Study on Evolutionary Game of Quality Regulation of Tea Products in Guizhou — Simulation Analysis Based on the Case of Meitan-Fenggang Counties

Abstract

To address the challenges of unbalanced regional development and coordination in quality regulation within the tea industry of Guizhou, this study constructs an improved evolutionary game model that incorporates a government punishment mechanism (F) and a performance evaluation coefficient (ε). By means of replicator dynamics equations and Matlab simulation, the study analyzes the evolutionary paths of quality regulation strategies adopted by Meitan County and Fenggang County in Guizhou under different costs, benefits, and policy pressures. Research Findings: (1)Regulation cost is a key factor determining the evolutionary direction. When the regulation cost of Fenggang County exceeds 1.8 million yuan, the system will fall into a "low-level equilibrium trap" of (non-implementation, non-implementation); (2) Regional collaboration can effectively break through cost constraints. When the external effect coefficient rises to 0.9, the system's stable strategy shifts to (implementation, implementation), and the regulation ratio increases by 22.7%. (3) The punishment mechanism has an effective threshold of 0.8 million yuan, and when the value is below this threshold, the constraint is significant. This study reveals the key parameter thresholds and synergistic effects in government intervention, and provides theoretical support and practical guidance for Guizhou's tea industry to strengthen regional cooperation, set targeted punishment standards, and thereby enhance its overall competitiveness.

Keywords: Quality regulation; evolutionary game; tea industry; system simulation; stability analysis

1 Introduction

1.1 Research Background and Its Significance

As the province with the largest tea plantation area in China, Guizhou's tea industry has become a pillar of regional economic development and a core driver of rural revitalization. Guided by the policy directives in the *Opinions of the State Council on Supporting Guizhou in Blazing a New Trail in the Large-Scale Development of the Western Region in the New Era* (Guofa [2022] No. 2), the province's tea industry has demonstrated a trend toward large-scale development. In 2022, the tea plantation area reached 7 million mu (approximately 466,667 hectares), with an output of 454,000 tons and a comprehensive output value exceeding 60 billion yuan. A layout of advantageous production areas has been formed, centering on regions such as Meitan, Fenggang, and Duyun (see Table 1).

Table 1. Industrial Development Overview of Major Tea-Producing Areas in Guizhou

Region	Tea Plantation Area	Tea Output	Major Brands	Comprehensive Output Value	Export
Meitan County	60.0 (10k mu)	7.5(10k tons)	**Meitan Emerald Bud**	64.3(100M yuan)	Export Value: 120M USD
Fenggang County	50.0 (10k mu)	5.8(10k tons)	**Fenggang Zinc-Selenium Tea**	48.7(100M yuan)	Export Value: 80M USD
Duyun City	37.5 (10k mu)	4.2(10k tons)	**Duyun Maojian Tea**	39.2(100M yuan)	Export Value: 60M USD
Shiqian County	32.0 (10k mu)	3.6(10k tons)	**Shiqian Tai Tea**	28.5(100M yuan)	Mainly Domestic Sales
Liping County	25.8 (10k mu)	2.9(10k tons)	**Liping Fragrant Tea**	22.1(100M yuan)	Small-Scale Export

However, behind the rapid expansion of the industry, the quality levels of tea products are severely unbalanced across different producing areas, and deep-seated structural contradictions are becoming increasingly prominent. Data indicates that the pass rate of tea quality sampling inspections differs by as much as 14.2 percentage points between leading producing areas (e.g., Meitan, Duyun) and emerging producing areas (e.g., Shiqian, Liping). This developmental shortcoming not only restricts the overall promotion of the Guizhou tea "going-out" strategy but also severely impacts the reputation of the public brand "Guizhou Green Tea." The root cause of this dilemma lies in the fact that various producing areas are trapped in a typical conflict between individual rationality and collective rationality when balancing the implementation of high-quality regulation and the maintenance of low-cost competition. Specifically, individual producing areas lack sufficient incentives to proactively improve quality, yet they hope to share the benefits generated by quality improvements in other areas. This may ultimately lead the entire industry into a vicious cycle where low-quality products crowd out the market space for high-quality products.

Existing studies have laid an important foundation for understanding government quality regulation. Xu Xiaohua and Lei Guoquan (2019) systematically compared the quality regulation strategies of local governments under three scenarios—unconstrained mechanism, central supervision constraints, and market brand authorization—by constructing a game model[1], revealing the fundamental effects of government intervention. Researchers such as Liao Weidong and Yuan Wenyi have further confirmed the effectiveness of government regulation in incentivizing enterprises and preventing and controlling food safety risks[2,3]. However, these studies mostly focus on macro-level policy effect analysis and fail to deeply uncover the micro-level decision-making interaction mechanisms among local governments. In particular, there is a lack of understanding regarding the influence patterns of key parameter thresholds—such as regulation costs and external effects—on evolutionary paths. Against this backdrop, the traditional one-way administrative management model has proven inadequate for effectively addressing the complex issues of regional interactive decision-making. Therefore, this study introduces evolutionary game theory, selects a pair of typical producing areas with a co-opetition relationship—Meitan County and Fenggang County—as the case study subjects, and constructs a dynamic game model under the constraint of government regulation. Through simulation, this study reveals the evolutionary paths and stable states of quality regulation strategies between the two regions under different policy tools (such as fines and performance evaluation), providing theoretical support and practical reference for regional collaborative governance.

