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Research on immature wheat harvesting behavior of farmers from the perspective of food security: An evolutionary game based analysis

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ABSTRACT

Food security constitutes a foundational cornerstone for social stability, with the achievement of sustainable agricultural production serving as a vital step towards this objective. Currently, the untimely harvesting of unripe wheat by farmers has led to a decline in food production, thereby posing a significant threat to the sustainability of China's food system and exacerbating food insecurity. Although the Chinese government has implemented various measures in response, their effectiveness has been limited. Limited scholarly literature exists on this particular issue. To advance food security in China, this study develops a tripartite evolutionary game model involving farmers, the government, and breeding enterprises. Adopting a systemic perspective, this study examines the interactions and impact mechanisms among these key actors during the wheat harvesting process. The findings indicate that the government should prioritize policies that enforce penalties. By implementing penalties within a reasonable range, the government can mitigate farmers' production costs and enhance the market price of grain. This approach discourages farmers from harvesting immature wheat and contributes to enhancing food security. Based on the research findings, this paper provides practical recommendations to guide the government in addressing food security governance issues.

1. Introduction

Food constitutes a strategic security resource vital for the survival and progress of nations and regions across the globe. In recent years, the global dietary consumption structure has undergone upgrades, resulting in a continuous rise in food demand [1]. However, agricultural resources such as arable land and water have significantly diminished, alongside challenges posed by extreme climate events and regional conflicts. Consequently, the global food system has experienced severe disruptions, exacerbating global food insecurity [2]. It is estimated that global food demand will increase by 35%–56% between 2010 and 2050, with the population at risk of hunger changing by −91% to +8% [3]. China, as the world's most populous country, faces the formidable task of feeding one-fifth of the global population with less than one-tenth of the arable land and freshwater resources [4]. While China's economy has exhibited strong growth in recent years, population growth and rapid shifts in nutritional preferences have intensified the demand for food, placing immense pressure on limited agricultural resources and the natural environment. This scenario has resulted in decreased food

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self-sufficiency and elevated food prices [5]. In this context, maintaining sustainable agricultural development is crucial to ensure the country's food security. However, in spring 2022, a significant number of farmers in China's Henan and Anhui provinces prematurely harvested immature wheat for non-consumption purposes, selling it at inflated prices to breeding companies for silage. This phenomenon directly contributed to a considerable reduction in China's annual grain output, creating an imbalance in the agricultural-food system and posing a serious threat to food security [6].

For a long time, the Chinese government has placed significant emphasis on the matter of food security [4]. In 1996, the Chinese government issued its first white paper on food security, proposing the policy of achieving basic self-sufficiency in food. In 2013, the Chinese government elevated "guaranteeing national food security" to the level of a national strategy. In 2015, China began to implement the governor responsibility system, requiring regional governments to promote sustainable agricultural development in their regions, creating a pattern of shared central and local responsibility for food security. In 2021, food security is considered an important part of national security, and the No. 1 central document has made necessary arrangements to implement the food security strategy. After farmers harvested immature wheat in May 2022, China s Ministry of Agriculture and Rural Affairs issued an emergency notice to seriously investigate and deal with the destruction of wheat. In August 2022, Anhui Province introduced the "Anhui Grain Crop Growing Season Protection Regulations", which stipulates that farmers or enterprises that harvest and store growing season wheat will be fined more than double or less than five times the value of the destroyed grain [7]. However, despite increased government supervision, prohibiting farmers from harvesting immature wheat has proven challenging, rendering the policy ineffective. On one hand, due to the prevailing reality of small-scale production and dispersed locations among many Chinese farmers, enforcing the government's penalty policy becomes arduous, often demanding significant human, material, and financial resources [8]. On the other hand, the government's policy to ban the cutting of immature wheat often lacks the implementation of complementary subsidy and guidance measures [9]. In this context, farmers' motivation to cultivate crops diminishes considerably, leading to the failure of government policies.

In recent years, an increasing number of scholars have focused on the field of food security. Since agri-food systems encompasses supply, access, and use, covering factors such as food prices, agricultural trade, and infrastructure, this determines that food security governance is a highly complex combination [10]. At the same time, governance is defined as a concerted effort to address food security issues and is the process of managing these interactions [11]. Academic research on food security governance has predominantly focused on three primary aspects. Firstly, there is an examination of the subjects involved in food security governance. Traditionally, the agri-food system was seen as primarily involving farmers, the government, and consumers. However, in recent years, the scope of stakeholders engaged in food security has expanded significantly. International organizations, civil society organizations, and private businesses now actively participate in various levels of governance and collaborate with government agencies. These diverse stakeholders represent different interests and provide valuable insights and information to the government [12–14]. The second aspect studied in food security governance focuses on the challenges faced at the global level. Several countries have encountered difficulties in effectively addressing the crises within their agri-food systems. These challenges arise from various factors such as inadequate government decision-making, weak institutional frameworks, and limited resources. In the context of Mexico, Shamah-Levy [15] conducted an evaluation of the country's food security and highlighted issues related to the vertical structure of the agricultural sector. This vertical structure contradicted the inherently interconnected and multifaceted nature of food policy, ultimately contributing to the weak governance capacity of food security. Similarly, Moragues-Faus [16] emphasized the need for the European food sector to address the vulnerability of food systems by addressing long-standing inequalities in food rights and entitlements. This recognition of persistent inequities underscores the importance of tackling underlying structural and systemic issues in ensuring food security. The third aspect explored in food security governance pertains to the government's strategies and approaches in improving food security. Research by Anser [17] suggests that good government efficiency and effective anti-corruption measures have the potential to significantly enhance food security, with potential increases ranging from 12 to 20%. Misselhorn [18] argues that countries must move from a predominantly monocentric governance perspective to a governance arrangement that stimulates and promotes multi-level and multi-scale interactions where stakeholders collaborate.

The literature on food security has extensively addressed the subject, establishing a robust theoretical foundation for this study. However, there are several shortcomings that warrant attention. Firstly, previous research has primarily concentrated on macro-level government governance, disregarding the examination of farmers' production behavior from a micro-level perspective. This oversight fails to account for the influence of government policy changes and fluctuations in market demand on farmers' decision-making. Secondly, existing literature predominantly adopts an incentive policy standpoint, suggesting that government subsidies and other incentivizing measures can augment farmers' production motivation. Nevertheless, the efficacy and effectiveness of these incentive policies remain a matter of debate. Thirdly, prior research frequently scrutinizes the issue from the standpoint of a single entity, neglecting the importance of incorporating market participants, such as breeding enterprises, to adopt a comprehensive viewpoint that encompasses the interactions and decision-making processes among farmers, the government, and breeding enterprises.

Food security is widely recognized as an integral element of China's national security, and ensuring the smooth functioning of food production is a paramount objective pursued by the government. Among China's three primary staple crops, wheat necessitates the government's assurance of farmers' robust wheat production capabilities. However, farmers often deviate from policy objectives due to risk-reward considerations. For instance, in the present context, farmers express discontent with the market price of mature wheat and anticipate higher income by harvesting immature wheat. To address this issue, this study constructs a tripartite evolutionary game model involving farmers, the government, and breeding enterprises, grounded in the Chinese context. The primary objectives are to answer three fundamental questions: Firstly, what is the equilibrium point of evolution in the tripartite dynamic model of farmers, government, and breeding enterprises? Secondly, what factors influence farmers' decision to harvest immature wheat? Thirdly, what measures can the government implement to discourage farmers from engaging in the practice of harvesting immature wheat?

This study makes three primary contributions. Firstly, employing an evolutionary game approach, we integrate farmers, the government, and breeding enterprises into a complex system. By employing authentic data, we simulate the dynamic evolution process of the government-farmer-breeding enterprise system and explore the stable state of their ultimate behavior. Secondly, we examine the characteristics of the tripartite system, identify key parameters influencing farmers' decision-making, and analyze how numerical variations affect farmers' behavior. Thirdly, through simulation, we underscore the limitations in the government's existing policies and propose viable solutions to enhance policy effectiveness.

The paper is structured as follows. Section 2 introduces the evolutionary game model, which describes the interaction of interests among farmers, government, and breeding enterprises. It also constructs an evolutionary model for these entities. In Section 3, the modeling process of the evolutionary game is presented, analyzing the evolutionary equilibrium and system stability points for the three parties. Section 4 focuses on the simulation analysis, exploring the effects of key parameter changes on the three parties and setting conditions for effective and efficient cooperation. Section 5 provides a discussion of the simulation results. Section 6 concludes the paper by providing final remarks and policy implications.

2. Model building

2.1. Theoretical basis

Classical game theory is based on Nash equilibrium and assumes that the participating agents can find the optimal solution that maximizes profit under the constraints. This model introduces the interaction between economic agents, thus bringing the theory closer to reality. However, in reality, participants are not fully rational and cannot make decisions strictly according to the profit maximization requirement [19]. Unlike classical game theory, evolutionary game theory is based on biological evolution, and its key assumptions are incomplete information and the limited rationality of the participants [20]. Firstly, participants in the real world do not have access to complete market information. In the context of wheat harvesting, farmers and breeding enterprises rely on local market signals, and their decision-making is influenced by historical and institutional factors. This limited information makes it challenging for them to make optimal decisions. Secondly, in evolutionary game theory, participants are considered finite-rational and achieve game equilibrium through dynamic adjustments. Farmers and breeding enterprises continuously adapt their decisions as the government implements stricter regulatory measures, eventually reaching a stable state. Therefore, evolutionary game theory offers a more realistic depiction of the complexity of participants and provides more accurate predictions of their behavior. This paper adopts evolutionary game theory as the basis for its research, recognizing its ability to reflect real-world dynamics and participant behaviors.

