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Multi-Party Collaboration in Agricultural Green Technology Innovation and Adoption: An Evolutionary Game Approach

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Abstract: The collaborative promotion of agricultural green technology innovation and adoption (AGTIA) is essential for achieving green agriculture. However, there remains a need to raise both innovation and adoption levels, necessitating explorations of the effects of government subsidies and collaborative mechanisms. To this end, this paper builds an evolutionary game model to analyze the collaborative promotion of AGTIA. By introducing relevant parameters, such as government subsidies for AGTIA, dividends and liquidated damages within industrial technology innovation alliances (ITISAs), and cost reduction coefficients, this paper explores the impacts of the technology spillover effect, price premium of green agricultural products, and government subsidies on the strategic choices of related participants. The main findings are as follows: (1) The key factors influencing AGTIA are different and the government can implement different combinations of dynamic and static subsidy mechanisms at distinct stages of agricultural green development. Government subsidies play a major role at the initial stage, while ITISAs should take fuller advantage of AGTIA as green agriculture matures. (2) Increasing subsidies can promote AGTIA at the initial stage. However, an optimal range of subsidies exists, and when subsidies are higher than a certain threshold, government subsidy willingness fluctuations may lead to decreased stability. (3) There is a threshold of liquidated damages within ITISAs. Only when liquidated damages exceed the threshold can they facilitate the development of durable ITISAs and discourage free-rider behavior. The above findings can provide theoretical support for relevant government sectors when issuing policies to promote AGTIA and agricultural green development.

Keywords: agricultural innovation; green technology adoption; innovation alliances; static subsidies; dynamic subsidies; evolutionary game

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1. Introduction

Green agriculture is an important approach to achieving sustainable development goals [1–3]. AGTIA offers effective solutions to ensuring food safety and reducing agricultural pollution [4,5]. However, according to statistics, the area under agricultural green cultivation accounts for only 8.78% of the country's total agricultural arable land in China [6]. On a global scale, only 1.5% of farmland is certified organic [7]. These necessitate a significant enhancement in AGTIA. Substantial financial investment and higher investment risks are major barriers impeding AGTIA [8,9], and the lower adoption rate further reduces the incentive of agricultural green technology innovation. For example, the adoption rate of green control techniques is only about 31.02% in China [10,11], and the adoption of sustainability-related technologies in Brazil is only 10% [12].

Many studies have shown that policy support is one of the main factors influencing AGTIA [13–17]. As a result, many countries and regions have issued subsidy policies on AGTIA, including green innovation subsidies to encourage the emergence of agricultural green technology and green adoption subsidies to advance agricultural green practice.

For example, Canada has invested nearly CAD 20 million in support of the organic sector focusing on facilitating adoption of innovative organic technology since October 2015 [18]. The United States has launched the Environmental Quality Incentive Program, which incentivized farmers to adopt cleaner, greener agricultural practices through financial subsidies and technological assistance. China's No. 1 Central Document for 2024 stated that investment in AGTIA should be increased, and green and ecological agriculture projects can receive an annual subsidy of about CNY 15 million.

Leading agricultural enterprises (LAEs) and cooperatives are important forces in promoting agricultural green development, involving nearly half of China's farmers by 2022 [6,19]. While LAEs and cooperatives play a crucial role in AGTIA, they are also the focus of government subsidies. Considering the high risk of AGTIA, more and more LAEs have established ITISAs with cooperatives to integrate resources, reduce innovation costs, and increase the adoption of agricultural green technology. ITISAs help establish long-term, stable, and efficient collaborative innovation relationships and serve as a collaborative innovation platform, enhancing innovation capabilities and sharing risks [20–22]. For example, Bayer, a globally renowned agricultural company developing green technology to drive sustainable development, has introduced a new seed technology called CoverCress, a cover crop that enables growers to safeguard their fields in a sustainable manner, enhance soil health, boost incomes, and facilitate the widespread adoption of regenerative agriculture. Bayer has initiated a farm adoption program to incentivize growers to use this seed. In the program, the company provides farmers with planting techniques and free CoverCress seeds (with an implied value of up to $2500 per acre per year), collaborates with the farmers to commence grain production together and is responsible for selling the harvested CoverCress. According to Bayer's financial reports, the company received innovation subsidies totaling 27 million euros in 2023. Master Kong, a leader in China's food industry, has partnered with cooperatives and farmers in diverse regions to build environmentally friendly vegetable bases, where green planting technology and professional guidance are provided, aiming to cultivate a fresh paradigm of ecological agriculture and enhance both planting efficiency and farmers' incomes.

In the context of advancing agricultural green technology, LAEs, cooperatives, and the government are all considered non-rational entities, because each participant has unique goals, constraints, and strategies and cannot accurately obtain the decision-making information of other participants to choose the optimal strategy at once [23]. The strategic choices of LAEs, cooperatives and the government are dynamic, interactive and continuously evolving processes. The multiplicity of actors and objectives often complicates decision-making processes, leading to increased complexity and uncertainty that traditional game models struggle to fully capture. Evolutionary game theory offers a unique perspective by acknowledging that decision-making strategies evolve over time through learning and adaptation [24,25]. By building game models involving multiple participants, evolutionary game methods accurately depict the evolution of decision-making processes among diverse entities, capturing how interactions and adaptability shape individual strategies in the long run [26]. This approach allows for more nuanced analysis and prediction of decision-making processes, offering valuable insights into AGTIA. At present, an increasing number of studies have analyzed the evolutionary path of agricultural green technology innovation from the perspective of innovation alliances [27,28] or examined the impact of government subsidies on promoting agricultural green innovation or the adoption of green technology through evolutionary game analysis [29–31]. However, no literature currently investigates AGTIA from the perspective of ITISAs. Since the government, LAEs, and cooperatives are three interacting entities driving AGTIA in the modern agricultural industry, it is highly necessary to study AGTIA from the perspective of ITISAs, considering government's subsidies. Therefore, this paper establishes a tripartite evolutionary game model involving the government and the ITISAs, consisting of LAEs and cooperatives, considering government subsidies, agricultural green technology spillover effect, and the price premium of green agricultural products. Specifically, our work aims to answer the following questions:

(1) What is the evolution stabilization strategy (ESS) in a replicative dynamic system comprising LAEs, cooperatives, and the government? What are factors affecting the ESS? How do these factors influence the ESS?
(2) How do the initial willingness, dividends, liquidated damages, costs, and incomes of the LAEs and cooperatives influence each other's strategies within ITISAs?
(3) How can the government optimize subsidy strategies to incentivize LAEs and cooperatives to implement AGTIA with limited financial resources?

This study first introduces a tripartite evolutionary game model to explore these issues and simulate the interactions among LAEs, cooperatives, and the government in AGTIA. On the basis of replicator dynamic equations and the stability analysis of equilibrium points, the study further examines ESS and primary influencing factors at distinct stages of agricultural green development and conducts simulation experiments accordingly. In addition, using breeding technology R&D and adoption as a case study, the study investigates the influence of each factor on the equilibrium decisions of all participants through simulation, validating the effectiveness of the game theory model and suggesting the feasibility of future policy-making. Finally, we extend our model by considering the combination of static and dynamic subsidy mechanisms to further optimize government subsidies at distinct stages of agricultural green development.

The main contributions of this paper are as follows: Firstly, in view of the high investment and risk of AGTIA, we incorporate the ITISAs composed of LAEs and cooperatives into our model, highlighting the leading role of LAEs, while previous studies only focused on innovation alliances between corporations and universities or institutes [27,28]. Secondly, considering the policy environment for AGTIA, a tripartite evolutionary game model among LAEs, cooperatives, and the government is constructed to depict the changing process of strategic choices and the escalation conditions at distinct stages of agricultural green development. Previous research has only focused on unilaterally promoting agricultural green technology innovation or adoption [5,32]. Finally, we conduct an in-depth analysis on the impact of factors such as the technology spillover effect, price premium of green agricultural products, dividends and liquidated damages in ITISAs, as well as the combination of static and dynamic subsidy mechanisms on the strategy selection evolution process of the three parties, which can effectively improve the scientific and realistic decision-making of the bounded rationality agents—LAEs, cooperatives, and the government—and put forward more appropriate managerial implication for promoting agricultural green development. Previous studies have primarily focused on the distribution of interests among stakeholders and rarely considered the benefit linkage mechanisms between ITISAs members and agricultural green technology's technology spillover effect [33].