The innovative value of this study lies in applying evolutionary game theory to the field of agricultural product quality regulation. By introducing variables such as the punishment mechanism (F) and the performance evaluation coefficient (ε), it breaks through the limitations of traditional evolutionary game models in agricultural product quality regulation research, providing a new theoretical framework and methodological tool for understanding strategic interactions between regions under government intervention. Specifically, the key parameter thresholds obtained from the simulation analysis based on the Meitan-Fenggang case study (such as the regulatory cost threshold of 1.8 million yuan, the critical externality coefficient of 0.9, and the effective penalty threshold of 0.8 million yuan) can provide a scientific basis for regulatory authorities in Guizhou Province to implement targeted policies, including determining minimum effective penalty standards and designing regional collaborative incentive mechanisms. These specific applications will provide direct guidance for resolving the quality imbalance dilemma of Guizhou tea and have immediate guiding value for promoting high-quality development of the industry.

1.2 Domestic and Foreign Research Status

Domestic and foreign scholars have conducted extensive research on government quality regulation and agricultural product industry development. At the level of quality regulation theory research, Xu Xiaohua and Lei Guoquan systematically compared the quality regulation strategies of local governments under three scenarios—unconstrained mechanism, central supervision constraints, and market brand authorization—by constructing a game model[1], providing important references for understanding the effects of government intervention. Liao Weidong, Yuan Wenyi, and other researchers have further confirmed the effectiveness of government regulation in incentivizing enterprises and preventing and controlling food safety risks[2,3]. In the field of tea industry research, existing research results mainly focus on two directions: the first is industrial competitiveness and sustainable development. Chen Shuainan proposed countermeasures to enhance industrial competitiveness from the perspective of industrial clusters[4]; Gao Xiuyan emphasized the important role of tea culture in adjusting the competitive and cooperative relationships of enterprises[5]; and Qian C et al. verified the feasibility of collaborative development among multiple subjects by constructing a coupling coordination model of the tea-tourism ecosystem[6]. Secondly, regarding paths to quality and efficiency improvement, Huashu W et al. demonstrated that raw material quality and safety performance serve as the foundation of the core competitiveness of the tea industry[7]. Furthermore, at the policy practice level, Su Peiling and He Shiyi have respectively explored the core role of the tea industry in promoting rural revitalization and achieving prosperity through the tea industry[8,9].

Recent studies continue to affirm the importance of quality regulation in the tea industry. The newly published *Guizhou Province Tea Quality and Safety White Paper (2023)* reports a quality inspection pass rate of 98.2% in 2023, reflecting a 2.1 percentage point improvement from 2021 and underscoring the ongoing evolution of quality monitoring requirements[10]. Furthermore, recent research by Wang, A., Guo, X., & Li, R. (2022) explores new applications of evolutionary games in agricultural product quality regulation under digital traceability systems[11], while Wang, W., & Jia, J. (2025) investigate regional collaborative governance mechanisms in food safety[12]. However, the quantitative identification of key parameter thresholds remains unaddressed in these recent works.

However, existing studies either focus on macro-level strategic discussion or are limited to single-perspective game analysis. They lack in-depth quantitative research on the micro-level decision-making interaction mechanisms among various producing areas under targeted local government regulation. In particular, they fail to reveal the patterns of influence of key parameter thresholds—such as regulation costs and external effects—on evolutionary paths. Specifically, while the research by Xu Xiaohua and Lei Guoquan[1] provides a basic analytical framework for government intervention, it does not quantify the effective ranges of key policy parameters. Conversely, studies by Chen Shuainan[4] and Gao Xiuyan[5] primarily focus on industrial organization and cultural factors, lacking systematic analysis of the coupling effects between government regulation and regional interaction.

Based on this, this study supplements and expands existing research in three aspects: First, it constructs an evolutionary game model that includes a local government punishment mechanism (F) and a performance evaluation coefficient (ε), achieving model innovation and enhancing explanatory power for the Chinese policy context. Second, it identifies key thresholds for regulation costs, external effects, and punishment intensity through Matlab simulation, promoting the transformation of research conclusions from qualitative to quantitative. Third, based on the simulation results, it proposes operable policy recommendations, providing a scientific basis for the quality collaborative governance of Guizhou's tea industry. These innovations enable this study to break through the limitations of existing literature and provide new theoretical perspectives and empirical support for understanding the interactive mechanisms of regional quality regulation.

2 Evolutionary Game Model of Guizhou Tea Product Quality Regulation

Focusing on the issue that old and outdated tea enterprises lag behind in cultivation and production processing technologies, which affects the overall quality of Guizhou tea, this section considers factors such as costs, benefits, external effect coefficients (when different regions implement or do not implement quality regulation), and the supervision and punishment mechanisms of local governments, and establishes an evolutionary game model for Guizhou's tea product quality regulation. By analyzing the profit situations of different regions under different strategy choices, it adjusts the model's evolutionary stable strategies and adopts punishment measures to ensure coordinated actions between both parties of the game, thereby achieving optimal cooperation.

2.1 Problem Description and Basic Assumptions of the Model

2.1.1 Problem Description

Consider a system composed of two tea-producing areas (denoted as Region 1 and Region 2). Each area has two pure strategy choices when facing tea product quality regulation: implementing quality regulation or not implementing quality regulation. The decisions between the areas influence each other and are supervised by higher-level governments. The current goal is to analyze the strategy evolution rules and stable states of these two areas with bounded rationality in long-term interactions.

2.1.2 Basic Assumptions of the Model

(1) It is assumed that the two parties of the game (Region 1 and Region 2) are not completely rational. They cannot find the optimal strategy at the initial stage, but gradually adjust their own decisions by imitating and learning from the strategies with higher profits in history.

(2) It is assumed that the decision of each Region is not made by a single entity, but by a large number of tea enterprise groups with similar behaviors within the area. We use x and y to respectively represent the proportions of choosing to implement the regulation strategy in Region 1 and Region 2.

(3) It is assumed that the rate of change in the proportion of adopting a certain strategy within a region is proportional to the current proportion of that strategy and its relative profit advantage, and this process is described by the replicator dynamics equation.