In the field of agriculture, numerous research endeavors have utilized evolutionary game approaches to investigate various aspects. For example, Lu [21] used an evolutionary game approach to analyze the government and farmers under China's arable land conservation policy to find optimization solutions. Using an evolutionary game approach, Xie [22] explored how to promote the adoption of low-carbon technologies by farmers from the perspective of low-carbon production, thus improving food quality and safety. Chen [23] employed an evolutionary game approach to study the government's management of farmers' abandonment behavior. The results show that the ideal stable equilibrium can be reached only when the farmers' transfer income is higher than their potential abandonment income. These studies have contributed novel insights and ideas for advancing the sustainable development and governance of China's agri-food system. By applying evolutionary game theory, researchers have shed light on optimizing policy implementation, and effectively managing farmers' behavior. These findings have implications for enhancing the long-term sustainability and security of China's agri-food system.

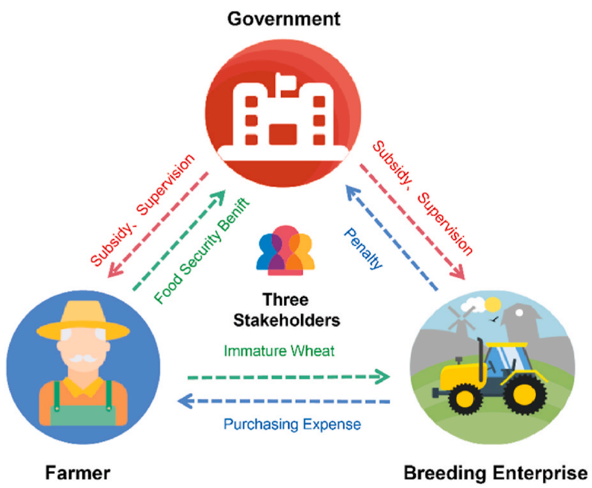

Fig. 1. Relationship diagram of the tripartite evolutionary game model.

2.2. Problem description

In 2022, a widespread phenomenon of harvesting immature wheat by farmers in China has emerged, leading to undesirable consequences such as a reduction in total grain production, which contradicts the government's long-term strategic goals. Consequently, establishing a model of tripartite cooperation among farmers, the government, and farming enterprises becomes crucial for achieving food security. Fig. 1 illustrates the three stakeholder scenarios of farmers' behavior in harvesting immature wheat.

Farmers serve as the backbone of grain production, and their actions are driven by economic interests, aiming to maximize expected returns encompassing product prices, production costs, and anticipated output [24]. In recent years, the rapid increase in agricultural costs has made the process of harvesting mature wheat more expensive, resulting in negative returns [25]. Coupled with climate instability, farmers have become more risk-averse. Additionally, China has witnessed a continuous rise in total grain production, leading to overcapacity and accumulation of grain stocks [26]. As a result, farmers anticipate that continuing to produce mature wheat may not be financially rewarding. The government holds a pivotal role in guiding grain production policies by implementing a minimum purchase price for grain and providing subsidies to support farmers. However, in practical terms, the financial subsidies provided by the government often translate into higher land rents, thereby increasing production costs and risks for farmers [27]. Furthermore, ineffective implementation of subsidy programs by local governments and inefficient distribution of subsidies have failed to enhance farmers' income through grain subsidy policies [28]. Breeding enterprises, as purchasers of immature wheat, primarily seek to supplement the feed requirements for cattle breeding. Currently, corn serves as the primary feed source for Chinese farming enterprises. However, floods in major corn-producing regions in China in 2021 resulted in significant yield reductions, leading to a shortage of stored feed for farming enterprises. Furthermore, stringent epidemic control measures implemented by the Chinese government impeded the inter-regional transportation of silage corn [29], Thus, farming enterprises are motivated to consider purchasing wheat as a substitute feed.

2.3. Model assumptions

The three participants in this paper are farmers, government, and breeding enterprises, all finite rational. We propose the following hypothesis.

Hypothesis 1. The participants in this scenario include the farmer (participant 1), the government (participant 2), and the breeding enterprise (participant 3). Each participant faces two choices. The farmer's choice consists of the probability of harvesting immature wheat (x, $0 \leq x \leq 1$) and the probability of harvesting mature wheat ($1\text{-}x$). The government's choice includes the probability of adopting an incentive-oriented policy (y, $0 \leq y \leq 1$) and the probability of choosing a punishment-oriented policy ($1\text{-}y$). The breeding enterprise's decision involves the probability of purchasing immature wheat (z, $0 \leq z \leq 1$) and the probability of buying corn ($1\text{-}z$).

Hypothesis 2. A farmer engaged in agricultural production will receive R_m from selling mature wheat. However, if they harvest the immature wheat ahead of schedule, the income will be R_i. According to the consistent prices on the Chinese grain market $R_m > R_i$. Correspondingly, farmers invested upfront planting costs C_m and C_i, $C_m > C_i$. In China, farmers who grow wheat receive government subsidies. The amount of wheat subsidies under the incentive-oriented policy is S_{f1}, and the number of subsidies under the punishment-oriented policy is S_{f2}. Due to stronger subsidies under the incentive policy, we have $S_{f1} > S_{f2}$. In addition, considering the possibility of farmers engaging in speculative behavior when harvesting immature wheat without being detected, T_f represents the resulting speculative gain. This gain includes additional management and harvesting costs, storage costs, potential losses from pests and rodents, and the opportunity cost associated with planting the next crop early during the period from the beginning of wheat filling to maturity.

Hypothesis 3. Historically, the Chinese government primarily relied on an incentive-oriented policy that involved providing subsidies for wheat production. However, as a response to the issue of farmers harvesting immature wheat, the government introduced punitive measures and regulatory actions. Both measures incurred significant human and material resources. C_{g1} and C_{g2} represent the costs of incentive-oriented and punishment-oriented policies, and the parameters α and β denote the corresponding regulatory intensity of the government, with higher financial costs associated with increased regulatory intensity. Under the incentive-oriented policy, the government imposes fines of P_{f1} on the farmer and P_{e1} on the buying enterprise if they are found to be involved in trading immature wheat. In contrast, the punishment-oriented policy entails heavier fines, with fines for farmers and enterprises designated as P_{f2} and P_{e2}, respectively. Therefore, we have $P_{f1} < P_{f2}$ and $P_{e1} < P_{e2}$. Additionally, when farmers harvest mature wheat, it brings positive benefits W to the government by increasing grain production. Conversely, harvesting immature wheat incurs losses D by damaging the agri-food production system. Moreover, in order to facilitate the transportation of agricultural products, the government implementing the incentive-oriented policy provides subsidies S_c to breeding enterprises that purchase corn.

Hypothesis 4. Breeding enterprises have the option to purchase immature wheat from local farmers or corn from other provinces. When a breeding enterprise acquires immature wheat, it experiences a contingency effect U_i as it resolves the feed shortage situation. Moreover, since wheat prices are relatively lower compared to corn, buying immature wheat results in additional speculative gains T_e for the breeding company. These gains include cost savings from avoiding cross-regional transportation expenses and other overhead costs. However, if the farmer chooses to harvest mature wheat, there will be no available suppliers in the market. Consequently, the breeding enterprise will have to transport corn from a distant location, incurring the cost of purchasing corn (C_e) and gaining utility U_c. Additionally, the process of transferring corn introduces feed supply shortages, resulting in losses denoted as L_e for the breeding enterprise.

Therefore, based on the above assumptions, we present the respective returns of the three participants in Table 1.

Table 1
Player payoff matrix.

		Government	Breeding enterprises Purchase of immature wheat (z)	Purchase of corn (1-z)
Farmers	Harvesting immature wheat (x)	Incentive-oriented Policy(y)	$R_i - C_i + T_f + S_{f1} - P_{f1}$ $P_{f1} + P_{e1} - C_{g1} - S_{f1} - D$ $U_i - R_i + T_e - P_{e1}$	$-C_i + S_{f1}$ $- C_{g1} - S_{f1} - D - S_c$ $U_c - C_e + S_c$
		Punishment-oriented Policy (1-y)	$R_i - C_i + T_f + S_{f2} - P_{f2}$ $P_{f2} + P_{e2} - C_{g2} - S_{f2} - D$ $U_i - R_i - P_{e2} + T_e$	$- C_i + S_{f2} - P_{f2}$ $P_{f2} - C_{g2} - S_{f2} - D$ $U_c - C_e$
	Harvesting mature wheat (1-*x*)	Incentive-oriented Policy(y)	$R_m - C_m + S_{f1} W - C_{g1} - S_{f1}$ $U_c - C_e$	$R_m - C_m + S_{f1} W - C_{g1} - S_{f1} - S_c$ $U_c - C_e + S_c$
		Punishment-oriented Policy (1-y)	$R_m - C_m + S_{f2}$ $W - C_{g2} - S_{f2}$ $U_c - C_e - L_e$	$R_m - C_m + S_{f2}$ $W - C_{g2} - S_{f2}$ $U_c - C_e$

3. Methods and data

3.1. Expected payoff and replicator dynamics equation of each participant

According to the profit matrix presented in Table 1, by calculating the expected returns and average expected returns of three participants: farmers, government, and breeding enterprises, under different decision scenarios, their replication dynamic equations are obtained as follows. The specific proof process is shown in the appendix (**Proposition 1**).

$$Fx = \frac{dx}{dt} = x(x-1)\left(C_i - C_m + P_{f2} + Rm - yP_{f2} - zR_i - zT_f + yzP_{f1}\right) \tag{1}$$

$$Fy = \frac{dy}{dt} = y(y-1)\left(C_{g1} - C_{g2} + S_{f1} - S_{f2} + S_c + xP_{f2} - zS_c - xzP_{f1} - xzP_{e1} + xzP_{e2}\right) \tag{2}$$

$$Fz = \frac{dz}{dt} = z(z-1)(L_e - xC_e - xL_e - yL_e + xP_{e2} + xR_i - xT_e + yS_c + xU_c) \tag{3}$$

3.2. Stable strategy analysis for each participant

According to the principle of differential equation stability, when the replicated dynamic equation reaches 0, it indicates that the variables (x, y, z) no longer change over time, and each participant has reached an optimal strategy. Therefore, the stability of strategies for farmers, government, and breeding enterprises will be analyzed as follows.