Our research has some interesting findings. Firstly, under the subsidized budget constraint, the government can implement different combinations of static and dynamic subsidy mechanisms to more effectively promote AGTIA at distinct stages of agricultural green development. Secondly, as an external factor, government subsidies for AGTIA have been shown to be the most effective means of incentivizing AGTIA at the initial stage of agricultural green development, while ITISAs play a major role at the maturity stage. Thirdly, optimal ranges of both green innovation and green adoption subsidies exist in the initial stage, as the innovation willingness of LAEs and the adoption willingness of cooperatives will fluctuate with the willingness of the government to subsidize when they exceed a certain range. As for internal incentives, LAEs and cooperatives should cooperate in ITISAs and strive to minimize the costs of AGTIA. The difference in liquidated damages and dividends of ITISAs should be within a reasonable range. A significant difference may hinder collaboration rather than promote it.

The outline of this paper is as follows. Related literature is reviewed in Section 2. Section 3 first describes the research problem, then introduces the fundamental assumptions, and constructs a tripartite evolutionary game model. Then, in Section 4, we summarize several possible ESS points and discuss the stability conditions of each ESS under static subsidy mechanisms. In Section 5, we use the case of breeding technology to carry out simulation analysis to describe the influence of related factors. In Section 6, we compare the subsidy performance of static and dynamic subsidy mechanisms at distinct stages of agricultural green development. Finally, Section 7 draws conclusions and provides managerial implications.

2. Literature Review

This section reviews previous research from three different lines: (1) related key factors affecting AGTIA, (2) government support policies for AGTIA, and (3) applications of evolutionary game theory in agriculture.

2.1. Related Key Factors Affecting AGTIA

The active promotion of AGTIA is an inevitable trend for the sustainable development of modern agriculture, making it a hot topic in academic research in recent years. Many scholars have analyzed the factors influencing AGTIA.

Collaboration among agricultural business entities can allow for the integration of resources and improve innovation efficiency, thereby fostering sustainable agricultural development [28,34]. Scholars have paid extensive attention to collaborative innovative models' significant role in stimulating AGTIA [28,35]. It has been demonstrated that a lack of linkages between institutions hampers the adoption of agricultural green technology, resulting in a loss of efficiency [36]. Research by Ma et al. [37] and Yang et al. [38] indicated that farmers' participation in cooperatives can facilitate green technology adoption in agriculture. In promoting the innovation of agricultural green technology, scholars have studied the collaborative model of innovation alliances aimed at facilitating knowledge sharing and accelerating technology transfer among enterprises, research institutions, and the government. Morandi [34] believed that the collaboration between industry and universities brings competitive advantages to enterprises, provides opportunities for field experiments, and facilitates the transfer of knowledge and technology among partners. Li et al. [35] believed that cooperative innovation between the government, industry and research institutes was becoming crucial in the agricultural sector. Their study highlighted the prominent role of enterprises in driving agricultural cooperative innovation, while indicating that the impact of government intervention is less significant. Luo et al. [27] studied the role of an innovation consortium formed by agricultural enterprises and universities, suggesting that innovation consortiums facilitate the accelerated transformation of innovation outcomes and enhance innovation efficiency. Chen et al. [28] explored collaborative innovation of improved variety in R&D and proposed improvements to the benefit allocation and cost-sharing mechanisms for collaborative innovation efforts. LAEs and cooperatives are the two main business entities promoting AGTIA [39–41]. However, currently, there is a lack of scholarly attention being paid to cooperation mechanisms between LAEs and cooperatives with a focus on AGTIA.

The technology spillover effect is also one of the important factors affecting AGTIA. Much research has shown that the technology spillover effect can increase the adoption rate of agricultural green technology and drive the green transformation of agriculture [42,43]. Costantini et al. [44] found that upstream industries' eco-innovative activities indirectly enhance downstream industries' environmental performance through a spillover effect on the supply chain. Luo et al. [45] empirically indicated that knowledge spillovers and technology acquisition modes are two factors influencing technology innovation in cooperatives. Zhou et al. [46] reckoned that knowledge spillovers positively impact innovation cooperation. The technology spillover effect from upstream to downstream in the supply chain can reduce costs for downstream members [47]. Numerous examples have shown that the technology spillover effect of LAEs can significantly reduce adoption costs for cooperatives [45,48]. Therefore, the technology spillover effect should be taken into account in promoting AGTIA.

In recent years, with the increasing environmental awareness and health concerns among consumers, there is a clear preference for green agricultural products. Many studies have shown that consumers are willing to buy and pay a premium for green agricultural products, and producers of green agricultural products will earn higher price premiums [13,49,50]. It has been found that the price premium of green agricultural products is one of the factors influencing AGTIA. For example, Yu et al. [51] highlighted that consumers who are willing to pay extra for "environmentally friendly rice" can impact farmers' motivation to embrace eco-conscious technology. Zhou et al. [52] underscored that farmers who benefit from ecological rice are more inclined to adopt sustainable agricultural practices. Valizadeh et al. [53] believed that circular premium is one of the most important factors to encourage producers or farmers to adopt agricultural green technology.

The above research has laid a solid theoretical foundation for our study. On this basis, we will comprehensively consider the influencing factors of AGTIA in our model, including ITISAs, the technology spillover effect, as well as the price premium of green agricultural products, and examine the effect of each on the innovation behavior of LAEs, the adoption behavior of cooperatives, and the subsidy strategies of the government.

2.2. Government Support Policies for AGTIA

To promote the sustainable development of agriculture, the government has issued a series of subsidy policies to promote AGTIA, so many scholars have paid attention to and gradually researched the impact of government subsidy policies on AGTIA.

Some scholars have analyzed the effect of subsidies on farmers' adoption of agricultural green technology, including green adoption subsidies such as the integrated application of water and fertilizer subsidy [16], quality seed subsidy [54], and organic fertilizer subsidy [13]. Omotilewa et al. [55] discovered that subsidies boost farmers' interest in new technologies, leading to a higher adoption rate of agricultural green technology. Akkaya et al. [14] developed a game model incentivizing farmers' adoption willingness through subsidies, and confirmed the effectiveness of the subsidy approach. Tian et al. [29] found that increasing ecological compensation can incentivize farmers to reduce the use of fertilizers. Ray et al. [56] constructed a dynamic game model between the government and farmers to analyze the impact of cost subsidies and indirect support on guiding farmers to adopt sustainable farming methods. They found that both policies had a positive impact. Shi et al. [16] found that green technology investment subsidies are more effective than green technology operation subsidies in promoting farmers' adoption of agricultural green technology, regardless of whether farmers choose to outsource green technology.

However, some scholars believe that providing subsidies to farmers has limited effectiveness, while providing subsidies to enterprises can effectively promote the green development of agriculture. Wu and Hu [57] suggested that government subsidies are crucial for encouraging enterprises to develop green/clean technology and promoting regional sustainability, particularly in addressing insufficient R&D investment and high R&D costs. Zhang et al. [58] revealed that neither subsidies aimed at increasing output quantity nor promoting environmental innovation alone can resolve the conflict between agricultural development and environmental protection in agricultural supply chains that include low-cost and high-cost competitive enterprises. Only through combining the two subsidies can innovation be stimulated to reduce pollution emissions. Laborde et al. [15] revealed that subsidies to agricultural production have minimal impact on reducing agricultural carbon emissions, whereas subsidies for developing green production technology that enhances productivity or reduces carbon emissions can effectively achieve this goal. Guo et al. [32] considered the heterogeneity of farmers and established a Stackelberg game model between the government, agricultural enterprises and farmers, and discussed the optimal subsidy policy of the government to promote the development of green and efficient raw materials (GRM). They showed that when the effectiveness of GRM is not high enough, the government should subsidize both farmers and GRM enterprises. Otherwise, subsidizing farmers is more effective than subsidizing GRM companies.