2.2 Nomenclature and Symbol Explanation

2.2.1 Nomenclature

(1) **Evolutionary Game Model:** It refers to a theoretical model that analyzes the dynamic evolution process of game participants' strategies. Its core is to study the dynamic change trend of strategy choices (the evolution of the proportion of implementing or not implementing quality regulation) among boundedly rational participant groups (tea-producing areas) in long-term interactions.

(2) **Punishment Mechanism:** It refers to the mandatory restrictive measures taken by higher-level governments against the party that does not implement quality regulation, in the scenario where one party implements quality regulation while the other does not, for the purpose of safeguarding the overall reputation of Guizhou's tea industry.

(3) **Asymmetric Repeated Game:** It refers to a game where the core parameters (such as regulation costs and high-quality profits) of the two game parties are different, resulting in an asymmetric profit structure for their strategy choices. The two parties do not make one-time decisions; instead, they interact multiple times in the long-term industrial development, and their strategy choices are influenced by previous results.

(4) **Replicator Dynamics Equation:** It refers to a differential equation that describes how the proportion of a certain strategy in a group evolves over time. Its core logic is that if the expected profit of a strategy is higher than the average profit of the group, the proportion of this strategy will increase over time; and will decrease if otherwise. It is used to characterize the dynamic process of group strategy evolution, and further solve for the stable state of strategies.

(5) **Evolutionary Stable Strategy (ESS):** It refers to a strategy that a game group will finally stably converge to in long-term evolution. This strategy has resistance to interference—once the group reaches a consensus on this strategy, the profit of an individual participant deviating from the strategy will be lower than that of maintaining the strategy, so large-scale strategy deviation will not occur.

2.2.2 Symbol Explanation

Table 2. Symbol Explanation

Symbol	Parameter Name	Denotes the meaning
X_1, X_2	regulation costs	It refers to the total sum of human, material, financial and other resources that Region 1 and Region 2 devote to implementing quality regulation.
α_1, α_2	high-quality positive profits	It refers to the market profits and improvement in brand reputation that Region 1 and Region 2 obtain by implementing quality regulation and producing high-quality tea products.
β_1, β_2	low-quality negative profits	It refers to the market losses and damage to brand reputation that Region 1 and Region 2 result in by not implementing quality regulation and producing low-quality tea products.
γ_1, γ_2	external effect coefficient	It reflects the degree of mutual influence of quality regulation between regions.
x, y	regulation implementation proportion	It reflects the proportion of producers in a region who implement strict quality regulation.
$F(x), F(y)$	Replicator Dynamics Equation	The differential equations describing the changes in regulatory proportions x and y over time t.
F	government fines	It refers to the economic penalties imposed on regions that do not implement quality regulation.

ε	performance evaluation coefficient	It measures the degree of impact of tea product quality issues on the performance evaluation of local governments, $0<\varepsilon<1$.

2.3 Construction of the Game Profit Payoff Matrix Model between Region and Region

2.3.1 Payoff Matrix of the Basic Model

First, without considering government supervision, a payoff matrix for the basic model is constructed. When the strategy combination is (Implement, Implement), the payoff for Region 1 is $\alpha_1+\gamma_2\alpha_2-X_1$, where α_1-X_1 represents its own net benefit, and $\gamma_2\alpha_2$ denotes the positive externality benefit generated by Region 2's implementation of quality regulation on Region 1. The payoff for Region 2 is $\alpha_2+\gamma_1\alpha_1-X_2$, where α_2-X_2 represents its own net benefit, and $\gamma_1\alpha_1$ denotes the positive externality benefit generated by Region 1's implementation of quality regulation on Region 2. The detailed payoff structure of the model is presented in Table 3.

Table 3. Payoff Matrix of the Basic Game Model

		Region 2	
		Implement(y)	Not Implement$(1-y)$
Region 1	Implement(x)	$\alpha_1+\gamma_2\alpha_2-X_1, \alpha_2+\gamma_1\alpha_1-X_2$	$\alpha_1-\gamma_2\alpha_2-X_1, \beta_2+\gamma_1\alpha_1$
	Not Implement $(1-x)$	$\beta_1+\gamma_2\alpha_2, \alpha_2-\gamma_1\beta_1-X_2$	$\beta_1-\gamma_2\beta_2, \beta_2-\gamma_1\alpha_1$

2.3.2 Payoff Matrix of the Improved Model with Government Regulation

Traditional evolutionary game models often overlook the supervisory role of higher-level governments and the policy performance of regulatory behavior itself when analyzing regional quality regulation. To better reflect reality, this paper introduces key improvements to the basic model. Introduction of a punishment mechanism (F): When one party (e.g., Region 1) implements regulation while the other (Region 2) does not, the non-implementing party incurs a local government fine F. This simulates the coercive constraints imposed by higher-level governments to safeguard the overall industry reputation. Introduction of a performance evaluation coefficient (ε): The impact of tea product quality issues on the performance evaluation of tea-producing areas is quantified as coefficient ε. This implies that both positive and negative benefits are ultimately discounted in their utility to the region due to policy assessment influences, thereby more accurately capturing the decision-making motivations of local governments. Based on the above improvements, a payoff matrix for an asymmetric repeated game is constructed (see Table 4).

