior strategy is (QE, NE).

Proof 4. The method is similar to the proof of Proposition 2. The results of four local equilibrium points are shown in Table 4.

The revenue of the supplier's effort is greater than the cost but less than the free-riding revenue. The revenue of the producer's quality-improving effort is less than the cost, so the producer is reluctant to improve quality. Therefore, $B(1, 0)$ is an ESS point, $O(0, 0)$ and $A(0, 1)$ are two saddle points, and $C(1, 1)$ is an unstable point. The evolutionary path is shown in Figure 1(c).

3.2.4. Scenario IV

Proposition 5. When $(C_1/e_1) < \alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$ and $(C_2/e_2) < \beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$ are satisfied, $A(0, 1)$ and $B(1, 0)$ are the ESS points. The behavior strategy is (QE, NE) and (NE, QE). The equilibrium state depends on the initial state of the system.

- (i) When the initial state falls into the area ACDO, $A(0, 1)$ is the ESS point.
- (ii) When the initial state falls into the area BCDO, $B(1, 0)$ is the ESS point.

Proof. The method is similar to the proof of Proposition 2. The results of five local equilibrium points are shown in Table 5.

TABLE 2: Evolutionary stability of local equilibrium points in Scenario I.

| Equilibrium point | trJ | detJ | State |
|-------------------|-----------|------|----------------|
| (0, 0) | – | + | ESS point |
| (0, 1) | Uncertain | – | Saddle point |
| (1, 0) | Uncertain | – | Saddle point |
| (1, 1) | + | + | Unstable point |

Both the supplier's revenue and the producer's revenue are greater than the cost but less than the free-riding revenue. Therefore, $A(0, 1)$ and $B(1, 0)$ are ESS points. $O(0, 0)$ and $C(1, 1)$ are two unstable points. $D(x^*, y^*)$ is the saddle point. The evolutionary path is shown in Figure 1(d). The equilibrium state depends on the initial state of system I. The possibility of the evolutionary result that eventually converges to $A(0, 1)$ or $B(1, 0)$ is determined by the size of the areas S_A (i.e., quadrangle ACDO) and S_B (i.e., quadrangle BCDO). When $S_A = S_B$, the probability of the system which will converge to $A(0, 1)$ or $B(1, 0)$ is the same. When $S_A > S_B$, the probability of the system which will converge to $A(0, 1)$ is greater than the probability of the system which will converge to $B(1, 0)$; that is to say, the supplier will choose the NE strategy and the producer will choose the QE strategy. When $S_A < S_B$, the probability of the system which will converge to $B(1, 0)$ is greater than the probability of the system which will converge to $A(0, 1)$; that is to say, the supplier will choose the QE strategy and the producer will choose the NE strategy.

The size of the area S_A is

$$S_A = \frac{1}{2} \left[\frac{\beta_0 e_2 - C_2}{T_2 + (\beta_0 - \beta_1) e_2 - R_2} + \frac{T_1 - R_1 + C_1 - \alpha_1 e_1}{T_1 + (\alpha_0 - \alpha_1) e_1 - R_1} \right]. \quad (13)$$

According to equation (13), we can draw some important conclusions:

Corollary. The size of the area S_A is affected by different parameters and has the following characteristics:

- (1) $(\partial S_A / \partial \alpha_0) < 0$, $(\partial S_A / \partial \alpha_1) < 0$, $(\partial S_A / \partial \beta_0) > 0$, and $(\partial S_A / \partial \beta_1) > 0$
- (2) $(\partial S_A / \partial R_1) < 0$ and $(\partial S_A / \partial R_2) > 0$
- (3) $(\partial S_A / \partial T_1) > 0$ and $(\partial S_A / \partial T_2) < 0$
- (4) $(\partial S_A / \partial C_1) > 0$ and $(\partial S_A / \partial C_2) < 0$

Corollary (1) shows that when the ratio of the input to the output of the supplier becomes smaller, and the ratio of the input to the output of the producer become greater, there is a higher probability that the system will converge toward $A(0, 1)$. Corollary (2) indicates that when the income of the supplier becomes smaller, and the income of the producer becomes higher, there is a higher probability that the system will converge toward $A(0, 1)$. Otherwise, there is a higher probability that the system will converge toward $B(1, 0)$. Corollary (3) shows that when the income of free-riding for the supplier becomes larger, and the income of free-riding for the producer becomes smaller, there is a higher probability that the system will converge toward $A(0, 1)$. Otherwise, there is a higher probability that the system will converge