After reviewing the above literature, we found that most existing studies only considered subsidy mechanisms for single entity: farmers or LAEs. However, only by promoting AGTIA simultaneously can we ensure that innovative achievements are effectively translated into tangible benefits, thus truly driving agricultural green development. Therefore, our research will consider both green innovation subsidies and green adoption subsidies for LAEs and cooperatives, respectively, and use the evolutionary game theory method to optimize government subsidy strategies. The results will provide feasible suggestions for the government to supervise the AGTIA behavior of LAEs and cooperatives.

2.3. Applications of Evolutionary Game Theory in Agriculture

Evolutionary game theory serves as a valuable analytical tool where bounded rational micro-economic entities, driven by their own interests, interact to shape the evolution of systems [59,60]. The widespread application of game theory models extends to fields including green supply chains, fisheries, carbon emission reduction, and cold chain logistics [61–63]. The practicality of evolutionary game theory has led to its increased utilization in agricultural management, particularly in promoting AGTIA. Researchers predominantly employ evolutionary game theory to examine how factors such as the costs and benefits of innovation and adoption, collaborative effects, environmental benefits, and government policy influence the strategic choices of key participants (e.g., enterprises, farmers, and the government) in the collaborative innovation and adoption of agricultural green technology involving multiple stakeholders.

Luo et al. [27] established an evolutionary game model to promote agricultural green technology innovation between agricultural enterprises, universities, and the government. They found that the benefits of collaborative innovation, default costs, and increases in additional social benefits can effectively promote agricultural low-carbon technology innovation. However, although increasing innovation subsidies has a certain impact on evolutionary results, the impact is limited. He et al. [64] constructed a tripartite evolutionary game model involving the government, businesses, and consumers to examine the impact of consumer preferences and government regulations on reducing the use of pesticides and chemical fertilizers. Chen et al. [28] developed evolutionary game models for collaborative innovation in salt-tolerant rice breeding between research institutions and seed companies, considering both scenarios with and without government participation. The study examined how profit-sharing coefficients, cost-sharing coefficients, and the strength of government penalty incentives affect the evolutionary outcomes of the system. Cao et al. [33] developed a tripartite evolutionary game model that includes the government, water-saving service companies, and farmers. They analyzed the decision-making process of water-saving service companies in investing in innovative water-saving technology and farmers' adoption of these technologies. Shen et al. [65] applied prospect theory and evolutionary game theory to develop a model that explores decision-making strategies of participants in the Taihu Basin and the influencing factors of basin ecological compensation. Their findings indicate that initial probability, costs of ecological compensation, and shifts in environmental tax rates impact the strategic decisions of both local governments and polluting enterprises.

In promoting agricultural green technology adoption, Tian et al. [66] investigated the influence mechanisms of environmental values, information awareness, and social network factors on farmers' adoption of green fertilization technology, constructing an evolutionary game model involving farmers A and B. Yu et al. [67] combined the Stackelberg game with the evolutionary game model to study the long-term impact of information sharing on producers' organic farming. Tian et al. [29] established an evolutionary game model involving the government, farmers, and consumers and highlighted the inadequacy of current ecological compensation for farmers and subsidies for consumers' green consumption to incentivize farmers to use green fertilizers and reduce pesticide use. He et al. [30] applied the dynamic penalty model and subsidy model to evolutionary game models to study how farmers choose to deal with straw—whether to burn straw or collect bioenergy for electricity generation to reduce carbon dioxide emissions and environmental degradation during agricultural production processes. Gong et al. [68] and Wang et al. [69] applied the evolutionary game theory to investigate farmers' green pesticide usage.

A comparison of our research with representative papers is shown in Table 1. In summary, the collaborative innovation alliances of LAEs and cooperatives as the ITISAs guided by government subsidies have not been fully taken into account in previous research. Therefore, this paper considers the ITISAs, comprising LAEs and cooperatives, for AGTIA and incorporates factors such as the green technology spillover effect, price premium of green agricultural products, etc., into the model to establish a tripartite evolutionary game model involving LAEs, cooperatives, and the government to make in-depth analyses of the impact of AGTIA costs and incomes, government subsidies, dividends, and liquidated damages within ITISAs on the evolutionary strategies of the three parties.

Table 1. Comparison between this study and existing related studies.

Authors	Parties	Policy Factors		Collaboration Mechanism		Price Premium	Technology Spillover Effect	Dynamic Subsidy Mechanism
		Technology Innovation Subsidies	Technology Adoption Subsidies	Dividends	Liquidated Damages			
Shen et al. [65]	The local governments and polluting enterprises	√						
Yu et al. [67]	One retailer and one producer					√		
He et al. [30]	The government, power plants, and farmers		√					√
Tian et al. [29]	The government, farmers, and consumers		√			√		
Tian et al. [66]	Farmers A and B					√		
Gong et al. [68]	The government, pesticide operators, and farmers		√			√		
Wang et al. [69]	Farmers, service organizations, and the government		√			√		
He et al. [64]	The government, businesses, and consumers		√			√		
Luo et al. [27]	Enterprises, universities, and the government	√			√	√		
Chen et al. [28]	Research institutions, companies, and the government	√						
Cao et al. [33]	The government, companies, and farmers	√	√	√				
This paper	LAEs, cooperatives and the government	√	√	√	√	√	√	√

3. The Model

3.1. Problem Description

LAEs and cooperatives are currently the two main business entities that implement AGTIA. However, despite being aware of consumer preferences for green agricultural products and the government's sustainability concerns, LAEs and cooperatives are disinclined to advance AGTIA. On the one hand, factors such as the difficulty of technology transfer, the long R&D cycle, and the lack of policy support discourage enterprises from spending astronomical sums on such innovation [70]. On the other hand, cooperatives hesitate to adopt agricultural green technology due to risk and limitations in green technological resources. Establishing ITISAs between LAEs and cooperatives helps to encourage the share of resources, technology, and market information and improve the efficiency of AGTIA. Government subsidies can stimulate LAEs and cooperatives to engage in AGTIA, thereby accelerating the process and enhancing the feasibility of long-term collaboration more actively. Therefore, to accelerate AGTIA, the LAEs, cooperatives, and the government must cooperate triadically. Thus, our research considers a tripartite evolutionary game model consisting of the LAEs, cooperatives, and the government. Examples of ITISAs between LAEs and cooperatives include Bayer's Farm Adoption Program and Master Kong's environmentally friendly vegetable base. The behavioral mechanism among the three participants in the AGTIA model is depicted in Figure 1.

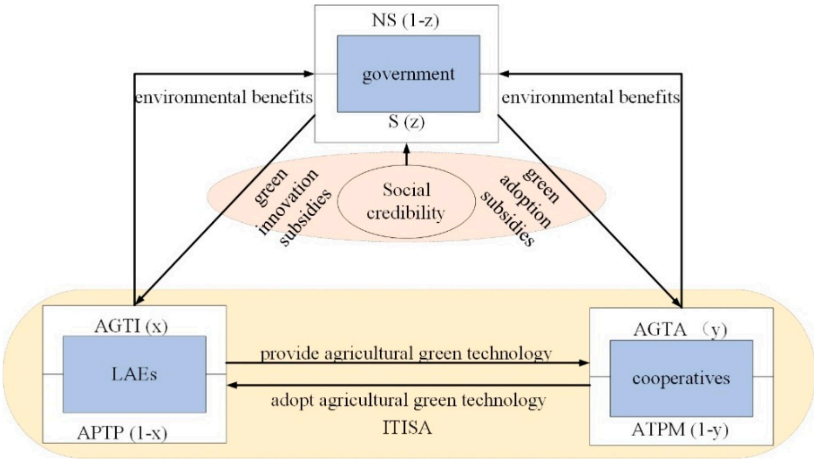


Figure 1. The behavioral mechanism among the three participants in the AGTIA model.