For farmers, the following conclusions can be drawn from Equation (1):

When $\frac{C_i - C_m + P_{f2} + R_m - zR_i - zT_f}{P_{f1} - zP_{f2}} < y < 1$, then $\left.\frac{dF(x)}{dx}\right|_{x=1} > 0, \left.\frac{dF(x)}{dx}\right|_{x=0} < 0$, it can be inferred that $x = 0$ is the evolutionary stability point for the farmer. It indicates that the farmer has shifted from harvesting immature wheat to harvesting mature wheat.

When $y = \frac{C_i - C_m + P_{f2} + R_m - zR_i - zT_f}{P_{f1} - zP_{f2}}$, then $F(x) \equiv 0$, it shows that farmers are as interested in choosing to harvest immature wheat as they are in harvesting mature wheat. All x is in an evolutionary steady state.

When $0 < y < \frac{C_i - C_m + P_{f2} + R_m - zR_i - zT_f}{P_{f1} - zP_{f2}}$, then $\left.\frac{dF(x)}{dx}\right|_{x=1} < 0, \left.\frac{dF(x)}{dx}\right|_{x=0} > 0,$ it can be inferred that $x = 1$ is the evolutionary stability point for the farmer. It indicates that the farmer shifts from harvesting immature wheat to harvesting mature wheat and eventually chooses to harvest mature wheat.

For the government, the following conclusions can be drawn from Equation (2):

When $\frac{C_{g1} - C_{g2} + S_{f1} - S_{f2} + xP_{f2} + S_c}{S_c + xP_{f1} + xP_e - xP_{f2}} < z < 1$, then $\left.\frac{dF(y)}{dy}\right|_{y=1} > 0, \left.\frac{dF(y)}{dy}\right|_{y=0} < 0$, it can be inferred that $y = 0$ is the evolutionary stability point of the government. It indicates that the government has shifted from incentive-to punishment-oriented policies.

When $z = \frac{C_{g1} - C_{g2} + S_{f1} - S_{f2} + xP_{f2} + S_c}{S_c + xP_{f1} + xP_e - xP_{f2}}$, then $F(y) \equiv 0$, it shows that the government has the same interest in choosing incentive-oriented policies and punishment-oriented policies. All y is in an evolutionary steady state.

When $0 < y < \frac{C_{g1} - C_{g2} + S_{f1} - S_{f2} + xP_{f2} + S_c}{S_c + xP_{f1} + xP_e - xP_{f2}}$, then $\left.\frac{dF(y)}{dy}\right|_{y=1} < 0, \left.\frac{dF(y)}{dy}\right|_{y=0} > 0$, it can be inferred that $y = 1$ is the government's evolutionary stability point. It indicates that the government has shifted from implementing a punishment-oriented policy to an incentive-oriented policy.

For breeding companies, the following conclusions can be drawn from Equation (3):

When $\frac{L_e - yL_e + yS_c}{C_e + L_e - P_{e2} - R_i + T_e - U_c + U_i - yL_e - yP_e + yP_{e2}} < x < 1$, then $\left.\frac{dF(z)}{dz}\right|_{z=1} > 0, \left.\frac{dF(z)}{dz}\right|_{z=0} < 0,$ it can be inferred that $z = 0$ is the evolutionary stability point for breeding enterprises. It indicates that the breeding enterprise has switched from acquiring immature wheat to corn.

When $x = \frac{L_e - yL_e + yS_c}{C_e + L_e - P_{e2} - R_i + T_e - U_c + U_i - yL_e - yP_e + yP_{e2}}, F(z) \equiv 0$, it suggests that breeding companies have the same interest in choosing to buy immature wheat as they do in acquiring corn. All z is in an evolutionary stable state.

When $0 < x < \frac{L_e - yL_e + yS_c}{C_e + L_e - P_{e2} - R_i + T_e - U_c + U_i - yL_e - yP_e + yP_{e2}}$, then $\left.\frac{dF(z)}{dz}\right|_{z=1} < 0$, $\left.\frac{dF(z)}{dz}\right|_{z=0} > 0$, it can be inferred that $x = 1$ is the evolutionary stability point for breeding enterprises. It indicates that breeding enterprises have shifted from acquiring corn to immature wheat.

3.3. System stability analysis

By setting equations (1), (2), and (3) equal to zero simultaneously, we obtained eight equilibrium points for the evolutionary game system: Case1 (0, 0, 0), Case2 (1, 0, 0), Case3 (0, 1, 0), Case4 (0, 0, 1), Case5 (1, 1, 0), Case6 (1, 0, 1), Case7 (0, 1, 1), and Case8 (1, 1, 1). These equilibrium points represent eight different tripartite game scenarios. To further determine the stability of these equilibrium points, we employed the Lyapunov's indirect method. According to this method, if all the eigenvalues of the Jacobian matrix have negative real parts, the equilibrium point is asymptotically stable. If any eigenvalue has a positive real part, the equilibrium point is unstable. If there are eigenvalues with a real part of zero and no positive real parts, the stability of the equilibrium point cannot be determined. In order for both ideal conditions to be met, all three eigenvalues must satisfy the condition of being less than zero. Based on the aforementioned stability criteria, we obtained the eigenvalues and stability conclusions for each point, as depicted in Table 2. The specific proof process is shown in the appendix (**Proposition 2**).

According to the assumptions presented in Section 2, the cost of harvesting immature wheat is less than that of mature wheat, $R_m > R_i > C_m > C_i$. Additionally, companies that transfer corn receive government subsidies $S_c > 0$ and may incur losses during the transfer process, $L_e > 0$. Therefore, Case2(1,0,0), Case4(0,0,1), Case5(1,1,0), Case6(1,0,1), Case7(0,1,1) and Case8(1,1,1) are all unstable points that do not maximize the benefits of the participants, so we do not discuss the above six points. Case1(0,0,0) and Case3(0,1,0) satisfy the condition that all three eigenvalues are less than 0, indicating that either one or all participants in the system achieve maximum benefit. Therefore, we will specifically analyze these two possible evolutionary stability scenarios.

Scenario 1: Case 1 (0,0,0) represents the evolutionary stability point. Referring to Table 2, we obtain the set of imbalanced Equation (4), which reveals that when the government penalty outweighs the farmers' benefit from growing mature wheat, the farmers' perceived risk of harvesting immature wheat surpasses the expected profit. Consequently, farmers opt to harvest mature wheat. In terms of the government, it chooses the incentive-oriented policy if the difference between the cost of implementing this policy and the cost of the punishment-oriented policy is smaller than the difference between the subsidy provided by the incentive-oriented policy and the punishment-oriented policy. If breeding enterprises are unable to replenish feed in a timely manner, it compromises production sustainability, leading them to choose to purchase corn. These findings underscore that the number of government penalties and the strength of government regulation are key factors influencing farmers' choices and the government's decision-making.

Table 2
Income matrix under corresponding strategies.

Equilibrium point	Jacobian matrix eigenvalues λ1; λ2; λ3	Real part notation	Stability condition
Case 1 (0, 0, 0)	$C_m - C_i - \beta P_{f2} - R_m$; $C_{g2} - C_{g1} - \alpha S_{f1} + S_{f2} - S_c$; $-L_e$	(-, -, -)	stable point
Case 2 (1, 0, 0)	$C_i - C_m + \beta P_{f2} + R_m$; $C_{g2} - C_{g1} - \beta P_{f2} - \alpha S_{f1} + S_{f2} - S_c$; $C_e - \beta P_{e2} - R_i + T_e - U_c + U_i$;	(+, -, -)	unstable point
Case 3 (0, 1, 0)	$C_m - C_i - R_m$; $C_{g1} - C_{g2} + \alpha S_{f1} - S_{f2} + S_c$; $-S_c$	(-, -, -)	stable point
Case 4 (0, 0, 1)	$C_m - C_i - \beta P_{f2} + R_i - R_m + T_f$; $C_{g2} - C_{g1} - \alpha S_{f1} + S_{f2}$; L_e	(-, -, +)	unstable point
Case 5 (1, 1, 0)	$C_i - C_m + R_m$; $C_{g1} - C_{g2} + \beta P_{f2} + \alpha S_{f1} - S_{f2} + S_c$; $C_e - P_{e1} - R_i - S_c + T_e - U_c + U_i$	(+, -, -)	unstable point
Case 6 (1, 0, 1)	$C_i - C_m + \beta P_{f2} - R_i + R_m - T_f$; $C_{g2} - C_{g1} + P_{f1} + P_{e1} - \beta P_{e2} - \beta P_{f2} - \alpha S_{f1} + S_{f2}$; $\beta P_{e2} - C_e + R_i - T_e + U_c - U_i$	(+, +, +)	unstable point
Case 7 (0, 1, 1)	$C_m - C_i - P_{f1} + R_i - R_m + T_f$; $C_{g1} - C_{g2} + \alpha S_{f1} - S_{f2}$ S_c	(-,+, +)	unstable point
Case 8 (1, 1, 1)	$C_i - C_m + P_{f1} - R_i + R_m - T_f$; $C_{g1} - C_{g2} - P_{f1} - P_{e1} + \beta P_{e2} + \beta P_{f2} + \alpha S_{f1} - S_{f2}$; $\beta P_{e2} - C_e + R_i - T_e + S_c + U_c - U_i$	(-, +, +)	unstable point

$$\begin{cases} R_m - C_m - C_I < P_{f2} \\ C_{g2} - C_{g1} < S_c + S_{f1} - S_{f2} \\ -L_e < 0 \end{cases} \tag{4}$$