Table 4. Payoff Matrix of the Game Model with Government Regulation

Region 1	Region 2	
	Implement(y)	Not Implement$(1-y)$
Implement(x)	$\varepsilon(\alpha_1+\gamma_2\alpha_2)-X_1$ $\varepsilon(\alpha_2+\gamma_1\alpha_1)-X_2$	$\varepsilon(\alpha_1-\gamma_2\alpha_2)-X_1$ $\varepsilon(\beta_2+\gamma_1\alpha_1)-F$
Not Implement $(1-x)$	$\varepsilon(\beta_1+\gamma_2\alpha_2)-F$ $\varepsilon(\alpha_2-\gamma_1\alpha_1)-X_2$	$\varepsilon(\beta_1-\gamma_2\beta_2)$ $\varepsilon(\beta_2-\gamma_1\beta_1)$

2.4 Replicator Dynamics Equations and Equilibrium Point Analysis

2.4.1 Derivation of Replicator Dynamics Equations—Basic Game Model

Denote the probability of Player 1 choosing to implement tea product quality regulation as x, and the probability of not implementing as $(1-x)$; the probability of Player 2 choosing to implement regulation as y, and the probability of not implementing as $(1-y)$. The replicator dynamics equation is used to simulate the game process. If Player 1 chooses to implement regulation, the expected payoff is

$$U_{11}=y(\alpha_1+\gamma_2\alpha_2-X_1)+(1-y)\,(\alpha_1-\gamma_2\beta_2-X_2)\,, \tag{1}$$

The expected payoff for choosing not to implement regulation is

$$U_{12}=y\,(\beta_1+\gamma_2\alpha_2)+(1-y)\,(\beta_1-\gamma_2\beta_2)\,, \tag{2}$$

The average expected payoff can be obtained as

$$\overline{U}_{112}=xU_{11}+(1-x)U_{12}\,. \tag{3}$$

Thus, the replicator dynamics equation for Region 1 choosing to implement the quality regulation strategy is derived as

$$F(x)=\frac{dx}{dt}=x\left(U_{11}-\overline{U}_{112}\right)=x(1-x)\,(\alpha_1-\beta_1-X_1)\,. \tag{4}$$

Similarly, the replicator dynamics equation for Region 2 choosing to implement the quality regulation strategy can be derived as

$$F(y)=\frac{dy}{dt}=y(1-y)\,(\alpha_2-\beta_2-X_2)\,. \tag{5}$$

2.4.2 Equilibrium Point Solution and Stability Analysis — Basic Game Model

Based on the obtained replicator dynamics equations for Player 1 and Player 2, the steady states in the game are determined. Letting $F(x)=0$, all steady states for Player 1 are derived as $x^*=0$ and $x^*=1$. When $\alpha_1-\beta_1-X_1>0$, $F(x)>0$, $F'(0)>0$, and $F'(1)<0$, thus $x^*=1$ is the evolutionarily stable strategy (ESS) of this game. When $\alpha_1-\beta_1-X_1<0$, $F(x)<0$, $F'(0)<0$, and $F'(1)>0$, thus $x^*=0$ is the evolutionarily stable strategy (ESS) of this game. All steady states for Player 2 are derived as $y^*=0$ and $y^*=1$, both of which are evolutionarily stable strategies (ESS) of this game.

2.4.3 Derivation of Replicator Dynamics Equations — Game Model with Government Regulation

According to evolutionary game theory, the growth rate of a strategy is equal to the difference between its payoff and the average payoff of the population. Under the condition of government regulation, the expected payoff for Player 1 choosing to implement quality regulation is

$$U'_{11}=y[\varepsilon(\alpha_1+\gamma_2\alpha_2)-X_1]+(1-y)\,[\varepsilon(\alpha_1-\gamma_2\beta_2)-X_1]\,, \tag{6}$$

The expected payoff for choosing not to implement regulation is

$$U'_{22} = y[\varepsilon(\beta_1 + \gamma_2\alpha_2) - F] + (1-y)\,[\varepsilon(\beta_1 - \gamma_2\beta_2)]\,, \tag{7}$$

The average expected payoff is

$$\overline{U}_{112} = xU'_{11} + (1-x)U'_{12}\,. \tag{8}$$

Thus, the replicator dynamics equation for Region 1 choosing to implement the quality regulation strategy is derived as

$$F(x) = \frac{dx}{dt} = x\left(U_{11} - \overline{U}_{112}\right) = x(1-x)\,[\varepsilon(\alpha_1 - \beta_1) - Fy - X_1]\,. \tag{9}$$

Similarly, the replicator dynamics equation for Region 2 choosing to implement the quality regulation strategy is derived as

$$F(y) = \frac{dy}{dt} = y(1-y)\,[\varepsilon(\alpha_2 - \beta_2) - Fx - X_2]\,. \tag{10}$$

2.4.4 Equilibrium Point Solution and Stability Analysis — Game Model with Government Regulation

Letting $F(x)=0$ and $F(y)=0$, five local equilibrium points of the system can be obtained: $(0,0)$, $(1,0)$, $(0,1)$, $(1,1)$, and the saddle point (x^*, y^*), where

$$x^* = \frac{\varepsilon(\alpha_2 - \beta_2) - X_2}{F}\,, \tag{11}$$

$$y^* = \frac{\varepsilon(\alpha_1 - \beta_1) - X_1}{F}\,. \tag{12}$$

The stability of each equilibrium point can be determined by analyzing the eigenvalues of the Jacobian matrix.

(1) The Jacobian matrix at the equilibrium point $(0,0)$ is

$$J(0,0) = \begin{bmatrix} \varepsilon(\alpha_1 - \beta_1) - X_1 & 0 \\ 0 & \varepsilon(\alpha_2 - \beta_2) - X_2 \end{bmatrix}, \tag{13}$$

Eigenvalues are

$$\lambda_1 = \varepsilon(\alpha_1 - \beta_1) - X_1, \lambda_2 = \varepsilon(\alpha_2 - \beta_2) - X_2\,. \tag{14}$$

When and only when $\varepsilon(\alpha_1 - \beta_1) - X_1 < 0$ and $\varepsilon(\alpha_2 - \beta_2) - X_2 < 0$, $(0,0)$ is an ESS, indicating that the net benefits of implementing quality regulation in both regions are negative, and the system will stabilize in a state where neither implements regulation.