LAEs: In the ITISAs, the LAEs take the lead in innovating and providing agricultural green technology and are also primarily responsible for selling agricultural products produced by the cooperatives. Considering the technology spillover effect, agricultural green technology innovated by LAEs, including precision fertilizer application techniques, integrated pest and weed control techniques, and standardized technology for agricultural machinery, can reduce the costs of green planting for cooperatives [44,47] and improve the quality and sales of agricultural products, thereby increasing the economic benefits derived from the sale of green agricultural products and environmental benefits. However, increased green innovation costs, as well as uncertainty about cooperatives' green adoption willingness and market demand for green agricultural products, discourage LAEs from taking the initiative in green technology innovation and increase the likelihood that they will engage in free-ride behavior [28].

Cooperatives: Cooperatives are responsible for adopting agricultural green technology to improve the quality and safety of agricultural products, bringing economic and environmental benefits. However, the adoption of agricultural green technology will also reduce productivity and thus increase the cooperatives' costs [14]. The free-rider behavior of LAEs and the uncertainty of market demand for green agricultural products will also increase the risk of adoption and reduce the cooperatives' willingness to adopt green technology.

Government: AGTIA requires significant capital and resource investment, posing a challenge for LAEs and cooperatives. In this context, government subsidy policies play a crucial role in facilitating technology R&D as well as its practical adoption. Government subsidies can reduce the costs of AGTIA, thus promoting agricultural green development and bringing environmental benefits and social credibility [29,69]. However, excessive subsidies will increase the government's financial burden.

3.2. Related Assumptions

The following assumptions are proposed regarding the behaviors and benefits of the participants in the evolutionary game model:

Assumption 1. *All three participants make strategic choices under the premise of finite rationality. The LAEs (Participant 1) can decide to innovate agricultural green technology or adhere to past traditional practices, and the probability of LAEs carrying out agricultural green technology innovation ($AGTI$) is x, whereas the probability of the LAEs adhering to agricultural past traditional practices ($APTP$) is $1-x$. The cooperatives (Participant 2) decide to adopt agricultural green technology or adopt agricultural traditional methods, and the probability of the cooperatives carrying out agricultural green technology adoption ($AGTA$) is y, whereas the probability of the cooperatives choosing agricultural traditional planting methods ($ATPM$) is $1-y$. The government (Participant 3) decides whether to provide subsidies to the LAEs and cooperatives or not, and z indicates the probability that the government will provide subsidies (S) whereas $1-z$ reflects the probability the* *government will provide no subsidies (NS). Consumers prefer green agricultural products and are willing to pay more for them [29,71].*

Assumption 2. *Within the ITISAs, there are four collaboration models between LAEs and cooperatives. In scenario I, the LAEs and the cooperatives follow conventional production practices, which means that the LAEs select the "APTP" strategy and the cooperatives select the "ATPM" strategy. Thus, in scenario I, the costs for the LAEs and cooperatives are C_{et} and C_{ct} respectively, and the their incomes are R_e^{tt} and R_c^{tt}, respectively.*

Assumption 3. *In scenario II, LAEs and cooperatives commit to developing AGTIA within the ITISAs, which means that LAEs choose the "AGTI" strategy and cooperatives choose the "AGTA" strategy. Through collaboration, LAEs can gain a deeper understanding of local realities, develop and apply green technology more effectively, and reduce the costs of experimentation and practice compared with independently innovating technology [34]. We set the LAEs' green innovation costs in this scenario as $(1-a)C_{eg}$ $(0 < a < 1)$, where C_{eg} is the green technology innovation costs of LAEs when they do not collaborate with the cooperatives in ITISAs and a is cost reduction coefficient of enterprises due to collaboration. Similarly, the cooperatives can benefit from the green technology spillover effect through the collaboration, which helps to reduce green adoption costs. We set the cooperatives' green adoption costs in this scenario as $(1-b)C_{cg}$ $(0 < b < 1)$, where C_{cg} is the cooperatives' green adoption costs when they do not collaborate with the enterprises in ITISAs, and b is cost reduction coefficient of cooperatives due to collaboration. At the same time, since green products can command a higher price premium, we assume the collaboration in ITISAs has resulted in the incomes of LAEs and cooperatives being R_e^{gg} and R_c^{gg}, respectively, and the LAEs will give dividends D_1 $(D_2 < R_e^{gg} - R_e^{tt})$ to the cooperatives.*

Assumption 4. *Considering the "free rider" speculation, both the LAEs and cooperatives sign contracts and prepay deposits before engaging in ITISAs [27]. If the LAEs break the contract, they should pay liquidated damages L_2 to the cooperatives. The cooperatives need to acquire and adopt agricultural green technology from other sources. Thus, the cooperatives' green adoption costs are C_{cg}. Since the greenness of agricultural products can still be improved due to the agricultural green technology used by cooperatives, the incomes of the LAEs and cooperatives from the sale of green agricultural products will still increase, which are recorded as R_e^{tg} and $R_c^{tg}\left(R_c^{gg} > R_c^{tg} > R_c^{tt}\right)$, respectively, and the LAEs should give dividends D_2 $(D_2 < D_1)$ to the cooperatives. This is scenario III. Scenario IV is that the cooperatives break the contract, and they should pay liquidated damages L_1 to the LAEs. The LAEs' green innovation costs are C_{eg}, and their incomes are R_e^{gt} $(R_e^{gg} > R_e^{gt} > R_e^{tt})$. Since the visibility of cooperatives can be improved due to the LAEs' brand spillover effect, the incomes of cooperatives will also increase, which are recorded as R_c^{gt} $(R_c^{gg} > R_c^{gt} > R_c^{tt})$.*

Assumption 5. *When the government chooses subsidy strategy (S), the LAEs that innovate agricultural green technology will receive a fixed subsidy of S_e, the cooperatives that adopt agricultural green technology will receive a fixed subsidy of S_c, and the social credibility M will be obtained by the government due to the government's active guidance [30]. Since the government's guidance will consume financial resources, material resources, and manpower, a cost of C_{gs} will be incurred. In order to urge the government to fulfill its responsibilities, we assume $M > C_{gs}$ [29]. In addition, environmental benefits are a key factor influencing the government's subsidy strategies. When LAEs carry out agricultural green innovation and cooperatives adopt agricultural green technology, the government will gain environmental benefits E_{g1} and E_{g2}, respectively.*

The specifications for each parameter are shown in Table 2.

Based on the above assumptions, the tripartite payoff matrixes of the LAEs, cooperatives, and the government are depicted in Tables 3 and 4.

Table 2. The definitions of parameters.

Participants	Parameters	Meaning
Government	C_{gs}	The cost of government after S
	S_c	Green adoption subsidies
	S_e	Green innovation subsidies
	M	Social credibility when government chooses S strategy
	E_{g1}	Environmental benefits due to green innovation
	E_{g2}	Environmental benefits due to the adoption of green technology
LAEs	C_{eg}	The LAEs' green innovation costs
	C_{et}	The LAEs' costs for APTP
	R_e^{gg}	The LAEs' green innovation incomes when cooperatives collaborate
	R_e^{gt}	The LAEs' green innovation incomes when the cooperatives default
	R_e^{tg}	Speculative incomes of LAEs
	R_e^{tt}	The LAEs' incomes for APTP
	D_1	Dividend in scenario II
	D_2	Dividend in scenario III
	L_2	LAEs' liquidated damages
	a	Cost reduction coefficient of LAEs due to collaboration
Cooperatives	C_{cg}	The cooperatives' green adoption costs
	C_{ct}	The cooperatives' costs for ATPM
	R_c^{gg}	The cooperatives' green adoption incomes when LAEs collaborate
	R_c^{tg}	The cooperatives' green adoption incomes when LAEs default
	R_c^{gt}	Speculative incomes of cooperatives
	R_c^{tt}	The cooperatives' incomes for ATPM
	L_1	Cooperatives' liquidated damages
	b	Cost reduction coefficient of cooperatives due to collaboration

Table 3. Tripartite payoff matrix when the government provides subsidies (S).