Scenario 2: Case 3 (0,1,0) represents the evolutionary stability point. Referring to Table 2, we obtain the set of imbalance Equation (5), which indicates that farmers opt to harvest mature wheat when the selling price of mature wheat exceeds the cost of cultivation. The government, on the other hand, chooses an incentive-oriented policy when the difference between the cost of implementing such a policy and a punishment-oriented policy is smaller than the difference between the subsidy provided by a punishment-oriented policy and an incentive-oriented policy. As for breeding enterprises, they decide to purchase corn when they receive subsidies for transferring it. These findings highlight that the market price of wheat, the strength of government regulation, and government subsidies to breeding enterprises are critical factors influencing the decision-making of the three participants.

$$\begin{cases} C_m - C_I < R_m \\ C_{g1} - C_{g2} < S_{f2} - (S_c + S_{f1}) \\ -S_c < 0 \end{cases} \tag{5}$$

3.4. Initial parameters

3.4.1. Case selection

Wheat is one of the world's top three grains, and China is the world's largest wheat producer and consumer. The Chinese government has been actively guiding wheat production in recent years by improving production conditions and increasing scientific and technological inputs. However, with the existing cropping structure, it is less likely that China will continue to expand the wheat acreage, and the increase in wheat unit production is gradually slowing down. Therefore, reducing the behavior of farmers that disrupts the maintenance of agri-food systems is an important guarantee to maintain food security. As the main wheat-producing area in China, Henan Province has a perennial sowing area of more than 5.3 million mu, accounting for about 1/6 of the national wheat area [30]. In 2022, the province of Henan will produce 76 billion kg of wheat, approximately 28% of the total national wheat production [31]. Therefore, we choose Henan Province as the source of the data of the primary parameters, which is representative and practical and can provide a reference for food security governance in other regions of China and countries around the world.

3.4.2. Data source

The main variables in this paper have been sourced from three channels. Firstly, official government websites were referenced, such as the National Grain and Materials Reserve Bureau, to obtain the national average market trading price of mature wheat in November 2022, which was recorded as 1600 yuan/mu [32]. The Henan Provincial Bureau of Statistics' survey report on wheat production costs

Table 3
Initial parameters for numerical simulations (unit: 10^2/mu).

Participants	Parameters	Variables	Value
Farmers	Cost of harvesting immature wheat	C_i [33]	4
	Cost of harvesting mature wheat	C_m [33]	5.8
	Price of selling immature wheat	R_i [6]	15
	Price of selling mature wheat	R_m [6]	16
	Government subsidy payments received by farmers under incentive-oriented policies	S_{f1} [34]	2
	Government subsidy payments received by farmers under punishment-oriented policies	S_{f2} [38]	1
	Farmers' speculative income from harvesting immature wheat	T_f [34,39]	4.8
Government	Implementation intensity of incentive-oriented policies	α	1
	Implementation intensity of punishment-oriented policies	β	1
	The cost of government regulation under incentive-oriented policies	C_{g1} [40,41]	20
	The cost of government regulation under punishment-oriented policies	C_{g2} [41]	20
	Social benefits gained by the government when farmers choose to harvest mature wheat	W [42]	30
	Social losses caused when farmers choose to harvest immature wheat	D [42]	30
	Fines for farmers harvesting immature wheat under incentive-oriented policies	P_{f2} [7]	3
	Fines for companies that purchase immature wheat under incentive-oriented policies	P_{e2} [22]	5
	Fines for harvesting immature farmers under punishment-oriented policies	P_{f1} [7,43]	1
	Fines for companies that purchase immature wheat under penalty-oriented policies	P_{f2} [7]	4
Breeding enterprise	Utility obtained by purchasing immature wheat	U_i [35,37]	23
	Utility obtained by purchasing corn	U_c [38]	28
	Cost of buying corn	C_e [35]	20.5
	Speculative gains from buying immature wheat	T_e [43]	8
	Government subsidies for enterprises to purchase corn under incentive-oriented policies	S_e [44]	1.2
	Losses suffered during the period when farmers chose to harvest mature wheat and companies turned to buy corn	L_e [43]	4

and benefits provided data indicating that mature and immature wheat production costs are approximately 580 yuan/mu and 400 yuan/mu, respectively [33]. Additionally, a news release from the Henan government stated that subsidies totaling 601,900 yuan were issued in 2022, with wheat growers receiving a one-time planting subsidy of 200 yuan per mu [34]. Secondly, official media reports were consulted. According to the CCTV agricultural channel, the purchase price of immature wheat in 2022 was reported as 1500 yuan/mu [35]. Considering that the cost of corn purchased by companies is approximately 530 yuan/ton and the yield is about 3.8 tons per mu, it was assumed that the cost of corn purchased by companies amounts to 2050 yuan/mu. Thirdly, relevant literature was reviewed. Scholarly research has indicated that breeding enterprises can generate economic benefits of more than 2800 yuan per mu by purchasing corn [36], Considering that immature wheat provides cattle with only 80% of the nutritional value of corn, it was estimated that each acre of immature wheat can bring economic benefits of 2300 yuan to breeding enterprises [37]. Based on the information obtained from the above sources, the detailed parameter settings are shown in Table 3.

In Section 3, the analysis resulted in the setting of parameters that lead to stable equilibrium points (0,0,0) and (0,1,0), where farmers choose not to harvest immature wheat and breeding companies choose not to purchase immature wheat. These outcomes align with the desired situation. To further enhance the effectiveness of government policies, we will focus on several key parameters that can be modified to promote better cooperation among farmers, the government, and breeding enterprises, thereby strengthening the overall agri-food system. Specifically, the selected key parameters for investigation include the market grain price (R_m), the production cost of mature wheat for farmers (C_m), the government's fine imposed on breeding enterprises (P_{e2}), and the speculative gains obtained by farmers through harvesting immature wheat (T_f). During the examination, the other parameters will be held constant while one specified variable is altered to evaluate its impact.

In the initial state, we assume that the government maintains a neutral stance between incentive-oriented and punishment-oriented policies, with a willingness value of 0.5. Farmers have a tendency to harvest immature wheat, and breeding enterprises lean towards purchasing immature wheat, resulting in a willingness value of 0.7 for both parties. In the subsequent data, we simplify the units to 10^2 ¥.

4. Results

4.1. Simulation of different policy scenarios initial parameters

We simulated the evolution of farmers, government, and breeding enterprises to verify our conclusions using MATLAB software. Fig. 2 shows the evolution of the decision in three dimensions, demonstrating that the three participants will eventually stabilize at (0,0,0) and (0,1,0). The difference between these two is that all else being equal, the government will consider the financial cost of the policy before making a decision. When $C_{g1} > C_{g2}$, the government will adopt a punishment-oriented policy, and the evolutionary equilibrium point will be stable at (0,0,0). When $C_{g2} > C_{g1}$, government will choose an incentive-oriented policy, and the evolutionary equilibrium point will be stable at (0,1,0) at this time.

4.1.1. The case of varying government incentive intensity under case 1 (0,0,0)

The Chinese government has implemented a longstanding incentive policy based on subsidies to safeguard farmers' basic income, providing annual planting subsidies specifically for wheat cultivation. To account for regional variations in subsidy data across different provinces in China, we establish government incentive intensities at 50%, 60%, 120%, and 150% of the initial value. Meanwhile, the incentive intensity is positively related to the cost of government spending. Fig. 3 illustrates the impact of varying government subsidies on the three key participants.