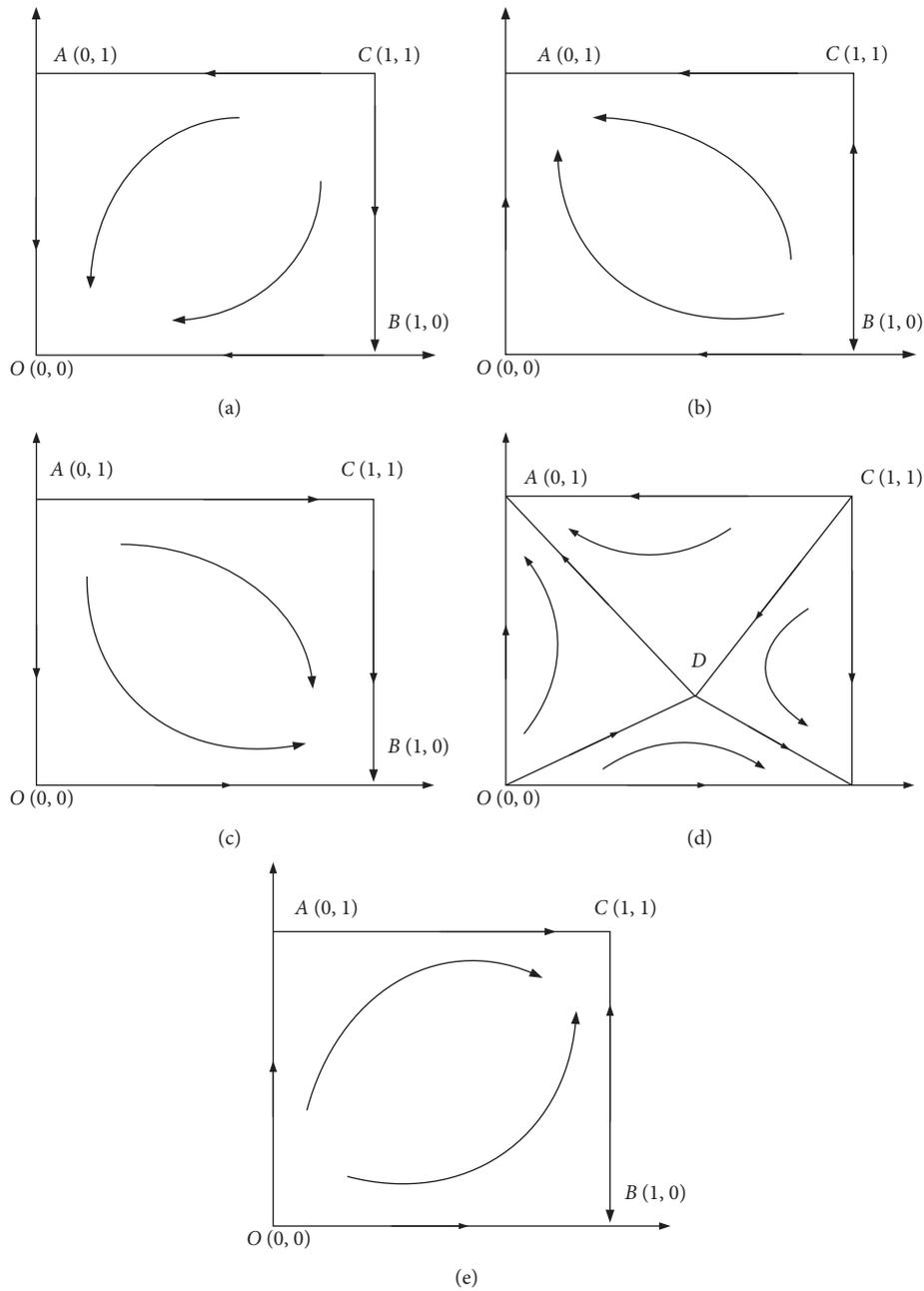


FIGURE 1: Phase diagrams of the evolutionary game.

TABLE 3: Evolutionary stability of local equilibrium points in Scenario II.

| Equilibrium point | $\text{tr}J$ | $\text{det}J$ | State |
|-------------------|--------------|---------------|----------------|
| $(0, 0)$ | Uncertain | - | Saddle point |
| $(0, 1)$ | - | + | ESS point |
| $(1, 0)$ | Uncertain | - | Saddle point |
| $(1, 1)$ | + | + | Unstable point |

TABLE 4: Evolutionary stability of local equilibrium points in Scenario III.

| Equilibrium point | $\text{tr}J$ | $\text{det}J$ | State |
|-------------------|--------------|---------------|----------------|
| $(0, 0)$ | Uncertain | - | Saddle point |
| $(0, 1)$ | Uncertain | - | Saddle point |
| $(1, 0)$ | - | + | ESS point |
| $(1, 1)$ | + | + | Unstable point |

toward $B(1, 0)$. Corollary (4) indicates that when the cost of the supplier becomes larger, and the cost of the producer becomes smaller, there is a higher probability that the system

will converge toward $A(0, 1)$. Otherwise, there is a higher probability that the system will converge toward $B(1, 0)$. The specific calculation process is presented in Appendix.

TABLE 5: Evolutionary stability of local equilibrium points in Scenario IV.

| Equilibrium point | trJ | detJ | State |
|-------------------|-----|------|----------------|
| (0, 0) | + | + | Unstable point |
| (0, 1) | - | + | ESS point |
| (1, 0) | - | + | ESS point |
| (1, 1) | + | + | Unstable point |
| (x^*, y^*) | | + | Saddle point |

3.2.5. Scenario V

Proposition 6. When $((T_1 - R_1 + C_1)/e_1) < \alpha_0 < \alpha_1$ and $((T_2 - R_2 + C_2)/e_2) < \beta_0 < \beta_1$ are satisfied, (1, 1) is the ESS point. The behavior strategy is (QE, QE).