		LAEs	
		AGTI(x)	**APTP($1-x$)**
Cooperatives	AGTA (y)	$R_e^{gg}-(1-a)C_{eg}-D_1+S_e$ $R_c^{gg}-(1-b)C_{cg}+D_1+S_c$ $M+E_{g1}+E_{g2}-S_e-S_c-C_{gs}$	$R_e^{tg}-C_{et}-D_2-L_2$ $R_c^{tg}-C_{cg}+D_2+L_2+S_c$ $M+E_{g2}-S_c-C_{gs}$
	ATPM ($1-y$)	$R_e^{gt}-C_{eg}+L_1+S_e$ $R_e^{gt}-C_{ct}-L_1$ $M+E_{g1}-S_e-C_{gs}$	$R_e^{tt}-C_{et}$ $R_c^{tt}-C_{ct}$ $M-C_{gs}$

Table 4. Tripartite payoff matrix when the government does not provide subsidies (NS).

		LAEs	
		AGTI(x)	**APTP($1-x$)**
Cooperatives	AGTA (y)	$R_e^{gg}-(1-a)C_{eg}-D_1$ $R_c^{gg}-(1-b)C_{cg}+D_1$ $E_{g1}+E_{g2}$	$R_e^{tg}-C_{et}-D_2-L_2$ $R_c^{tg}-C_{cg}+D_2+L_2$ E_{g2}
	ATPM ($1-y$)	$R_e^{gt}-C_{eg}+L_1$ $R_c^{gt}-C_{ct}-L_1$ E_{g1}	$R_e^{tt}-C_{et}$ $R_c^{tt}-C_{ct}$ 0

4. Analysis

4.1. Expected Payoff and Replicator Dynamic Equation of Each Participant

According to the payoff matrixes in Tables 2 and 3, we calculate each participant's expected return, average return, and replicator dynamic equation, and further analyze the stable points.

The LAEs' expected returns for choosing "AGTI" and "APTP" strategies are denoted as E_{11} and E_{12}, respectively. Let E_1 represent the average return of the LAEs. Then, E_{11}, E_{12} and E_1 can be calculated as follows:

$$\begin{aligned}
E_{11} &= yz\left(R_e^{gg} - (1-a)C_{eg} - D_1 + S_e\right) + (1-y)z\left(R_e^{gt} - C_{eg} + L_1 + S_e\right) + y(1-z)\left(R_e^{gg} - (1-a)C_{eg} - D_1\right) \\
&\quad +(1-y)(1-z)(R_e^{gt} - C_{eg} + L_1) = zS_e + yR_e^{gg} + ayC_{eg} - yD_1 - yR_e^{gt} - yL_1 + R_e^{gt} - C_{eg} + L_1 \\
E_{12} &= \mathrm{y}\mathrm{z}\left(R_e^{tg} - C_{et} - D_2 - L_2\right) + \mathrm{y}(1-\mathrm{z})\left(R_e^{tg} - C_{et} - D_2 - L_2\right) + (1-\mathrm{y})\mathrm{z}\left(R_e^{tt} - C_{et}\right) + (1-\mathrm{y})(1-\mathrm{z})\left(R_e^{tt} - C_{et}\right) \\
&= yR_e^{tg} - yD_2 - yL_2 + R_e^{tt} - C_{et} - yR_e^{tt} \\
E_1 &= xE_{11} + (1-x)E_{12}
\end{aligned}$$

The replicator dynamic system in evolutionary game theory is employed to investigate the strategies selected by the majority of a population at given time points [72]. When a certain strategy's expected return surpasses the entire population's average expected return, the proportion of individuals adopting this strategy increases. Differential equations are used to portray the rate at which this proportion escalates over continuous time. The dynamic replication equation for the LAEs can be expressed as:

$$F(x) = x(1-x)\left(C_{et} - C_{eg} + L_1 + R_e^{gt} - R_e^{tt} + y\left(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\right) + zS_e\right) \quad (1)$$

Regarding the cooperatives, the expected returns for choosing "AGTA" and "ATPM" strategies are designated by E_{21} and E_{22}, respectively. Also, let E_2 represent the average return of the cooperatives that adopt the former two strategies. E_{21}, E_{22}, and E_2 can be calculated as follows:

$$\begin{aligned}
E_{21} &= xz\left(R_c^{gg} - (1-b)C_{cg} + D_1 + S_c\right) + (1-x)z\left(R_c^{tg} - C_{cg} + D_2 + L_2 + S_c\right) + x(1-z)\left(R_c^{gg} - (1-b)C_{ccg} + D_1\right) \\
&\quad +(1-x)(1-z)\left(R_c^{tg} - C_{cg} + D_2 + L_2\right) \\
&= zS_c + xR_c^{gg} + xbC_{cg} + xD_1 + R_c^{tg} - C_{ccg} + D_2 + L_2 - xR_c^{tg} - xD_2 - xL_2 \\
E_{22} &= xz\left(R_c^{gt} - C_{ct} - L_1\right) + (1-x)z\left(R_c^{tt} - C_{ct}\right) + x(1-z)\left(R_c^{gt} - C_{ct} - L_1\right) + (1-x)(1-z)\left(R_c^{tt} - C_{ct}\right) \\
&= R_c^{tt} - C_{ct} - xL_1 + xR_c^{gt} - xR_c^{tt} \\
E_2 &= yE_{21} + (1-y)E_{22}
\end{aligned}$$

Then, the replicated dynamic equation of the cooperatives is:

$$F(y) = y(1-y)\left(C_{ct} - C_{cg} + D_2 + L_2 + R_c^{tg} - R_c^{tt} + x\left(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\right) + zS_c\right) \quad (2)$$

Similarly, let E_{31} and E_{32} refer to expected returns of the government, whose strategies may include "S" and "NS", and E_3 be the average return of the government that adopts the former two strategies. E_{31}, E_{32}, and E_3 can be calculated as follows:

$$\begin{aligned}
E_{31} &= xy\left(M + E_{g1} + E_{g2} - S_e - S_c - C_{gs}\right) + (1-x)y\left(M + E_{g2} - S_c - C_{gs}\right) + x(1-y)\left(M + E_{g1} - S_e - C_{gs}\right) \\
&\quad +(1-x)(1-y)\left(M - C_{gs}\right) = yE_{g2} - yS_c + xE_{g1} - xS_e + M - C_{gs} \\
E_{32} &= xy\left(E_{g1} + E_{g2}\right) + (1-x)yE_{g2} + x(1-y)E_{g1} = yE_{g2} + xE_{g1} \\
E_3 &= zE_{31} + (1-z)E_{32}
\end{aligned}$$

Accordingly, the replicated dynamic equation of the government is:

$$F(z) = z(1-z)\left(M - C_{gs} - xS_e - yS_c\right) \quad (3)$$

4.2. Analysis on the Impact of Participants' Initial Willingness

In order to study the impact of changes in LAEs' initial green innovation willingness on the green adoption probability of cooperatives, we calculate the partial derivative of F(y) with respect to x.

$$\frac{\partial F(y)}{\partial x} = y(1-y)\left(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\right)$$

It can be inferred from the assumption that $D_1 - D_2 > 0$, $R_c^{gg} - R_c^{tg} + bC_{cg} = (R_c^{gg} - (1 - bC_{cg})) - \left(R_c^{tg} - C_{cg}\right) > 0$, $R_c^{tt} - R_c^{gt} = \left(R_c^{tt} - C_{ct}\right) - \left(R_c^{gt} - C_{ct}\right) < 0, 0 < \text{y} < 1$. Hence, $F(y)$ is increasing in x when $(D_1 - D_2) + \left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) > (L_2 - L_1) + \left(R_c^{gt} - R_c^{tt}\right)$. This means that the green adoption probability of cooperatives will increase with the increases in LAEs' initial green innovation willingness when the difference between retained profits of cooperatives in scenarios II and III is more than that between scenarios IV and I. Conversely, $F(y)$ is decreasing in x when $(D_1 - D_2) + \left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) < (L_2 - L_1) + \left(R_c^{gt} - R_c^{tt}\right)$, which means that the green adoption probability of cooperatives will decrease with an increase in LAEs' initial green innovation willingness when the difference between retained profits of cooperatives in scenarios II and III is less than that between scenarios IV and I.