Fig. 3(a) depicts that when the government allocates 50% of the funds, the subsidy fails to generate sufficient attraction. The

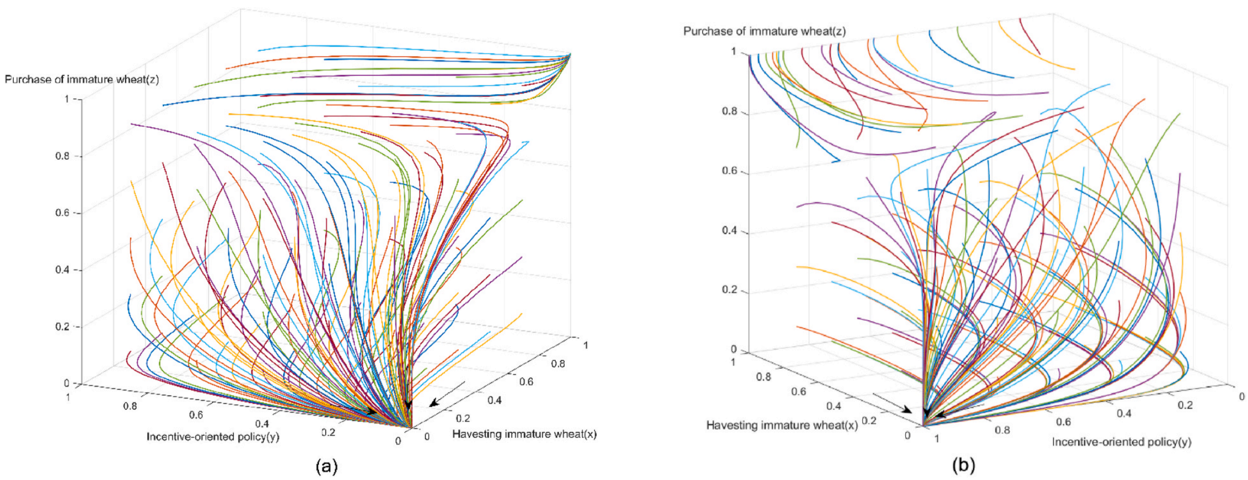

Fig. 2. Evolutionary trajectories of the farmer, government and breeding enterprises under different stable states: **(a)** (0, 0, 0), **(b)** (0, 1, 0).

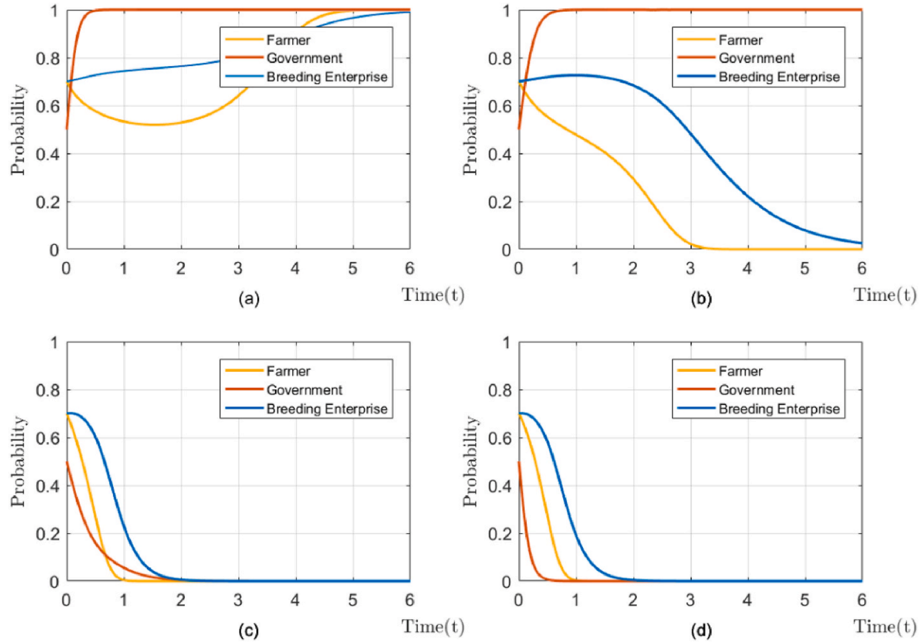

Fig. 3. The evolutionary trajectory of the three parties under different government incentive strengths **(a)** $\alpha = 0.5$ **(b)** $\alpha = 0.6$ **(c)** $\alpha = 1.2$ **(d)** $\alpha = 1.5$.

income received by farmers through the subsidy falls short of ensuring profitability. Consequently, farmers initially exhibit hesitation and eventually opt to harvest immature wheat driven by profit motives. Initially, breeding enterprises display a stronger willingness to acquire immature wheat compared to farmers, which gradually reaches a value of 1 once farmers become willing to harvest immature wheat. Fig. 3(b) demonstrates that farmers' decisions undergo a shift when the government invests 60% of the financial resources, leading them to choose the option of harvesting immature wheat due to the influence of subsidies. However, this transition is not entirely smooth, likely attributable to farmers' speculative behavior and apprehension regarding strict government penalties.

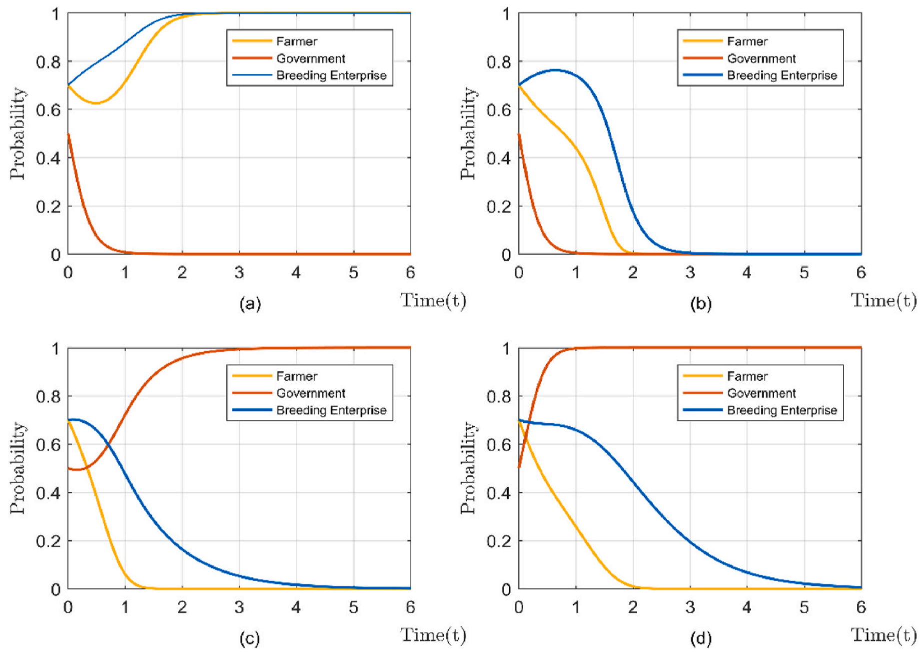

Fig. 4. The evolutionary trajectory of the three parties under different government punishment intensity **(a)** $\beta = 0.5$ **(b)** $\beta = 0.6$ **(c)** $\beta = 1.2$ **(d)** $\beta = 1.5$.

Furthermore, although farmers' inclination to harvest immature wheat continues to decline, breeding companies still display a high willingness to acquire immature wheat, but due to supply shortages, they resort to acquiring corn instead. Fig. 3(c) reveals that when the government commits 120% of its financial resources, there is a noticeable increase in farmers' willingness to harvest mature wheat, indicating the role of subsidies in promoting wheat harvesting behavior. However, simultaneously, the government adjusts its regulatory policy due to the escalating costs associated with government regulation, favoring a policy centered around punishment as it proves more economically viable. Fig. 3(d) illustrates that when the government allocates 150% of its financial resources, an increase in financial support to agriculture does not significantly stimulate farmers to harvest mature wheat.

The four graphs indicate that, on one hand, to discourage farmers from harvesting immature wheat, the government should invest a minimum of 50% of the initial subsidy amount. On the other hand, increasing financial support for agriculture will raise farmers' inclination to harvest mature wheat. However, this effect remains limited to incentive levels exceeding 120%, at which point government decisions will undergo a change.

4.1.2. The case of varying government punishment intensity under case 3 (0,1,0)

In order to ensure regular grain production, the Chinese government has implemented policies that involve regulation and penalties for farmers engaging in the harvesting of immature wheat, as well as for enterprises that purchase such wheat. Considering the current penalty policy, we set the punitive fine intensities at 50%, 60%, 120%, and 150% of the initial value. It is important to note that the intensity of punishment is directly related to government expenditure costs. The outcomes of the simulation are presented in Fig. 4.

Fig. 4(a) depicts that when the government allocates 50% of the financial resources for regulation, the light penalties fail to serve as a sufficient deterrent for farmers and breeding enterprises. Farmers weigh the economic benefits against the social impacts but ultimately choose to harvest immature wheat. Conversely, breeding enterprises consistently maintain their preference for acquiring immature wheat to supplement feed. In Fig. 4(b), as the government increases its investment to 60% of the financial resources for regulation, penalties become stronger. Consequently, the willingness of farmers to harvest immature wheat diminishes before that of breeding enterprises due to their higher sensitivity to government penalties. Fig. 4(c) highlights that when the government invests 120% of fiscal funds into regulation, the policy significantly accelerates farmers' willingness to harvest immature wheat, ultimately reaching zero. Simultaneously, due to the escalating financial burden on the government, there is a shift towards an incentive-oriented policy. In Fig. 4(d), with the government investing 150% of fiscal funds, a faster transition occurs towards a punishment-oriented policy. However, the progression towards zero willingness in both farmers and breeding enterprises is slowed.

These four graphs collectively illustrate that, on one hand, to deter farmers from harvesting immature wheat and breeding companies from purchasing it, the government must impose penalties on farmers and breeding companies that are not less than 60% of the original penalty amount. On the other hand, increasing penalties can enhance farmers' willingness to harvest mature wheat, but the effectiveness of this policy is limited to penalties greater than 120%, ultimately leading to a shift in government decisions.