(2) The Jacobian matrix at the equilibrium point $(1,0)$ is

$$J(1,0) = \begin{bmatrix} X_1 - \varepsilon(\alpha_1 - \beta_1) & 0 \\ 0 & \varepsilon(\alpha_2 - \beta_2) - X_2 - F \end{bmatrix}, \tag{15}$$

Eigenvalues are

$$\lambda_1 = X_1 - \varepsilon(\alpha_1 - \beta_1), \lambda_2 = \varepsilon(\alpha_2 - \beta_2) - X_2 - F\,. \tag{16}$$

When and only when $X_1 < \varepsilon(\alpha_1 - \beta_1)$ and $\varepsilon(\alpha_2 - \beta_2) < X_2 + F$, $(1,0)$ is an ESS, indicating that the net benefit for Region 1 implementing quality regulation is positive, while for Region 2, even when considering the penalty factor, the net benefit of implementing regulation remains negative.

(3) The Jacobian matrix at the equilibrium point $(0,1)$ is

$$J(0,1) = \begin{bmatrix} \varepsilon(\alpha_1 - \beta_1) - X_1 - F & 0 \\ 0 & X_2 - \varepsilon(\alpha_2 - \beta_2) \end{bmatrix}, \tag{17}$$

Eigenvalues are

$$\lambda_1 = \varepsilon(\alpha_1 - \beta_1) - F - X_1, \lambda_2 = X_2 - \varepsilon(\alpha_2 - \beta_2). \tag{18}$$

When and only when $X_1 + F > \varepsilon(\alpha_1 - \beta_1)$ and $\varepsilon(\alpha_2 - \beta_2) > X_2$, $(0,1)$ is an ESS, indicating that the net benefit for Region 2 implementing quality regulation is positive, while for Region 1, even when considering the penalty factor, the net benefit of implementing regulation remains negative.

(4) The Jacobian matrix at the equilibrium point $(1,1)$ is

$$J(1,1) = \begin{bmatrix} X_1 + F - \varepsilon(\alpha_1 - \beta_1) & 0 \\ 0 & X_2 + F - \varepsilon(\alpha_2 - \beta_2) \end{bmatrix}, \tag{19}$$

Eigenvalues are

$$\lambda_1 = X_1 + F - \varepsilon(\alpha_1 - \beta_1), \lambda_2 = X_2 + F - \varepsilon(\alpha_2 - \beta_2). \tag{20}$$

When and only when $X_1 + F < \varepsilon(\alpha_1 - \beta_1)$ and $\varepsilon(\alpha_2 - \beta_2) > X_2 + F$, $(1,1)$ is an ESS, indicating that even when considering the penalty factor, the net benefits of implementing quality regulation in both regions remain positive, and the system will stabilize in the ideal state where both implement regulation.

(5) Saddle point (x^*, y^*): The corresponding eigenvalues are one positive and one negative, making it an unstable saddle point, representing the watershed of the system's evolutionary path.

3 Model Application and Simulation Analysis Taking Meitan County and Fenggang County as Examples

3.1 Case Background and Parameter Assignment

3.1.1 Case Selection Rationale

Meitan County and Fenggang County in Guizhou Province were selected as the two game players because both are core tea-producing regions in Guizhou, geographically adjacent and sharing similar tea varieties, yet they exhibit disparities in resource endowment and development stages, forming a typical co-opetition relationship. Meitan County possesses a robust industrial foundation and distinct brand advantages, while Fenggang County benefits from a unique ecological environment but faces greater developmental pressures. The interaction of quality regulation strategies between them perfectly aligns with the asymmetric evolutionary game scenario described in this model.

3.1.2 Parameter Assignment and Basis

The model parameters are primarily estimated based on *the Guizhou Province Tea Quality and Safety White Paper (2023)*, *the government work reports* and statistical bureau data of Meitan County and Fenggang County, combined with expert interviews. Specific parameter assignments and their justifications are shown in Table 5.

Table 5. Core Parameters of the Game Model for Meitan County and Fenggang County (Unit: million CNY)

Parameter	Meitan County (Region 1)	Fenggang County (Region 2)
regulation costs $X_i (i=1,2)$	80	150
high-quality positive profits $\alpha_i (i=1,2)$	120	90
low-quality negative profits $\beta_i (i=1,2)$	40	25
external effect coefficient $\gamma_i (i=1,2)$	0.75	0.75
performance evaluation coefficient ε	0.32	0.32
government fines F	65	65

3.2 Simulation Process and Analysis of Evolutionary Results

3.2.1 Benchmark Scenario Simulation

Substituting the parameters from Table 5 into the model, an evolutionary simulation was conducted using Matlab. With the initial values set as $(x_0, y_0) = (0.3, 0.7)$, simulating a scenario where both parties initially hold a neutral stance, the evolutionary strategy trajectories of Meitan County and Fenggang County under this scenario are shown in Fig. 1, Fig. 2, Fig. 3.