To investigate the impact of changes in cooperatives' initial green adoption willingness on the green innovation probability of LAEs, we calculate the partial derivative of $F(x)$ with respect to y

$$\frac{\partial F(x)}{\partial \text{y}} = x(1 - x)\left(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\right)$$

It can be inferred that $\frac{\partial F(x)}{\partial \text{y}} > 0$ when $\left(R_e^{gg} - R_e^{gt} + aC_{eg}\right) + (L_2 - L_1) > \left(R_e^{tg} - R_e^{tt}\right) + (D_1 - D_2)$, which means that the green innovation probability of LAEs will increase with an increase in cooperatives' initial green adoption willingness when the difference between LAEs' retained profits in scenarios II and IV is more than that between scenarios III and I. $\frac{\partial F(x)}{\partial \text{y}} < 0$ when $\left(R_e^{gg} - R_e^{gt} + aC_{eg}\right) + (L_2 - L_1) < \left(R_e^{tg} - R_e^{tt}\right) + (D_1 - D_2)$, which signifies that the green innovation probability of LAEs' will decrease with an increase in cooperatives' initial green adoption willingness when the difference between LAEs' retained profits in scenarios II and IV is less than that between scenarios III and I.

Proposition 1. *The mutual influence between cooperatives and LAEs within the ITISAs can be categorized into four cases.*

(1) *Cooperatives' increased green adoption probability can drive LAEs into green innovation, and LAEs' increased green innovation probability can encourage cooperatives to choose the "AGTA" strategy when* $\left(R_e^{tg} - R_e^{tt}\right) - \left(R_e^{gg} - R_e^{gt} + aC_{eg}\right) < (L_2 - L_1) - (D_1 - D_2) < \left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) - \left(R_c^{gt} - R_c^{tt}\right)$.
(2) *Cooperatives' increased green adoption probability can inhibit LAEs moving into green innovation, while LAEs' increased green innovation probability can drive cooperatives to adopt agricultural green technology when* $(L_2 - L_1) - (D_1 - D_2) < \left(R_e^{tg} - R_e^{tt}\right) - \left(R_e^{gg} - R_e^{gt} + aC_{eg}\right)$ *and* $(L_2 - L_1) - (D_1 - D_2) < \left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) - \left(R_c^{gt} - R_c^{tt}\right)$.
(3) *Cooperatives' increased adoption probability can drive LAEs into green innovation, while LAEs' increased green innovation probability can inhibit cooperatives from choosing the "AGTA" strategy when* $\left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) - \left(R_c^{gt} - R_c^{tt}\right) < (L_2 - L_1) - (D_1 - D_2)$ *and* $(L_2 - L_1) - (D_1 - D_2) > \left(R_e^{tg} - R_e^{tt}\right) - \left(R_e^{gg} - R_e^{gt} + aC_{eg}\right)$.
(4) *Cooperatives' increased green adoption probability can inhibit the green innovation of LAEs, and LAEs' increased green innovation probability can inhibit cooperatives from adopting green technology when* $\left(R_c^{gg} - R_c^{tg} + bC_{cg}\right) - \left(R_c^{gt} - R_c^{tt}\right) < (L_2 - L_1) - (D_1 - D_2) < \left(R_e^{tg} - R_e^{tt}\right) - \left(R_e^{gg} - R_e^{gt} + aC_{eg}\right)$.

Proposition 1 shows that the mutual influence between LAEs and cooperatives within ITISAs may not always result in positive outcomes. Increasing the incomes of collaboration innovation and cost reduction factors or decreasing the incomes for free-riders to some extent can drive them into AGTIA within the ITISAs.

4.3. Stability Analysis of Each Participant

The replicator dynamic equation reflects the learning speed and direction of the individual. If the replicator dynamics value is 0 and the learning rate is 0, the game has reached a stable and balanced state [25]. According to the differential equation stability principle, the strategy chosen by the participant is optimal when the replicator dynamic equation is 0, and its first derivative is less than 0.

4.3.1. The Stability Analysis of LAEs

For LAEs, we define $z^{*} = \frac{C_{eg}-C_{et}+R_e^{tt}-R_e^{gt}-L_1+y\left(D_1-D_2+L_1-L_2+R_e^{gt}-R_e^{gg}+R_e^{tg}-R_e^{tt}+aC_{eg}\right)}{S_e}$. When $\mathrm{F(x)} = 0$, LAEs' evolutionary game is in the stable state. Proposition 2 outlines the result.

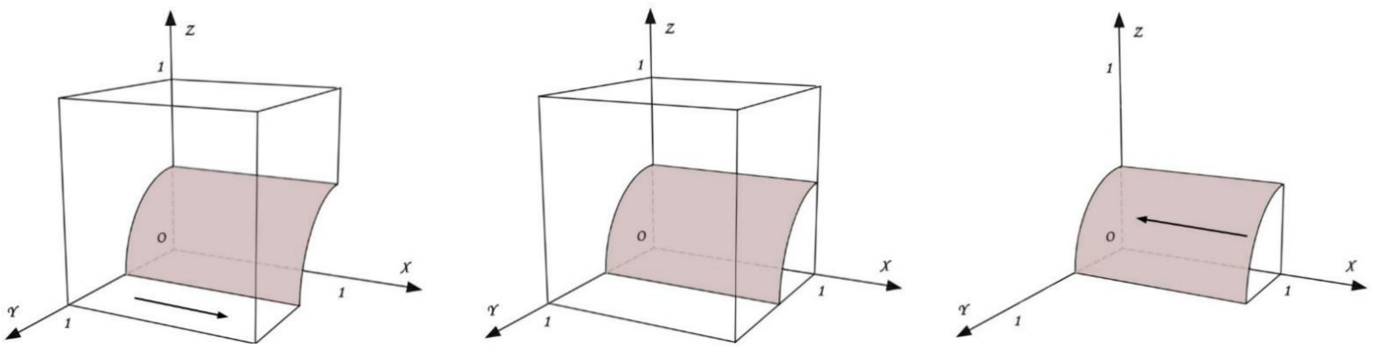
Proposition 2. *The ESS of LAEs is as follows:*

(1) *When* $z* < z < 1$, $\frac{d(f(x))}{dx}|_{x=0} > 0$ *and* $\frac{d(f(x))}{dx}|_{x=1} < 0$. $x = 1$ *is the ESS of the LAEs.*
(2) *When* $z = z*$, $F(x) \equiv 0$, *then* $x \epsilon [0,\ 1]$ *is in steady.*
(3) *When* $0 < z < z*$, $\frac{d(f(x))}{dx}|_{x=1} > 0$ *and* $\frac{d(f(x))}{dx}|_{x=0} < 0$. $x = 0$ *is the ESS of the LAEs.*

Proposition 2 indicates that when the probability of the government selecting the "S" strategy is lower than $z*$, the LAEs' strategy shifts from "AGTI" to "APTP", and finally stabilizes at choosing "APTP" strategy. If the probability is higher than $z*$, LAEs' strategy changes from "APTP" to "AGTI", and finally stabilizes at choosing "AGTI" strategy. If the probability is $z*$, LAEs choosing "APTP" and "AGTI" have the same benefits, and the strategic choice does not change with time. To enhance the preference of LAEs for the "AGTI" strategy, the government should consider elevating green innovation subsidies. Since $z*$ decreases with the increase in $\left(R_e^{tt} - C_{et}\right) - \left(R_e^{gt} - C_{eg}\right)$ and $\left(R_e^{tg} - C_{et}\right) - \left(R_e^{gg} - (1-a)C_{eg}\right)$, LAEs are more inclined to innovate agricultural green technology when it results in higher gross profits.

Green innovation subsidies serve as a guiding force towards agricultural green technology innovation. However, due to the non-permanence of government subsidies, the key factors that encourage LAEs to engage in agricultural green technology innovation proactively are green innovation incomes, collaboration benefits, and cost reduction coefficients from ITISAs. Therefore, LAEs should actively collaborate with cooperatives in ITISAs to make the most of collaborative effects to reduce green innovation costs and enhance collaborative incomes. The government can promote agricultural green development by encouraging and supporting ITISAs to facilitate the realization of collaborative effect.

The replicator dynamic phase diagrams for LAEs are depicted in Figure 2.