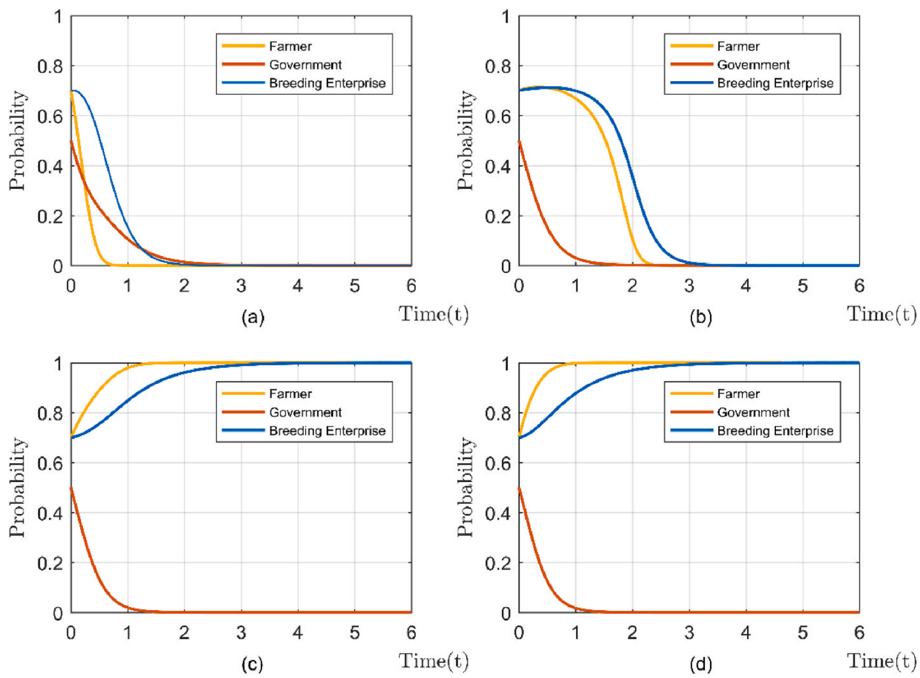

Fig. 5. Impact of different production costs on the tripartite evolutionary trajectory **(a)** $C_m = 480$ **(b)** $C_m = 840$ **(c)** $C_m = 1050$ **(d)** $C_m = 1250$.

4.2. Optimization of punishment-oriented policies

According to the above analysis, both incentive-oriented and penalty-oriented policies discourage farmers from harvesting immature wheat and breeding enterprises from buying immature wheat, and the cost significantly affects the choice of government policy. During the simulation, we find that the government will adopt the punishment-oriented policy when the punishment-oriented and incentive-oriented policies invest the same cost ($C_{g1} = C_{g2}$). Therefore, in this section, we will analyze the impact of R_m, C_m, and T_e, which are the key parameters based on the punishment-oriented policy, and discuss how to optimize the punishment-oriented policy.

4.2.1. The impact of C_m on punishment-oriented policies

In recent years, there has been a significant increase in the prices of agricultural inputs such as fertilizers and diesel, leading to a rise in agricultural production costs. To examine the impact of production costs on farmers' decisions, we conducted simulations using four values of $C_m = 480$, $C_m = 840$, $C_m = 1050$, and $C_m = 1250$. These values correspond to farmers' wheat production costs being 83%, 121%, 145%, and 181% of the initial values, respectively. Notably, $C_m = 480$ represents a lower-than-average cost of agricultural production, while the remaining three values were obtained from the websites of the Hubei, Anhui, and Sichuan provincial governments [45–47]. The simulation results are presented in cases (a), (b), (c), and (d) in Fig. 5.

Fig. 5(a) demonstrates that when wheat production costs are 83% of the initial value, farmers tend to opt for harvesting mature wheat due to the relatively low additional cost involved in the wheat maturation process. In Fig. 5(b), with wheat production costs at 121% of the initial value, farmers' willingness to adopt the harvest of mature wheat decreases as they face economic pressures stemming from increased costs. However, driven by the fear of penalties, farmers ultimately choose to harvest mature wheat. Fig. 5(c) reveals that when wheat production costs reach 145% of the initial value, the additional cost rises significantly. This substantial cost burden reduces farmers' profit margins, leading them to harvest immature wheat to avoid the heightened expenses and risks associated with production. Additionally, given the availability of market supply, breeding companies also acquire immature wheat as an emergency measure. Fig. 5(d) shows that when wheat production costs stand at 181% of the initial value, the high cultivation costs prompt farmers to quickly sell immature wheat to stabilize their returns. The evolutionary trajectory of farmers exceeds that of breeding enterprises.

These four graphs illustrate that as production costs increase, the likelihood of farmers harvesting immature wheat also rises. Among the provinces, Anhui and Sichuan exhibit a higher possibility of farmers engaging in immature wheat harvesting compared to others, primarily due to current agricultural production costs. Therefore, to deter farmers from harvesting immature wheat and discourage breeding enterprises from purchasing it, the government should enhance efforts to support farmers in the production process and alleviate the decline in farmers' motivation to grow grains caused by rising agricultural production costs.

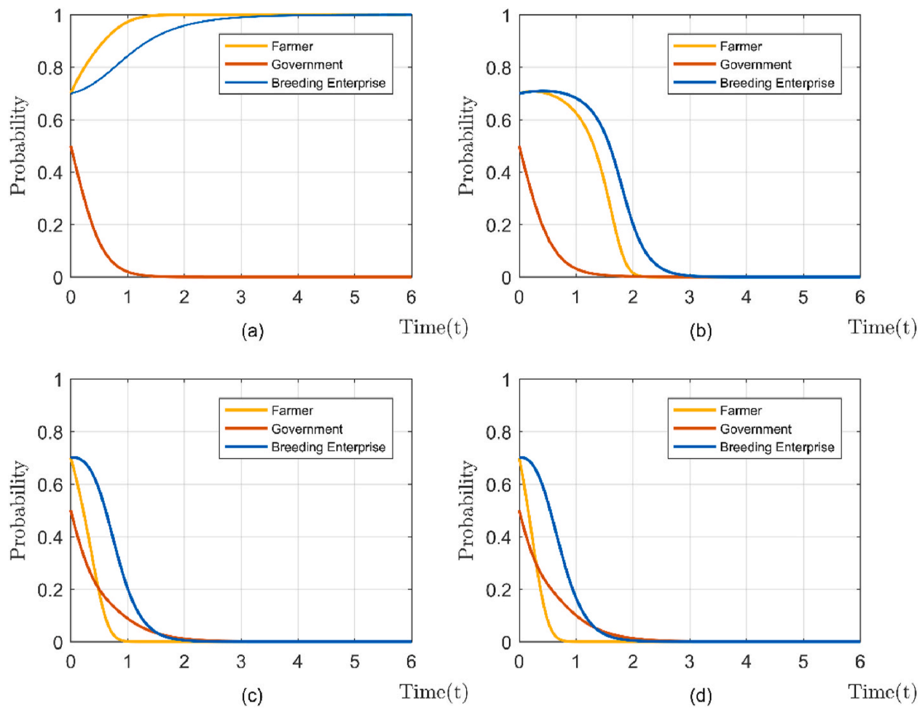

Fig. 6. Impact of mature wheat prices on the tripartite trajectory **(a)**$R_m = 1150$ **(b)**$R_m = 1350$ **(c)**$R_m = 1740$ **(d)**$R_m = 1900$.

4.2.2. The impact of R_m on punishment-oriented policies

We added four values of $R_{\mathrm{m}} = 1150$, $R_{\mathrm{m}} = 1350$, $R_{\mathrm{m}} = 1740$, and $R_{\mathrm{m}} = 1900$ for simulation, representing market prices of mature wheat equivalent to 72%, 84%, 108%, and 118% of the initial value, respectively. Among these values, $R_{\mathrm{m}} = 1150$ corresponds to the minimum purchase price set by the National Development and Reform Commission for 2022, while $R_{\mathrm{m}} = 1900$ represents the high-selling price of wheat in China during the same year [48]. The simulation results are shown in cases (a), (b), (c), and (d) in Fig. 6.

Fig. 6(a) demonstrates that when the market price of mature wheat is 72% of the initial value, and the selling price of immature wheat surpasses that of mature wheat, farmers are enticed by financial gains and become willing to take the risk of harvesting immature wheat, leading to a rapid evolution of their willingness to 1, which occurs faster than that of breeding enterprises. Additionally, a substantial amount of immature wheat becomes available in the market, ensuring sufficient feed supply for breeding enterprises. In Fig. 6(b), as the market price of mature wheat reaches 84% of its initial value, farmers carefully weigh the profit margin between selling mature wheat and the risk of administrative penalties. Although the willingness of breeding enterprises to purchase immature wheat remains relatively high, it gradually diminishes due to supply shortages. Fig. 6(c) shows that with the market price of mature wheat rising to 108% of its initial value, farmers experience increased returns, which effectively enhances their incentive to harvest mature wheat, resulting in a faster convergence towards the ideal state of the game. In Fig. 6(d), the market price of mature wheat reaches 118% of its initial value, representing a rare high price observed in the Chinese wheat market. This escalation influences farmers to lean towards harvesting mature wheat, although the change is not as significant.

These four graphs illustrate that an increase in the market price of grain contributes to an elevated likelihood of farmers harvesting mature wheat. When farmers anticipate excess grain capacity in the current year and expect the price of mature wheat to decline, they opt to harvest immature wheat early to preserve their profits. However, if the market price of mature wheat surpasses 1350 yuan/mu, despite it still being slightly lower than that of immature wheat, farmers choose to harvest mature wheat under the threat of a punishment-oriented policy. Moreover, the higher the price, the more inclined farmers are to harvest mature wheat.