Proof 6. The method is similar to the proof of Proposition 2. The results of four local equilibrium points are shown in Table 6.

The revenue of the producer's quality-improving effort is greater than the cost, and the revenue of the supplier's quality-improving effort is greater than the cost. Therefore, suppliers and producers are willing to exert effort to improve product quality. Therefore, $C(1, 1)$ is an ESS point, $A(0, 1)$ and $B(1, 0)$ are two saddle points, and $O(0, 0)$ is an unstable point. The evolutionary path is shown in Figure 1(e).

4. Analysis of Evolutionary Game under Punishment Mechanism

According to the above analysis results, when the ratios of the input to the output $\alpha_0, \alpha_1, \beta_0,$ and β_1 are relatively small, and the benefit of the player is less than the cost, or the benefit of the player is greater than the cost but less than the free-riding benefit, the player is reluctant to choose the QE strategy. In this case, government regulation is necessary. Suppose that the player choosing free-riding will be punished P by the government. If both sides are reluctant to exert quality-improving efforts, neither is punished. The payoff under the punishment mechanism is presented in Table 7.

The two-dimensional dynamic autonomy system II can be expressed as

$$\begin{cases} \frac{dx}{dt} = x(1-x)(\alpha_0 e_1 - C_1 + y(R_1 - T_1 + P - (\alpha_0 - \alpha_1)e_1)), \\ \frac{dy}{dt} = y(1-y)(\beta_0 e_2 - C_2 + x(R_2 - T_2 + P - (\beta_0 - \beta_1)e_2)). \end{cases} \quad (14)$$

Proposition 7. The equilibrium points of the replicator dynamic system are $O(0, 0)$, $A(0, 1)$, $B(1, 0)$, and $C(1, 1)$. If and only if $0 < P < \min(T_2 - R_2 + C_2 - \beta_1 e_2, T_1 - R_1 + C_1 - \alpha_1 e_1)$, $D(x^*, y^*)$ is the equilibrium point.

TABLE 6: Evolutionary stability of local equilibrium points in Scenario V.

| Equilibrium point | trJ | detJ | State |
|-------------------|-----------|------|----------------|
| (0, 0) | + | + | Unstable point |
| (0, 1) | Uncertain | - | Saddle point |
| (1, 0) | Uncertain | - | Saddle point |
| (1, 1) | - | + | ESS point |

TABLE 7: Payoff matrix under the punishment mechanism.

| Supplier | Producer | |
|----------|---|-------------------------------------|
| | QE | NE |
| QE | $R_1 + \alpha_1 e_1 - C_1, R_2 + \beta_1 e_2 - C_2$ | $R_1 + \alpha_0 e_1 - C_1, T_2 - P$ |
| NE | $T_1 - P, R_2 + \beta_0 e_2 - C_2$ | R_1, R_2 |

$$\begin{aligned} x^* &= \frac{\beta_0 e_2 - C_2}{T_2 + (\beta_0 - \beta_1)e_2 - R_2 - P}, \\ y^* &= \frac{\alpha_0 e_1 - C_1}{T_1 + (\alpha_0 - \alpha_1)e_1 - R_1 - P}. \end{aligned} \quad (15)$$

Proposition 8. The necessary and sufficient condition that $D(1, 1)$ is the only ESS point of system II is $P > \max(T_1 + C_1 - R_1 - \alpha_1 e_1, C_2 + T_2 - R_2 - \beta_1 e_2)$.

Proof 8. According to data in Table 8, the necessary and sufficient condition that $D(1, 1)$ is the only ESS point of system II is $\det J > 0$ and $\text{tr} J < 0$. That is, $-(R_1 - T_1 + P - C_1 + \alpha_1 e_1) - (R_2 - T_2 + P - C_2 + \beta_1 e_2) < 0$ and $(R_1 - T_1 + P - C_1 + \alpha_1 e_1)(R_2 - T_2 + P - C_2 + \beta_1 e_2) > 0$. Therefore, we can get $(R_1 - T_1 + P - C_1 + \alpha_1 e_1) > 0$ and $(R_2 - T_2 + P - C_2 + \beta_1 e_2) > 0$. Therefore, $P > \max(T_1 + C_1 - R_1 - \alpha_1 e_1, C_2 + T_2 - R_2 - \beta_1 e_2)$.