(**a**) $z^{*}<z<1$ (**b**) $z = z^{*}$ (**c**) $0 < z < z^{*}$

Figure 2. The replicator dynamic phase diagrams for LAEs.

4.3.2. The Stability Analysis of Cooperatives

For cooperatives, we define $z* = \frac{C_{cg} - C_{ct} - D_2 - L_2 - R_c^{tg} + R_c^{tt} - x\left(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\right)}{S_c}$. When $\mathrm{F}(\mathrm{y}) = 0$, cooperatives' evolutionary game is in the stable state. Proposition 3 shows the outcome.

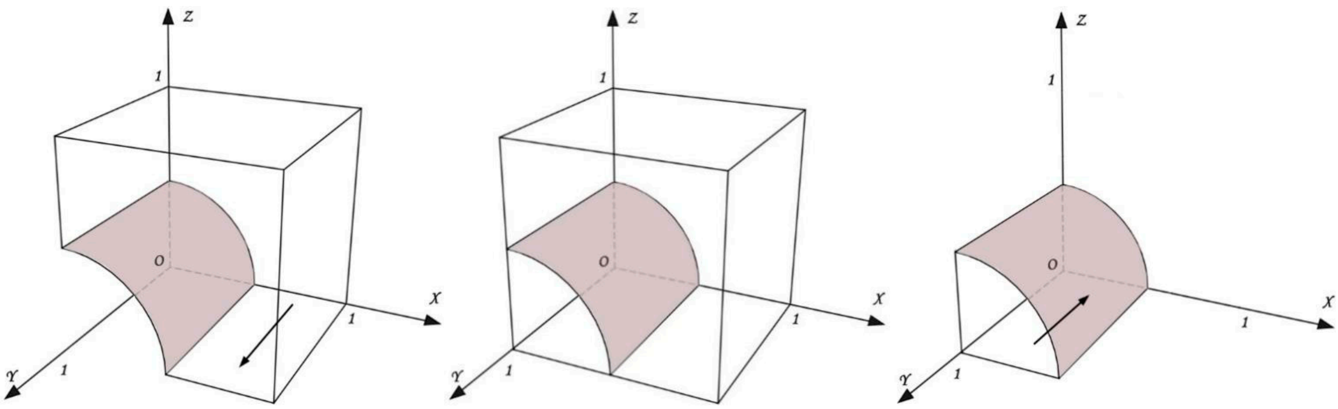
Proposition 3. *The ESS of cooperatives is as follows:*

(1) *When* $z* < z < 1$, $\frac{d(f(y))}{dy}|_{y=0} > 0$ *and* $\frac{d(f(y))}{dy}|_{y=1} < 0$. $y = 1$ *is the ESS of cooperatives.*
(2) *When* $z = z*$, $F(y) \equiv 0$, *then* $y\ \epsilon\ [0,\ 1]$ *is in steady.*
(3) *When* $0 < z < z*$, $\frac{d(f(y))}{dy}|_{y=1} > 0$ *and* $\frac{d(f(y))}{dy}|_{y=0} < 0$. $y = 0$ *is the ESS of the cooperatives.*

Proposition 3 reveals that if the proportion of the government choosing the "S" strategy is less than $z*$, the cooperatives' strategy changes from "AGTA" to "ATPM", and cooperatives finally choose "ATPM". When the proportion is higher than $z*$, the "AGTA" strategy is the optimal choice for the cooperatives. When the probability is $z*$, choosing "AGTA" or "ATPM" brings the same benefits for cooperatives, and the choice remains constant over time. To boost the adoption of the "AGTA" strategy among cooperatives, the government ought to boost green adoption subsidies for cooperatives. Since $z*$ decreases with the increase in $\left(R_c^{tt} - C_{ct}\right) - \left(R_c^{tg} - C_{cg}\right)$ and $\left(R_c^{gt} - C_{ct}\right) - \left(R_c^{gg} - (1-b)C_{cg}\right)$, cooperatives are more inclined to adopt agricultural green technology when the gross profits increase.

Similarly, green adoption subsidies are a primary factor influencing cooperatives' "AGTA" strategy. Other key factors affecting cooperatives' "AGTA" strategy include the price premium of green agricultural products, technology spillover effect, and green adoption costs. Therefore, the government can first guide cooperatives to adopt agricultural green technology through subsidies to reduce green adoption costs. Furthermore, the government can utilize macroeconomic measures to control the price premium of green agricultural products in the market and promote collaboration between cooperatives and LAEs through ITISAs.

The replicator dynamic phase diagrams for cooperatives are depicted in Figure 3.



(**a**) $z^* < z < 1$ (**b**) $z = z^*$ (**c**) $0 < z < z^*$

Figure 3. The replicator dynamic phase diagrams for cooperatives.

4.3.3. The Stability Analysis of the Government

For the government, we define $x* = \frac{M - C_{gs} - yS_c}{S_e}$. When $\mathrm{F}(\mathrm{z}) = 0$, the government's evolutionary game is in a stable state. Proposition 4 suggests the result.

Proposition 4. *The ESS of the government is as follows:*

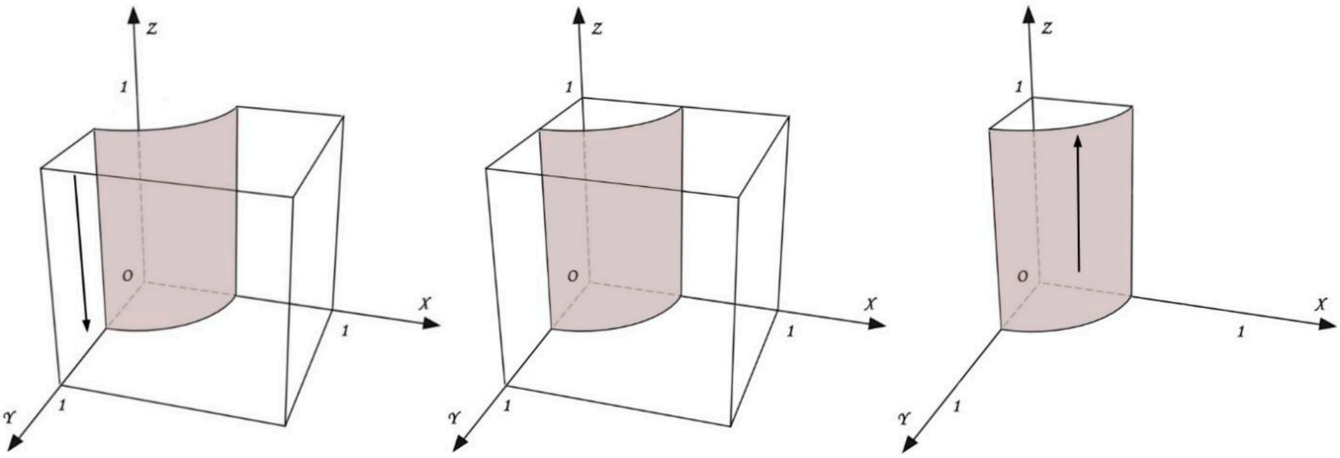
(1) *When* $x* < x < 1$, $\frac{d(f(z))}{dz}|_{z=1} > 0$ *and* $\frac{d(f(z))}{dz}|_{z=0} < 0$. $z = 0$ *is the ESS of the government.*
(2) *When* $x = x*$, $F(z) \equiv 0$, *then* $z\ \epsilon\ [0,\ 1]$ *is in steady.*

(3) *When* $0 < x < x*$, $\frac{d(f(z))}{dz}|_{z=0} > 0$ *and* $\frac{d(f(z))}{dz}|_{z=1} < 0$. *This indicates that* $z = 1$ *is the ESS of the government.*

Proposition 4 shows that if the proportion of cooperatives choosing the "AGTA" strategy is less than $x*$, the government's strategy shifts from "NS" to "S", and the government finally chooses the "S" strategy. When the proportion is higher than $x*$, the government's strategy changes from "S" to "NS", and the government finally chooses the "NS" strategy. When the probability is $x*$, "S" and "NS" have the same benefits for the government. All z are evolutionary stable, and the choice remains constant over time. As the subsidies for AGTIA increase, $x*$ decreases, resulting in a reduced likelihood of the government selecting the "S" strategy. Meanwhile, the green innovation probability of LAEs and the green adoption probability of cooperatives increase with the rise in AGTIA subsidies. Therefore, it is essential for the government to maintain an appropriate subsidy level to incentivize both LAEs and cooperatives for AGTIA.