4.2.3. The impact of T_e on punishment-oriented policies

In this section, we examine the impact of variations in the speculative gain T_{e} for breeding enterprises and the government fine P_{e} for enterprises on the trajectory of the three entities. Breeding enterprises that take the risk of buying immature wheat will receive the speculative gain T_{e} of reduced transportation costs and timely feed supply compared to shipping corn from distant locations. We add $T_{\mathrm{e}} = 11$, $P_{\mathrm{e}} = 5$; $T_{\mathrm{e}} = 10$, $P_{\mathrm{e}} = 5$; $T_{\mathrm{e}} = 8$, $P_{\mathrm{e}} = 8$ and $T_{\mathrm{e}} = 8$, $P_{\mathrm{e}} = 10$ for our study.

Fig. 7(a) illustrates that when $T_{\mathrm{e}} = 11$ and $P_{\mathrm{e}} = 5$, breeding enterprises experience relatively higher cost savings and greater benefits by acquiring immature wheat. Consequently, their speculative returns increase, leading to a rapid evolution of their willingness to 1. Moreover, by signaling their intention to purchase large quantities of immature wheat in the market, breeding enterprises incentivize farmers to harvest wheat. Fig. 7(b) shows that when $T_{\mathrm{e}} = 10$ and $P_{\mathrm{e}} = 5$, there is a slight reduction in speculative returns for breeding enterprises, resulting in hesitation. Ultimately, they decide against purchasing immature wheat due to concerns about the negative repercussions on their reputation and corporate image in the event of administrative penalties. Fig. 7(c) shows that when $T_{\mathrm{e}} = 8$ and $P_{\mathrm{e}} = 8$, the speculative returns of the breeding enterprises return to our initial setting when the government penalty is raised, and the

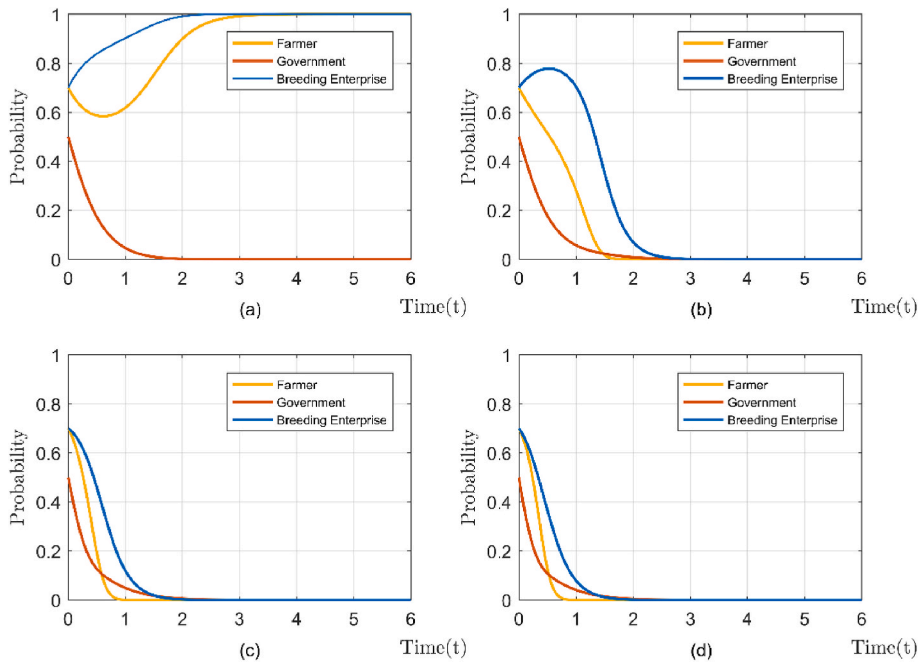

Fig. 7. Impact of different speculative returns on the tripartite trajectory **(a)** $T_{\mathrm{e}} = 11$, $P_{\mathrm{e}} = 5$ **(b)** $T_{\mathrm{e}} = 10$, $P_{\mathrm{e}} = 5$ **(c)** $T_{\mathrm{e}} = 8$, $P_{\mathrm{e}} = 8$ **(d)** $T_{\mathrm{e}} = 8$, $P_{\mathrm{e}} = 10$.

speculative returns are equal to the government penalty returns. At this point, the breeding enterprise will choose not to acquire wheat. Fig. 7(d) showcases the scenario where $T_e = 8$ and $P_e = 10$, as the amount of government fines rises. In this case, the willingness of breeding enterprises to purchase immature wheat rapidly declines to 0. Simultaneously, the government fines imposed on enterprises serve as a warning to farmers, leading to a swift drop in their willingness to harvest wheat early.

5. Discussion

The global agri-food system is facing unprecedented complexity and vulnerability, as it grapples with the impacts of climate change, natural disasters, water scarcity, and population growth [2]. This interconnected system has witnessed a significant rise in food interdependence among countries in recent decades, prompting nations to take proactive measures to strengthen food security governance. Australia, a leading agricultural producer, launched the Agriculture 4.0 program in 2019. This visionary initiative seeks to foster strong linkages between farmers and cutting-edge technologies in agriculture, harnessing innovation to propel the development of the agricultural sector and unlock the potential of emerging domains [49]. In 2020, the United States Department of Agriculture (USDA) unveiled the "USDA Science Blueprint: A Roadmap for USDA Science from 2020 to 2025." This strategic blueprint prioritizes sustainable production intensification and the expansion of agricultural production capacity as key focus areas. Likewise, at the 2022 Special EU Summit, France spearheaded the "Food & Agriculture Resilience Mission" initiative, emphasizing the promotion of local, sustainable food production and the facilitation of unhindered agricultural trade to alleviate the food security crisis faced by European Union member states. These concerted efforts reflect the global commitment to addressing food security challenges through innovative approaches and collaborative governance.

Over the past four decades, the Chinese government has prioritized the sustainability of its agri-food system as it rapidly develops into a thriving economy. China's food production has outpaced the global average, showcasing significant growth [50]. However, despite this progress, it is important to note that China's food security cannot be conclusively affirmed based on the normative food security framework. Several factors, such as the irrational allocation of agricultural resources and land ownership mechanisms, have had adverse effects on farm production and hindered agricultural productivity growth [51,52]. Moreover, the current state of Chinese agriculture, characterized by high input costs and low returns, results in grain market prices that fail to reflect actual production costs and provide insufficient price support to farmers. Previous studies have shown that increasing government subsidies can enhance farmers' production incentives to some extent. However, the effectiveness of these policies is often hampered by inefficiencies in implementation, leaving farmers struggling to increase their income and leading to policy failures [53].

The agri-food system operates as a complex mechanism [54], and our study aims to address this complexity by introducing and simulating the behaviors of three key subjects: farmers, government, and farming enterprises. Through our analysis, we have identified several factors that significantly influence the dynamics of the model, including government regulatory costs, food production costs, market prices, and speculative returns of enterprises. Firstly, it is crucial to prioritize the reduction of food production costs in order to stabilize agricultural production. Failing to control the continuous rise in cultivation costs may drive farmers to shift towards non-farm activities, resulting in a decline in food production. Secondly, farmers' price forecasting and risk aversion have a profound impact on their marketing behavior. Thus, the government should closely monitor the grain market to mitigate price volatility. Scholars [55,56] have also emphasized the importance of appropriate price incentives to encourage farmers to invest more in improving agricultural productivity. Thirdly, breeding enterprises play a significant role as buyers in the immature wheat market. Government intervention in the grain market can effectively reduce the speculative gains made by breeding enterprises, thereby mitigating illegal profit-making and monopolistic buying. In conclusion, this study offers a viable solution to mitigate farmers' behaviors related to the premature harvesting of wheat, which disrupts the production order. By addressing this issue, it contributes to the development of sustainable agri-food systems that play a crucial role in ensuring national food security.

6. Conclusions and policy implications

6.1. Conclusions

This paper utilizes evolutionary game theory to establish a model incorporating farmers, government, and breeding enterprises. By integrating real data from local provinces in China, we examine the evolutionary trajectory of the behavior of these three entities. The findings are highly significant for the stable development and security of China's agri-food system. The key conclusions of this study are as follows.

First, both incentive-oriented and punishment-oriented policies have proven effective in mitigating the issue of farmers harvesting immature wheat. Incentive-oriented policies provide farmers with greater income security and enhance their motivation to cultivate grains. Conversely, punishment-oriented policies discourage farmers and breeding enterprises from engaging in illegal practices through administrative penalties. Our study reveals that a government subsidy below 50% of the initial value fails to adequately safeguard farmers' profitability, leaving them susceptible to the temptations offered by breeding enterprises, thus compromising national food security. Similarly, if government penalties for breeding enterprises fall short of 60% of the initial value, the effectiveness of the punishment-oriented policy as a deterrent diminishes. However, increasing regulation beyond the 120% threshold only burdens the government financially without significantly reducing the willingness of farmers and breeding enterprises to engage in undesirable practices.

Secondly, we conducted a comparison between incentive-oriented and punishment-oriented policies. Our findings indicate that, under the same regulatory costs and other constant conditions, the willingness of farmers and farming firms to harvest or acquire immature wheat diminishes more rapidly under the punishment-oriented policy. This suggests that the punishment-oriented policy is more effective in achieving the desired outcomes.