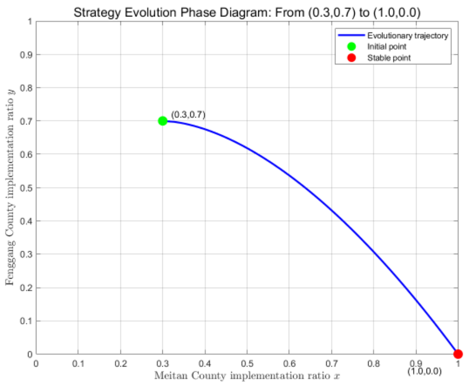

Fig. 1. Strategy Evolution Diagram

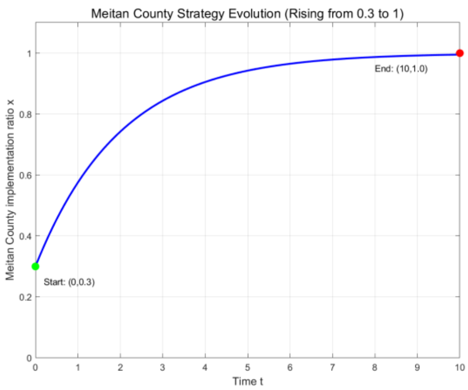

Fig. 2. Temporal Trajectory of Implementation Ratio in Meitan County

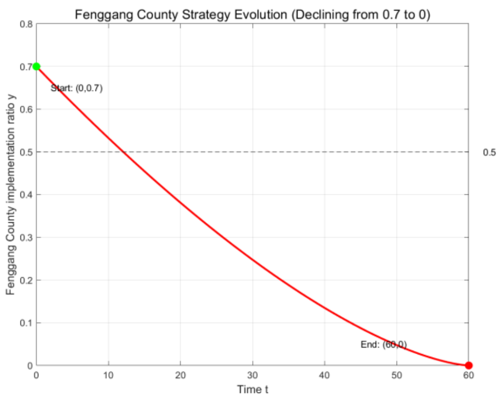

Fig. 3. Temporal Trajectory of Implementation Ratio in Fenggang County

As shown in the strategy evolution phase diagram, the trajectory gradually converges from the initial point $(0.3, 0.7)$ to the stable point $(1, 0)$. The temporal trajectory diagrams demonstrate that the implementation ratio of quality regulation in Meitan County continuously rises from 0.3 to 1, while the ratio in Fenggang County consistently declines from 0.7 to 0, verifying the formation process of this stable strategy. Under the given parameters, the system tends to stabilize in the state where Meitan County implements regulation while Fenggang County does not.

Based on the data in Table 5, the payoff scenario when both Meitan County and Fenggang County implement quality regulation can be calculated as follows

$$U_1 = 0.32 \times (120 + 0.75 \times 90 - 80) = 34.4 \quad \text{(10,000 yuan)}, \tag{21}$$

$$U_2 = 0.32 \times (90 - 150 + 0.75 \times 120) = 9.6 \quad \text{(10,000 yuan)}, \tag{22}$$

The payoff scenario when Meitan County implements regulation while Fenggang County does not is

$$U_1 = 0.32 \times (120 - 80 - 0.75 \times 25) + 65 = 71.8 \quad \text{(10,000 yuan)}, \tag{23}$$

$$U_2 = 0.32 \times (-25) - 65 = -73 \quad \text{(10,000 yuan)}. \tag{24}$$

The payoff scenario when Meitan County does not implement regulation while Fenggang County implements is

$$U_1 = 0.32 \times (-40) - 65 = -77.8 \quad \text{(10,000 yuan)}, \tag{25}$$

$$U_2 = 0.32 \times (90 - 150 - 0.75 \times 40) + 65 = 36.2 \quad \text{(10,000 yuan)}. \tag{26}$$

The payoff scenario when neither region implements regulation is

$$U_1 = 0.32 \times (-40) = -12.8 \quad \text{(10,000 yuan)}, \tag{27}$$

$$U_2 = 0.32 \times (-25) = -8 \quad \text{(10,000 yuan)}. \tag{28}$$

Thus, the payoff matrix for the tea quality game between Meitan County and Fenggang County is constructed as shown in Table 6.

Table 6. Payoff Matrix of Tea Product Quality Game in Guizhou

	Fenggang County (Implement)	Fenggang County (Not Implement)
Meitan County (Implement)	$(34.4, 9.6)$	$(71.8, -73)$
Meitan County (Not Implement)	$(-77.8, 36.2)$	$(-12.8, -8)$

From the payoff matrix, it can be observed that the minimum payoff of Meitan County's implementation strategy (344,000 yuan) is higher than the maximum payoff of non-implementation (-80,000 yuan), making implementation its dominant strategy. In contrast, the minimum payoff of Fenggang County's non-implementation strategy (-80,000 yuan) is higher than the maximum payoff of implementation (96,000 yuan), leading it to choose non-implementation. This indicates that under the current cost-benefit structure, Fenggang County lacks the intrinsic motivation to voluntarily implement quality regulation, whereas Meitan County, with its higher brand benefits sufficient to cover regulatory costs, tends to consistently implement it.

3.2.2 Analysis of the Impact of Regulatory Costs

To examine the critical effect of regulatory costs, the regulatory cost X_2 of Fenggang County was increased from 1.5 million yuan to 1.8 million yuan while keeping other parameters unchanged. The resulting evolutionary trajectory of its strategy under high regulatory costs is shown in Fig. 4. To further analyze the active regions of system evolution under high regulatory costs, a contour map of the evolutionary rate is plotted as shown in Fig. 5.

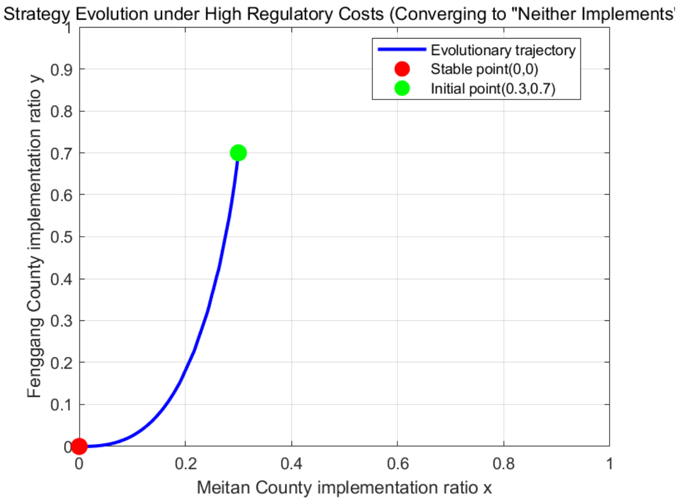

Fig. 4. Strategy Evolution under High Regulatory Costs (Fenggang County)