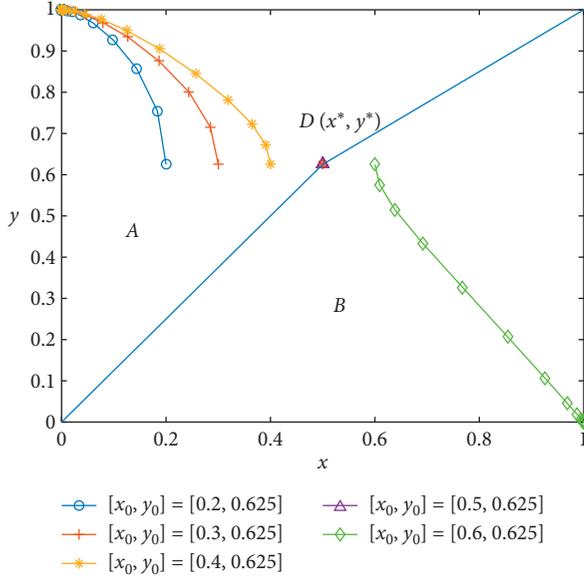
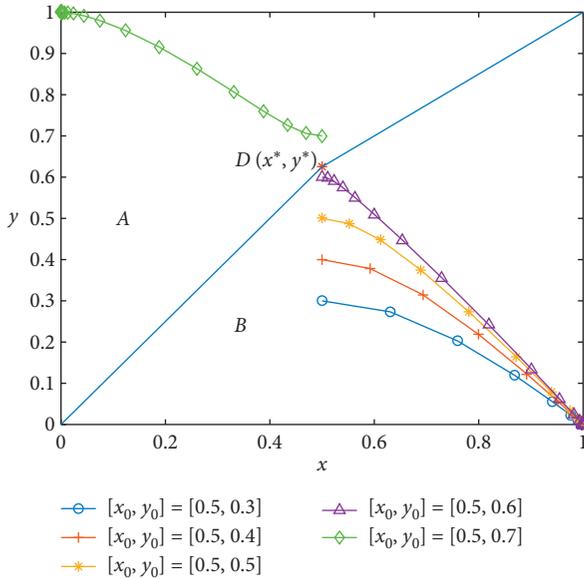
This proposition represents that when $P > \max(T_1 + C_1 - R_1 - \alpha_1 e_1, C_2 + T_2 - R_2 - \beta_1 e_2)$ is satisfied, the evolutionary stable strategy (ESS) point of system II is $C(1, 1)$. That is to say, the penalty imposed by the government is greater than the difference between the benefits of the free-riding of the supplier or producer and the benefits of the supplier- or producer-exerted effort to improve the quality. Suppliers and producers are willing to work together to improve product quality because the government's punishment is very high. Therefore, if the government increases the penalty for players, it will make the free-riding behavior unprofitable and thus reduce the opportunistic behavior of both sides.

5. Numerical Simulation

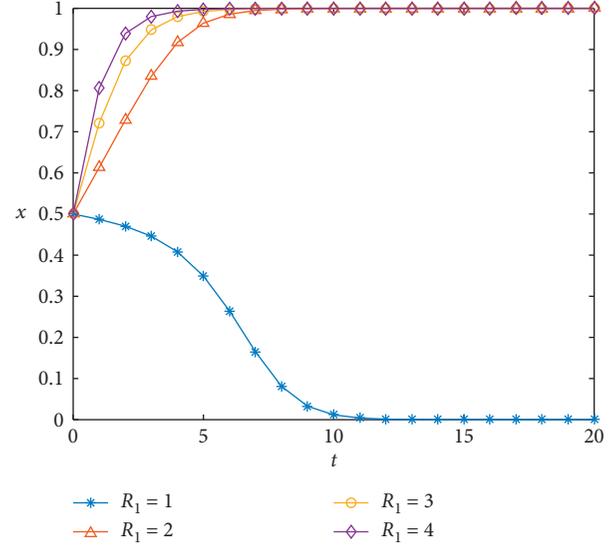
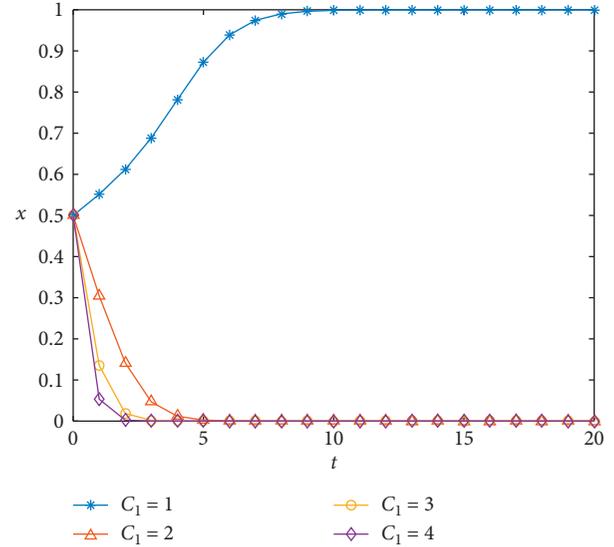
In order to further understand the influence of the initial value, different factors, and government regulation, the numerical experiment is conducted to observe changes in strategic choices of the supplier and producer under different initial values, parameter values, and degrees of government penalty.