Thirdly, the behavior of farmers in harvesting immature wheat is influenced by two key factors: the planting cost and the market price of wheat. When the planting cost (C_m) per mu exceeds 1050 yuan, the increasing production cost diminishes the impact of the initial subsidy policy, and the diminishing returns undermine farmers' willingness to cooperate. Moreover, if the grain market experiences a downturn and wheat prices weaken, farmers anticipate that they will only be able to sell their wheat at the national minimum purchase price of 1150 yuan per mu. In response, they choose to harvest immature wheat early to safeguard their profits. Therefore, lowering the wheat production costs to below 480 yuan per mu or increasing the market price of wheat to approximately 1900 yuan per mu would incentivize farmers to harvest mature wheat.

Fourthly, the behavior of breeding enterprises in acquiring immature wheat is influenced by two factors: the speculative gain and the government fine. When the speculative gain for breeding enterprises from acquiring immature wheat exceeds 200% of the government fine, they are highly likely to engage in the acquisition of immature wheat. However, when the speculative gain drops below 200% of the government fine, breeding enterprises choose not to acquire immature wheat due to the potential negative consequences of administrative penalties.

6.2. Policy implications

Based on the aforementioned findings, this paper suggests the following policy implications:

Firstly, the government should enhance the effectiveness of the food subsidy policy to provide greater benefits for farmers. This will ensure that the subsidy policy has a positive impact on food cultivation. Additionally, the government should allocate more resources to agricultural infrastructure and promote the adoption of advanced technologies by farmers. This will help reduce farming costs and achieve sustainable productivity growth. Furthermore, in response to the feed shortage in breeding enterprises, the government can facilitate the smooth transportation of grains and guide farmers in adjusting their planting structure. This will strengthen domestic feed supply and contribute to the smooth operation of the agri-food system.

Secondly, it is crucial for the government to prioritize the protection of farmers' interests as they are the key actors in food production. By increasing farmers' income, their motivation to engage in food cultivation will be stimulated, resulting in increased production of high-quality food. If farmers feel dissatisfied with the implemented policies or if local governments fail to provide sufficient protection for farmers, their motivation to produce will be significantly reduced. Therefore, the government should continuously enhance farmers' trust in the rewards of food cultivation to unlock the full potential of food production and strengthen food security in the long run.

Thirdly, the government should strive to improve the stability and sustainability of its policies. Given the tripartite interest relationship between farmers, breeding enterprises, and the government, it is essential for the government to regulate and enforce strict penalties to deter illegal actions by breeding enterprises. However, it is also important for the government to avoid excessive financial burden. Precision in policy implementation is crucial, and the government should allocate subsidies in a targeted manner to regions with advantageous production conditions. This approach will enhance policy efficiency and ensure effective implementation.

6.3. Limitations

It should be noted that this paper has set the penalty parameter for harvesting and purchasing immature wheat based on previous agricultural administrative penalty cases and relevant literature, as a national penalty standard has not been issued by the Chinese government. However, it is important to acknowledge that regional variations in penalties may exist in practice. Additionally, since China has multiple wheat-producing regions with varying costs of cultivation and selling prices, the parameters used in this paper are based on the average price in Henan Province, which is a major wheat-producing region in the country. Future research can consider incorporating additional parameters and data to construct a more comprehensive model.

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Author contribution statement

Yanhu Bai: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data. Mengdi Huang: Performed the experiments; Wrote the paper. Minmin Huang: Analyzed and interpreted the data. Jianli Luo: Conceived and designed the experiments. Zhuodong Yang: Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Proof of Proposition 1:

According to the payoff matrix in Table 1, E_{ij} and $\overline{E_i}$ is assumed to represent the participants' expected payoff and average payoff, respectively. $I = 1, 2, 3$ represent farmers, government, and breeding enterprises, respectively, and $j = 1, 2$ represent two different decisions of participants. The expected benefits of different choices for farmers, government, and breeding enterprises are as follows:

$$E_{11} = yz\left(R_i - C_i + T_f + S_{f1} - P_{f1}\right) + y(1-z)\left(S_{f1} - C_i\right) + z(1-y)\left(R_i - C_i + T_f + S_{f2} - P_{f2}\right) + (1-z)(1-y)\left(S_{f2} - C_i - P_{f2}\right) \tag{6}$$

$$E_{12} = yz\left(R_m - C_m + S_{f1}\right) + y(1-z)\left(R_m - C_m + S_{f1}\right) + z(1-y)\left(R_m - C_m + S_{f2}\right) + (1-z)(1-y)\left(R_m - C_m + S_{f2}\right) \tag{7}$$

$$\begin{aligned} E_{21} = {} & yz\left(P_{f1} + P_{e1} - C_{g1} - S_{f1} - D\right) + x(1-z)\left(P_{f2} - C_{g2} - S_{f2} - D - S_c\right) + z(1-x)\left(W - C_{g1} - S_{f1}\right) + (1-z)(1-x)\left(W - C_{g1}\right. \\ & \left. - S_{f1} - S_c\right) \end{aligned} \tag{8}$$

$$\begin{aligned} E_{22} = {} & xz\left(P_{f2} + P_{e2} - C_{g2} - S_{f2} - D\right) + x(1-z)\left(P_{f2} - C_{g2} - S_{f2} - D - S_c\right) + z(1-x)\left(W - C_{g2} - S_{f2}\right) \\ & + (1-z)(1-x)\left(W - C_{g2} - S_{f2} - S_c\right) \end{aligned} \tag{9}$$

$$E_{31} = yx(U_i - R_i + T_e - P_{e1}) + x(1-y)(U_i - R_i + T_e - P_{e2}) + y(1-x)(U_e - C_e) + (1-x)(1-y)(U_e - C_e - L_e) \tag{10}$$

$$E_{32} = yx(U_c - C_e + S_c) + x(1-y)(U_c - C_e) + y(1-x)(U_e - C_e + S_c) + (1-x)(1-y)(U_e - C_e) \tag{11}$$

According to the above formula, the average expected return of the three participants can be obtained as follows:

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \tag{12}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22} \tag{13}$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32} \tag{14}$$

According to the expected returns of the three participants, the dynamic replication equation is calculated as follows:

$$F_x = \frac{dx}{dt} = x(x-1)\left(C_i - C_m + P_{f2} + R_m - yP_{f2} - zR_i - zT_f + yzP_{f1}\right) \tag{15}$$

$$F_y = \frac{dy}{dt} = y(y-1)\left(C_{g1} - C_{g2} + S_{f1} - S_{f2} + S_c + xP_{f2} - zS_c - xzP_{f1} - xzP_{e1} + xzP_{e2}\right) \tag{16}$$

$$F_z = \frac{dz}{dt} = z(z-1)(L_e - xC_e - xL_e - yL_e + xP_{e2} + xR_i - xT_e + yS_c + xU_c) \tag{17}$$

Proof of Proposition 2:

According to Lyapunov's indirect method: If all the real parts of the eigenvalues of the Jacobi matrix are negative, the equilibrium point is asymptotically stable. If there are positive real parts in the eigenvalues, the equilibrium point is unstable. If there are real parts in the eigenvalues that are zero and no positive real parts, the stability of the equilibrium point cannot be judged. In order to achieve these two ideal states, the 3 eigenvalues must satisfy the condition that they are less than 0. The specific analysis is as follows.

$$J=\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{11} & a_{11} \\ a_{11} & a_{11} & a_{11} \end{pmatrix}=\begin{pmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{pmatrix} \tag{18}$$

$$a_{11}=x\left(C_i-C_m+P_{f2}+R_m-yP_{f2}-zR_i-zT_f+yzP_{f1}+2yzS_{f1}\right)+(x-1)\left(C_i-C_m+P_{f2}+R_m-yP_{f2}-zR_i-zT_f+yzP_{f1}+2yzS_{f1}\right)\# \tag{19}$$

$$a_{12}=-x(x-1)\left(P_{f2}-2zS_{f1}\right) \tag{20}$$

$$a_{13}=-x(x-1)\left(R_i+T_f-2yS_{f1}\right) \tag{21}$$

$$a_{21}=y(y-1)\left(P_{f2}+zP_{e2}\right) \tag{22}$$

$$\begin{aligned} a_{22} \; &= (y-1)\left(C_{g1}-C_{g2}+S_{f1}-S_{f2}+S_c+xP_{f2}-zS_c-xzP_{f1}-xzP_{e1}+xzP_{e2}\right) \\ &+y\left(C_{g1}-C_{g2}+S_{f1}-S_{f2}+S_c+xP_{f2}-zS_c-xzP_{f1}-xzP_{e1}+xzP_{e2}\right) \end{aligned} \tag{23}$$

$$a_{23}=xy(y-1)P_{e2} \tag{24}$$

$$a_{31}=-z(z-1)(C_e-P_{e2}-R_i+T_e-U_c+U_i+yP_{e2}) \tag{25}$$

$$a_{32}=-xz(z-1)P_{e2} \tag{26}$$

$$a_{33}=z(S_c-xC_e+2xP_e+xR_i+xU_c-xU_i+xyP_{e1}-2xyP_e)+(z-1)(S_c-xC_e+xP_{e2}+xR_i+xU_c-xU_i+xyP_{e1}-2xyP_{e2}) \tag{27}$$

According to the evolutionary game theory, only all the eigenvalues of the Jacobian matrix are non-positive, we can obtain this system's asymptotic stability point. The eigenvalues of the Jacobian matrices of each point are listed in Table 2.

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