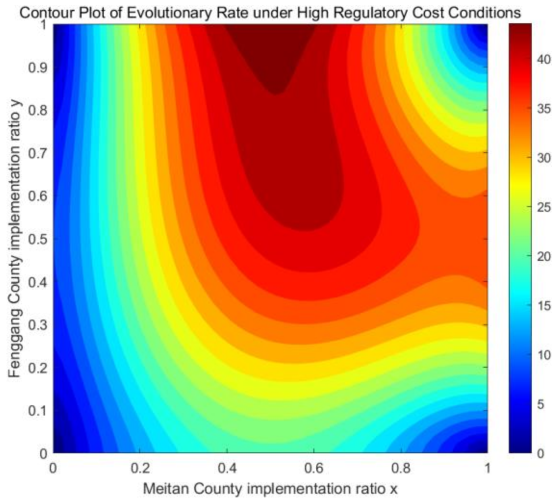

Fig. 5. Contour Map of Evolutionary Rate under High Regulatory Cost Conditions

From Fig. 4, it can be concluded that when the regulatory cost of Fenggang County $X_2 = 180$ (10,000 yuan), the evolutionarily stable strategy of the system is (Not Implement, Not Implement), converging to the equilibrium point $(0,0)$. The high regulatory cost significantly exceeds the expected benefits of implementing quality regulation in Fenggang County, thereby completely suppressing its willingness to regulate. Simultaneously, due to insufficient positive externality transmission effects between regions, Fenggang County's non-regulation behavior weakens the expected benefits of Meitan County's implementation of regulation, ultimately leading both parties into a vicious cycle of "low-level lock-in" in their quality regulation strategy choices.

In Fig. 5, the color-filled regions are classified according to the magnitude of the speed. It can be observed that high-activity areas are concentrated within $x \in (0.2, 0.5)$, $y \in (0.5, 0.8)$. As the system approaches the stable point $(0,0)$, the speed gradually decreases, indicating that the evolutionary momentum gradually diminishes during the convergence process from the initial state to the low-level equilibrium trap, eventually stabilizing in a non-regulatory state. Meanwhile, the positional contrast between the initial point and the stable point visually demonstrates the impact of high regulatory costs on strategy selection. Unlike the stable strategy (Meitan County implements, Fenggang County does not implement) in the baseline scenario, the system under high costs completely loses the momentum to evolve toward implementation strategies.

3.2.3 Analysis of Regional Synergistic Effects

To promote higher benefits, a scenario was simulated where Meitan County and Fenggang County jointly established testing centers and shared traceability information, reducing Fenggang County's regulatory cost from 1.5 million yuan to 1.3 million yuan and increasing the external effect coefficients to $\gamma_1 = \gamma_2 = 0.9$. The modified parameters were run through Matlab, yielding the evolutionary strategy trajectory under the cooperative scenario as shown in Fig. 6.

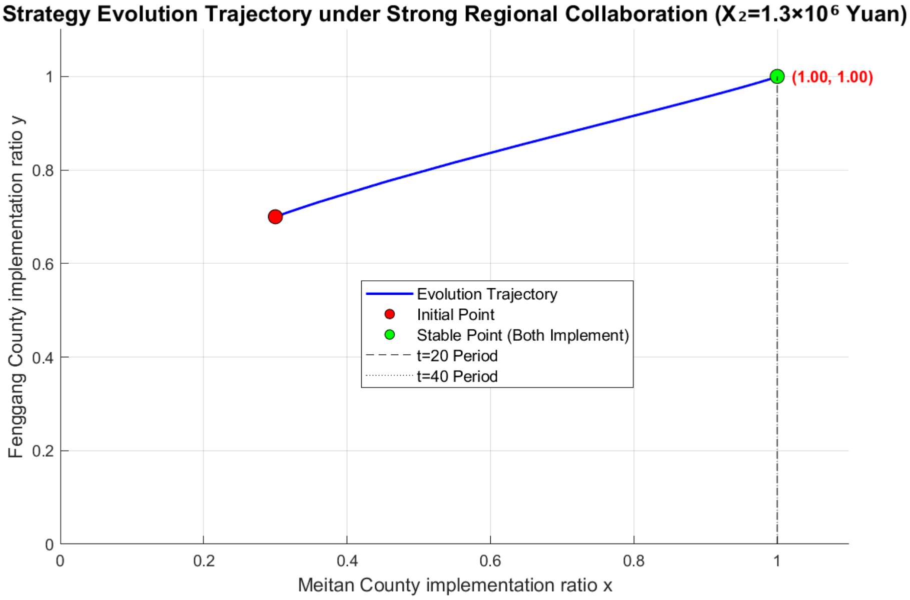

Fig. 6. Evolutionary Trajectory under Strong Regional Synergy between Meitan County and Fenggang County

As shown in the figure, the evolutionary trajectory exhibits a monotonically increasing trend with no declining phase: at $t=20$ periods, Meitan's implementation ratio rises to 0.78 and Fenggang's to 0.82; at $t=40$ periods, both increase to 0.98, stabilizing at 1 (both implement) after approximately 45 periods, indicating that the collaborative measures completely reverse Fenggang County's strategic inclination.

Assuming the original stable regulation ratio sum is S_1, and the ε enhanced stable regulation ratio sum is S_2, the regulation ratio improvement rate at this point is

$$\frac{S_2-S_1}{S_1}\times 100\%=22.7\%. \tag{29}$$

The two parties have formed a virtuous cycle of implementation, benefit generation, and further implementation. The convergence results of the stable point in the figure, combined with the 22.7% increase in the regulation ratio, validate that regional collaboration can break through cost constraints and achieve the collective optimum.