TABLE 8: Values of a_{11} , a_{12} , a_{21} , and a_{22} at the local stable equilibrium point.

| Equilibrium point | a_{11} | a_{12} | a_{21} | a_{22} |
|-------------------|---|----------|----------|--|
| (0, 0) | $\alpha_0 e_1 - C_1$ | 0 | 0 | $\beta_0 e_2 - C_2$ |
| (0, 1) | $R_1 - T_1 + P - C_1 + \alpha_1 e_1$ | 0 | 0 | $-(\beta_0 e_2 - C_2)$ |
| (1, 0) | $-(\alpha_0 e_1 - C_1)$ | 0 | 0 | $R_2 - T_2 + P - C_2 + \beta_1 e_2$ |
| (1, 1) | $-(R_1 - T_1 + P - C_1 + \alpha_1 e_1)$ | 0 | 0 | $-(R_2 - T_2 + P - C_2 + \beta_1 e_2)$ |

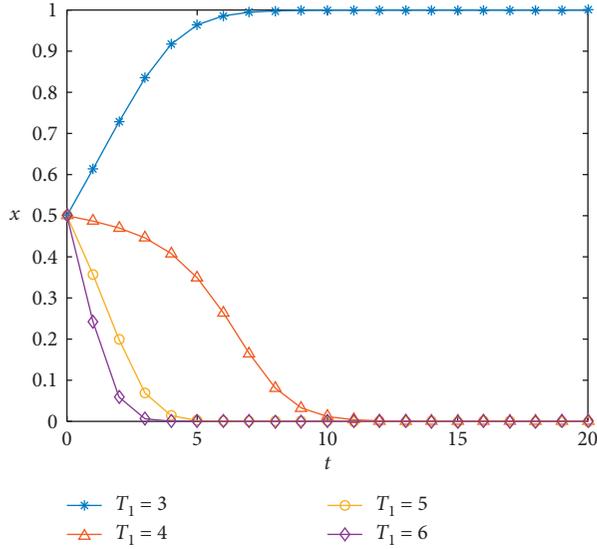
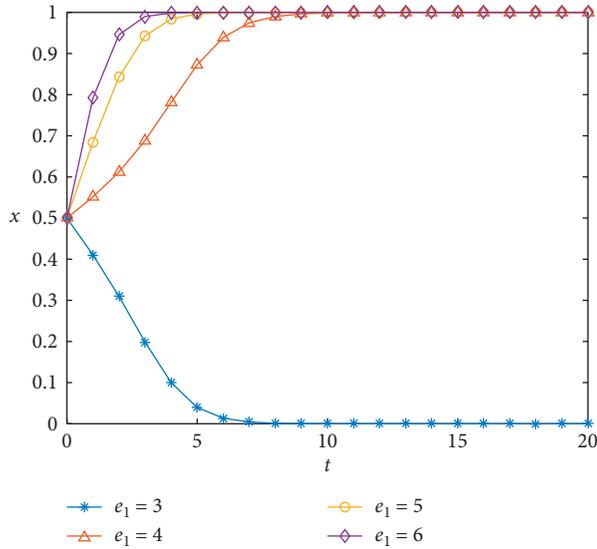
FIGURE 2: Influences of the changes in the initial value x_0 on the evolutionary result.FIGURE 3: Influences of the changes in the initial value y_0 on the evolutionary result.

The parameters should conform to the following constraints: $(C_1/e_1) < \alpha_0 < \alpha_1 < ((T_1 - R_1 + C_1)/e_1)$, $(C_2/e_2) < \beta_0 < \beta_1 < ((T_2 - R_2 + C_2)/e_2)$, $C_1 < R_1 < T_1$, and $C_2 < R_2 < T_2$. Therefore, we assume the following parameter values:

FIGURE 4: Influences of the profit R_1 on the supplier.FIGURE 5: Influences of the cost C_1 on the supplier.

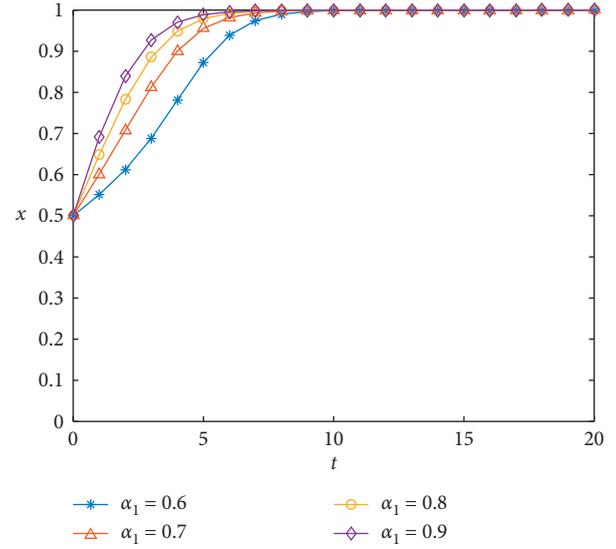
$C_1 = 1$, $C_2 = 2$, $\alpha_0 = 0.5$, $\alpha_1 = 0.6$, $\beta_0 = 0.6$, $\beta_1 = 0.7$, $e_1 = 4$, $e_2 = 5$, $R_1 = 1.5$, $T_1 = 3.5$, $R_2 = 2.5$, and $T_2 = 5$. According to the above parameters, the saddle point of the evolutionary game can be obtained as $(x^*, y^*) = (0.5, 0.625)$.