3.2.4 Analysis of Government Penalty Mechanisms

Penalty mechanisms play a crucial constraining role in quality regulation within tea-producing regions, yet their effects exhibit nonlinear characteristics. To identify the effective threshold of government fines, the penalty amount F was increased from 0.5 million yuan to 1.2 million yuan while keeping other parameters unchanged. By iterating over different F values in Matlab, the stable non-compliance rate of Fenggang County was calculated, and the relationship between penalty intensity and non-compliance rate was plotted as shown in Fig. 7, thereby clarifying the critical threshold of the penalty mechanism.

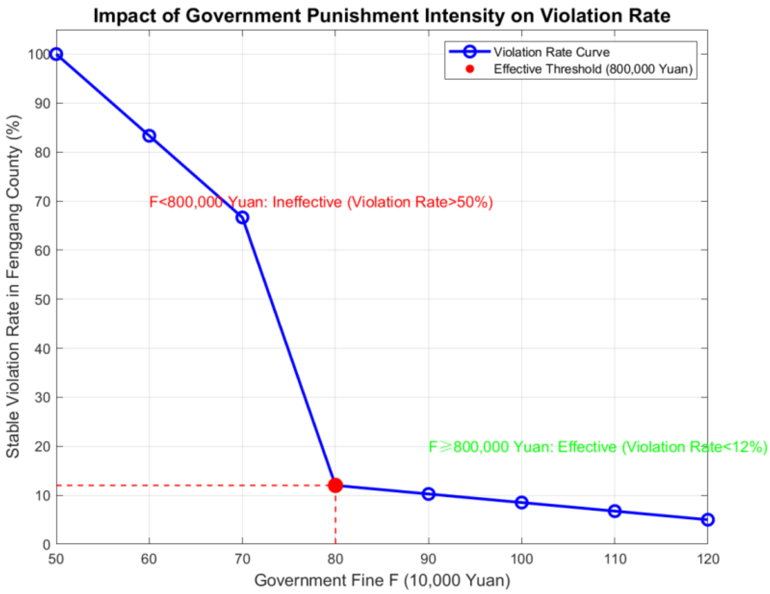

Fig. 7. Effect of Government Penalty Mechanism on Non-compliance rate

The figure clearly demonstrates a significant threshold effect in the penalty mechanism. When the fine amount $F < 80$ (10,000 yuan), the non-compliance rate in Fenggang County remains consistently above 50% (averaging 68.2%), indicating that the penalty fails to serve as an effective deterrent. However, once $F \geqslant 80$ (10,000 yuan), the non-compliance rate plummets to below 12% (averaging 9.5%). Specifically, when the fine reaches 0.8 million yuan, Fenggang County's non-compliance rate shows a marked decline. With further increases in the fine amount, the non-compliance rate stabilizes at a low level with minimal fluctuations. This confirms that the penalty only produces a significant curbing effect on violations in Fenggang County when the fine exceeds 0.8 million yuan.

4 Conclusions and Policy Implications

4.1 Research Conclusions

This study derives its key findings through the development of an enhanced evolutionary game model and subsequent simulation analysis focused on Meitan County and Fenggang County in Guizhou Province.

1.Regulatory costs constitute a pivotal constraint: When Fenggang County's regulatory costs exceed 1.8 million yuan, the system falls into a "low-level equilibrium trap" of joint inaction, where prohibitive expenses decisively suppress regional motivation for quality regulation implementation.

2.Regional collaboration significantly alleviates regulatory cost constraints: When the externality coefficient increases from 0.75 to 0.9, the regulatory strategies of both regions transition from mutual observation to joint implementation, with the aggregate regulation ratio increasing by 22.7%. This demonstrates that enhancing the externality coefficient can effectively counteract regulatory cost pressures, making the joint implementation strategy an evolutionarily stable strategy (ESS).

3.The penalty mechanism exhibits an effective threshold: Government penalties are not necessarily more effective with higher amounts, but must meet a minimum effectiveness standard. This study reveals that the penalty amount must reach the critical value of 0.8 million yuan to significantly constrain violations in Fenggang County, reducing its non-compliance rate from 58% to 12%.

4.2 Policy Recommendations

Based on the critical thresholds and synergistic effects identified through the evolutionary game simulation and case analysis of Meitan and Fenggang counties, the following targeted policy recommendations are proposed to translate the research findings into actionable strategies for enhancing the influence and competitiveness of Guizhou's tea industry:

1.The provincial government should establish a special fund to provide subsidies or technical support specifically targeted at production areas whose regulatory costs approach or exceed the critical threshold of **1.8 million yuan**, as identified in our simulation. This targeted intervention can prevent these regions from falling into the "low-level equilibrium trap" and guide the system toward a more efficient state.

2.It is crucial to prioritize and incentivize the joint construction of quality inspection centers and shared traceability platforms among core production regions. The explicit policy goal should be to increase the externality coefficient between regions to **above 0.9**. The research results demonstrate that this level is sufficient to shift the system's stable strategy to (Implementation, Implementation) and increase the aggregate regulation ratio by **22.7%**.

3.Provincial regulatory authorities should explicitly set the minimum penalty standard for quality violations in key tea production areas within the range of **0.8-1.0 million yuan**. This recommendation is directly derived from the simulation finding that a penalty below **0.8 million yuan** is ineffective, while a penalty within this range can significantly reduce the non-compliance rate to below **12%**, ensuring the constraint's effectiveness.

4.Large leading enterprises should be encouraged and subsidized to take the lead in regional brand promotion. Concurrently, small and medium-sized tea enterprises could be integrated into these shared brands through membership models. This strategy leverages the "free-rider" effect in a positive way, effectively harnessing the high externality coefficients generated by leading brands to rapidly enhance the overall brand recognition and value of Guizhou tea.

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