5.1. Influence of the Initial Value on Evolutionary Results. Assuming that other parameters are constant, we study the effect of the initial value (x_0, y_0) changes on the evolutionary

FIGURE 6: Influences of the free-riding benefit T_1 on the supplier.FIGURE 7: Influences of the quality-improving effort input e_1 on the supplier.

results. In the case of $y_0 = 0.625$, x_0 takes the values 0.2, 0.3, 0.4, 0.5, and 0.6. When $x_0 = 0.2, 0.3, 0.4 (< 0.5)$, the system evolves to the state $A(0, 1)$. When $x_0 = 0.6 (> 0.6)$, the system state changes from $A(0, 1)$ to $B(1, 0)$, as shown in Figure 2.

In the case of $x_0 = 0.5$, y_0 takes the values 0.3, 0.4, 0.5, 0.6, and 0.7. When $y_0 = 0.3, 0.4, 0.5, 0.6$, the system state evolves to the state $B(1, 0)$. When $y_0 = 0.7$, the system state changes from $B(1, 0)$ to $A(0, 1)$, as shown in Figure 3. Based on the above analysis, we can see that whether the system eventually converges to $A(0, 1)$ or $B(1, 0)$ depends on the initial state of the system. When the initial state falls into region A, the system will converge to $A(0, 1)$. When the initial state falls into region B, the system will converge to $B(1, 0)$. The results show that if the quality effort of the supplier or the producer exceeds a certain threshold, the participants will change to

FIGURE 8: Influences of the ratio of the input to the output α_1 on the supplier.

the free-rider state, which indicates that the behavior strategies between suppliers and producers influence each other.

5.2. Influence of Factors on Evolutionary Results. Since the supplier and producer are similar, this paper only takes supplier as an example to analyze the influence of factor changes on the supplier's effort strategies. Supposing that other factors are constant, we analyze the influence of $R_1 = 1, 2, 3, 4$ on the evolutionary results of the suppliers' strategy. Figure 4 shows that, with the increase of income R_1 , the rate of the suppliers choosing the QE strategy will increase quickly. The result shows that if the food suppliers get considerable income without quality input, they can afford a large number of funds to quality input and take the risk of quality input. Suppliers expect to get more income from quality input, so they have more motivation to make quality input.

When other factors are constant, the increase in C_1 reduces the return on the quality-improving efforts of the supplier. Figure 5 shows that when C_1 exceeds a certain value, the suppliers choose the NE strategy instead of the QE strategy. At the same time, with the increase of cost C_1 , the rate of the suppliers choosing the NE strategy will increase quickly. The result shows that the supplier adopts an effective management strategy to reduce the cost of the quality input. With the reduction of quality input cost, suppliers are more likely to make quality input.

When other factors are unchanged, the increase of T_1 curbs the motivation of the supplier to choose the QE strategy. Figure 6 shows that when T_1 exceeds a certain value, the suppliers would rather hitchhike instead of choosing the QE strategy. At the same time, with the increase of T_1 , the rate of the suppliers choosing the NE strategy will increase quickly. The result shows that if the hitchhiker can get more benefit from the other side's

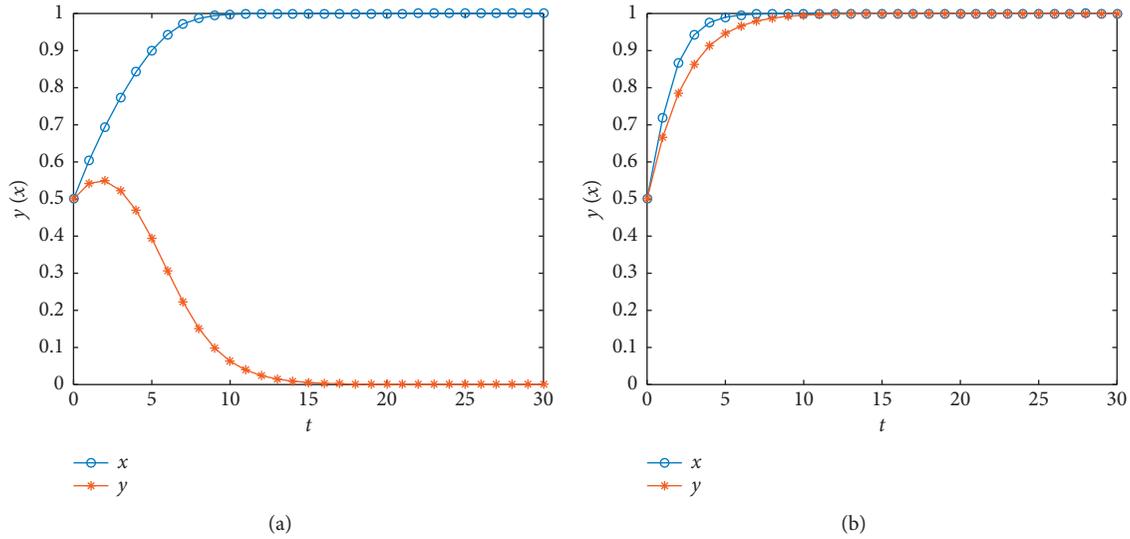


FIGURE 9: Influences of government penalty P on the evolutionary results. (a) $P = 0.5$. (b) $P = 1.5$.

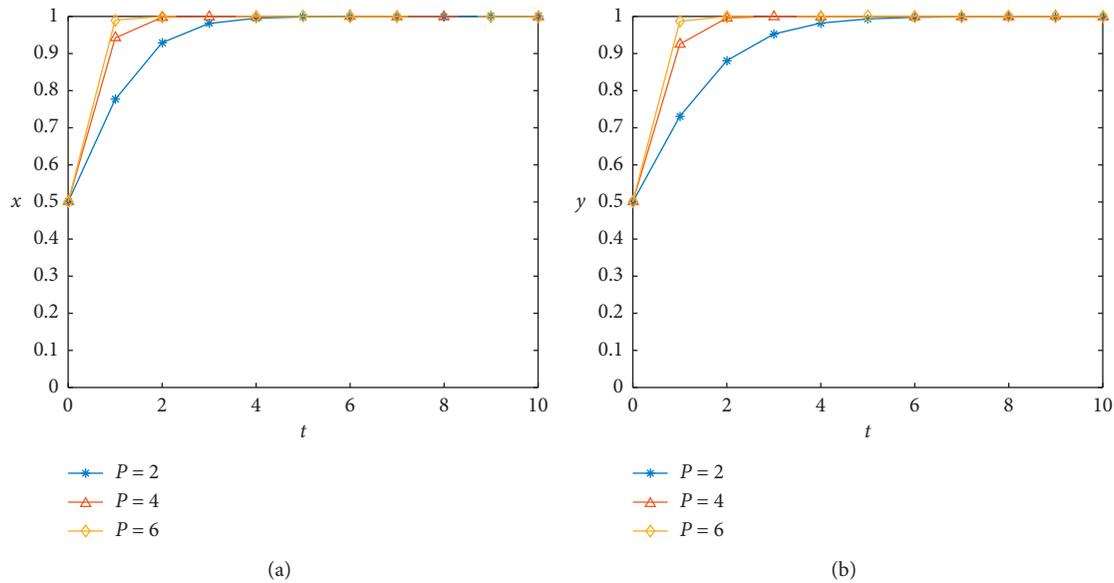


FIGURE 10: Influences of government penalty P on the evolutionary results ($P = 2, 4, 6 (>1)$).

quality input, the enthusiasm of the hitchhiker’s quality input will be greatly reduced.

When other factors remain unchanged, the increase of e_1 improves the motivation of the supplier to choose the QE strategy. Figure 7 shows that when e_1 exceeds a certain value, the suppliers would rather choose the QE strategy instead of the NE strategy. At the same time, with the increase of e_1 , the rate of the suppliers choosing the QE strategy will increase quickly. This shows that, with the increase of the supplier’s quality input, the price and market demand will continue to increase. A supplier can get more benefits and gain higher brand loyalty, and then the probability of using quality input by the supplier will be higher. Generally speaking, food enterprises with higher brand loyalty and large market share pay more attention to

food safety and have greater motivation to invest in quality because the occurrences of food safety accidents will bring serious consequences to enterprises. For example, the Sanlu milk powder incident in 2008 brought a serious impact on Sanlu Group.

When other factors remain unchanged, the increase of α_1 improves the motivation of the supplier to choose the QE strategy. Figure 8 shows that, with the increase of α_1 , the rate of the suppliers choosing the QE strategy will increase quickly. This shows that if the supplier adopts effective management strategies to increase the ratio of the input to the output, the quality input cost of the same unit can bring greater benefits to itself, and the probability of quality input by the supplier will be higher.

5.3. Influence of Government Punishment on the Evolutionary Results. We discuss the influence of government regulation on the evolutionary results. According to Proposition 7, we can obtain the following results: $T_1 - R_1 + C_1 - \alpha_1 e_1 = 0.6$ and $T_2 - R_2 + C_2 - \beta_1 e_2 = 1$.

Assuming $P = 0.5$, which satisfies the condition $0 < P < \min\{0.6, 1\}$, we can find that the supplier chooses the QE strategy, while the producer chooses the NE strategy, as shown in Figure 9(a). This verifies Proposition 7.

Assuming $P = 1.5$, which satisfies the condition $P > \max\{0.6, 1\}$, we can find that both suppliers and producers choose the QE strategy, as shown in Figure 9(b). This verifies Proposition 8.

With other factors being constant, we analyze the influence of $P = 2, 4, 6 (>1)$ on the evolutionary results of the supplier's strategy and producer's strategy, as shown in Figure 10. With the increase of punishment P , the rate of the supplier and producer choosing the QE strategy will increase quickly.

6. Conclusions

Using evolutionary game theory, this paper analyzes the behavior strategy of suppliers and producers considering the quality-improving effort in the food supply chain. The research results show that the behavioral strategies are closely related to the factors such as the ratios of the input to the output, the cost of quality-improving effort, the hitchhiking benefits, and the initial strategy.

The increase of the parameters including the normal profit of participants, the ratio of the input to the output of participants, and the effort input of participants has a promoting effect on the evolution of the system. The decline of the parameters including the cost of quality-improving effort and a free-riding benefit of participants has a promoting effect on the evolution of the system. The government can refer to the model proposed in this research and take corresponding measures to formulate the best food regulation policy.

If the free-riding behavior of one participant gains a large benefit, then no one in the food supply chain is willing to make efforts to improve quality. Under this situation, the government needs to impose a penalty on hitchhikers to ensure food safety. Only when the punishment exceeds a certain threshold, suppliers and producers can work together to improve the quality of the product. Furthermore, the greater the intensity of regulation punishment is, the faster the system evolves into a stable state.

It can be seen that the ratios of the input to the output of the supplier and producer are important factors which influence the direction of the game system evolution. The ratio of the input to the output influences the benefits of the quality-improving effort of both sides, which further influences the choice of the effort input or free-riding behavior. The greater the ratio of the input to the output of the participant is, the more the participant chooses to exert the

quality-improving effort. Therefore, the government should actively guide food enterprises to strengthen industry-university-research technology cooperation and support enterprises to reduce investment risks through policies such as achievements transformation and tax incentives. By improving the technology and management level, food enterprises improve the ratio of the input to the output.

This paper only considers the impact of price and quantity changes on quality-improving effort. However, it ignores the volatility of the market, the changes in consumers' income, and the market competition. Moreover, this study does not consider the possible coordination and incentive problems between suppliers and producers in the food supply chain. Therefore, how to design a reasonable contract to motivate participants in the supply chain is an important direction in future research.

Appendix

Inference A.1

Proof. S_A takes the first derivative of $\alpha_0, \alpha_1, \beta_0$, and β_1 . Thus, we can obtain

$$\begin{aligned}\frac{\partial S_A}{\partial \alpha_0} &= \frac{-e_1(T_1 - R_1 + C_1 - \alpha_1 e_1)}{2[T_1 + (\alpha_0 - \alpha_1)e_1 - R_1]^2} < 0, \\ \frac{\partial S_A}{\partial \alpha_1} &= \frac{-e_1(\alpha e_1 - C_1)}{2[T_1 + (\alpha_0 - \alpha_1)e_1 - R_1]^2} < 0, \\ \frac{\partial S_A}{\partial \beta_0} &= \frac{e_2(T_2 - R_2 - \beta_1 e_2 + C_2)}{2[T_2 + (\beta_0 - \beta_1)e_2 - R_2]^2} > 0, \\ \frac{\partial S_A}{\partial \beta_1} &= \frac{e_2(\beta_0 e_2 - C_2)}{2[T_2 + (\beta_0 - \beta_1)e_2 - R_2]^2} > 0.\end{aligned}\tag{A.1}$$

Inference A.2

Proof. S_A takes the first derivative of R_1 and R_2 . Thus, we can obtain

$$\begin{aligned}\frac{\partial S_A}{\partial R_1} &= \frac{C_1 - \alpha_0 e_1}{2[T_1 + (\alpha_0 - \alpha_1)e_1 - R_1]^2} < 0, \\ \frac{\partial S_A}{\partial R_2} &= \frac{\beta_0 e_2 - C_2}{2[T_2 + (\beta_0 - \beta_1)e_2 - R_2]^2} > 0.\end{aligned}\tag{A.2}$$

Inference A.3

Proof. S_A takes the first derivative of T_1 and T_2 . Thus, we can obtain

$$\frac{\partial S_A}{\partial T_1} = \frac{\alpha_0 e_1 - C_1}{2[T_1 + (\alpha_0 - \alpha_1)e_1 - R_1]^2} > 0, \quad (A.3)$$

$$\frac{\partial S_A}{\partial T_2} = \frac{-(\beta_0 e_2 - C_2)}{2[T_2 + (\beta_0 - \beta_1)e_2 - R_2]^2} < 0.$$

Inference A.4

Proof. S_A takes the first derivative of C_1 and C_2 . Thus, we can obtain

$$\frac{\partial S_A}{\partial C_1} = \frac{1}{2[T_1 + (\alpha_0 - \alpha_1)e_1 - R_1]^2} > 0, \quad (A.4)$$

$$\frac{\partial S_A}{\partial C_2} = \frac{-1}{2[T_2 + (\beta_0 - \beta_1)e_2 - R_2]^2} < 0.$$

Data Availability

The data used to support the findings of this study have not been made available because raw data are hard to reach, and this paper uses hypothetical data for simulation rather than real data.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work was funded by the National Nature Science Foundation of China (grant no. 11501236) and the National Social Science Foundation of China (grant no. 18BRK003).

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