The government should adjust its strategy flexibly to adapt to the dynamic changes in AGTIA. This means that the government must closely monitor market and technological trends and make timely policy adjustments to align with the needs of agricultural green development and address current technological challenges, thus maximizing the efficiency of government subsidies.

The replicator dynamic phase diagrams for the government are depicted in Figure 4.



(**a**) $x^* < x < 1$ (**b**) $x = x^*$ (**c**) $0 < x < x^*$

Figure 4. The replicator dynamic phase diagrams for the government.

4.4. Evolutionary Equilibrium Stability Analysis

Equations (1)–(3) constitute a three-dimensional dynamic system for the evolutionary game, as depicted below:

$$\begin{cases} F(x) = x(1-x)\Big(C_{et} - C_{eg} + L_1 + R_e^{gt} - R_e^{tt} + y\Big(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\Big) + zS_e\Big) \\ F(y) = y(1-y)\Big(C_{ct} - C_{cg} + D_2 + L_2 + R_c^{tg} - R_c^{tt} + x\Big(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\Big) + zS_c\Big) \\ F(z) = z(1-z)\big(M - C_{gs} - xS_e - yS_c\big) \end{cases} \quad (4)$$

For equation $F(x) = F(y) = F(z) = 0$, there exist eight special pure-strategy equilibrium points and seven hybrid strategy equilibrium points. It is uncertain whether they are asymptotically stable or not or whether they are ESS or not. According to Lyapunov indirect method, an equilibrium point can be an asymptotically stable equilibrium point only if it meets Nash equilibrium and pure strategy Nash equilibrium. Consequently, the eight possible stable equilibrium points are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$. In order to analyze the ESSs of LAEs, cooperatives, and the government, we need to calculate the Jacobian matrix of the dynamic equation and the eigenvalues of its corresponding Jacobian matrix. Based on Friedman (1991), the Jacobian matrix J of the game is shown in Equation (5).

$$\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \tag{5}$$

$$\begin{aligned}
J &= \\
J_{11} &= (1-2x)\Big(C_{et} - C_{eg} + L_1 + R_e^{gt} - R_e^{tt} + y\Big(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\Big) + zS_e\Big) \\
J_{12} &= x(1-x)\Big(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\Big) \\
J_{13} &= x(1-x)S_e \\
J_{21} &= y(1-y)\Big(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\Big) \\
J_{22} &= (1-2y)\Big(C_{ct} - C_{cg} + D_2 + L_2 + R_c^{tg} - R_c^{tt} + x\Big(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\Big) + zS_c\Big) \\
J_{23} &= y(1-y)S_c \\
J_{31} &= -z(1-z)S_e \\
J_{32} &= -z(1-z)S_c \\
J_{33} &= (1-2z)\big(M - C_{gs} - xS_e - yS_c\big)
\end{aligned}$$

According to Lyapunov indirect method, the equilibrium point is asymptotically stable only when all eigenvalues are negative. By substituting the eight equilibrium points into the Jacobian matrix, the eigenvalues of the Jacobian matrix corresponding to the equilibrium points can be measured, as shown in Table 5. In order to be convenient for the analysis of the signs of the eigenvalues corresponding to different equilibrium points, without losing generality, we assume that $C_{eg} - C_{et} - D_2 + D_1 - L_2 - R_e^{gg} + R_e^{tg} - aC_{eg} < 0$, $C_{cg} - C_{ct} - D_1 - L_1 - R_c^{gg} + R_c^{gt} - bC_{cg} < 0$. This means that the cooperatives and the LAEs receive higher net profits when they both participate in ITISAs. The signs of the eigenvalues and the stability of equilibrium points are shown in Table 4, where "+", "−", and "s" denote eigenvalues greater than 0, less than 0, and positive and negative undetermined, respectively. Therefore, only $E_4(0,0,1)$, $E_5(1,1,0)$, and $E_8(1,1,1)$ are possible stable equilibrium points.

Based on the industry life cycle theory, the green development of agriculture can be divided into the initial stage, developmental stage, and maturity stage [73,74]. There is an increasing trend in AGTIA as agricultural green development advances [75]. Therefore, stability conditions can be further analyzed from the perspective of agricultural green development, and we selected the ESSs corresponding to the three stages for detailed analysis.

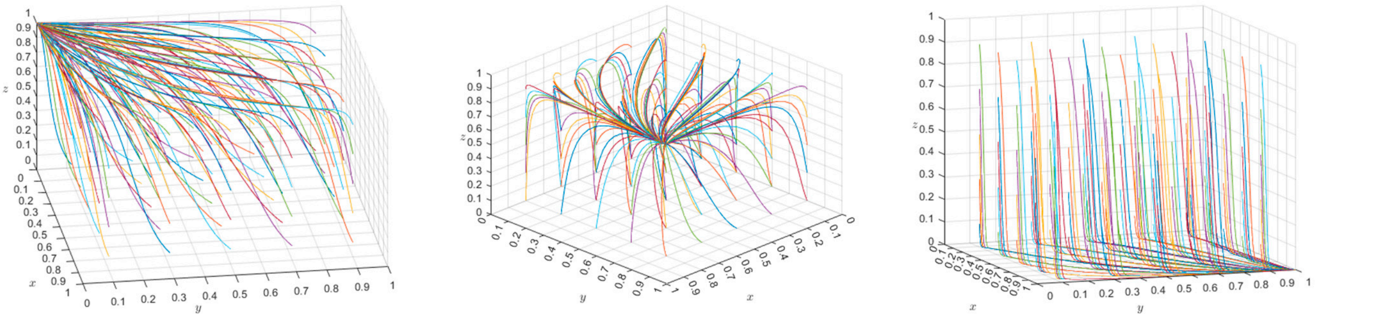
At the initial stage of agricultural green development, LAEs and cooperatives usually take hesitant attitudes towards the market due to risks being unknown. ITISAs that are aimed at promoting AGTIA have not yet formed on a large scale. Then, LAEs and cooperatives choose the "APTP" and "ATPM" strategy, respectively. The government faces the pressure of sustainable development and acknowledges that AGTIA is a key driver of agricultural sustainability. As a result, LAEs and cooperatives receive AGTIA subsidies, respectively. Consequently, the stable point corresponding to the initial stage of agricultural green development is $E_4(0,0,1)$. We then draw Proposition 5.

Proposition 5. *When* $R_e^{gt} - C_{eg} + L_1 + S_e < R_e^{tt} - C_{ct}$, $R_c^{tg} - C_{cg} + S_c + L_2 + D_2 < R_c^{tt} - C_{ct}$ *and* $M - C_{gs} > 0$, $E_4(0,0,1)$ *is ESS at the initial stage.*

Proposition 5 indicates that when both LAEs and cooperatives earn less retained profits from innovating or adopting agricultural green technology solely with government subsidies, then the optimal strategies for LAEs, cooperatives, and the government are "APTP", "ATPM", and "S", respectively. The simulation results in Matlab also confirm this conclusion, as shown in Figure 5a. According to Proposition 5, at the initial stage, there are two main reasons why LAEs are reluctant to innovate agricultural green technology. First, the immaturity of the green technology poses a challenge for LAEs in making significant investments in agricultural green technology innovation; next, the insufficient liquidated damages and green innovation subsidies fail to provide adequate motivation. At the initial stage, the collaboration between LAEs and cooperatives is relatively fragile. Therefore, government subsidies for AGTIA are a crucial factor influencing the strategic choices of LAEs and cooperatives at this stage. Hence, the government should actively encourage LAEs and cooperatives to participate in AGTIA by providing subsidies.

Table 5. The eigenvalues of pure-strategy equilibrium points.

Equilibrium Points	Eigenvalues			Sign	Stability
	λ_1	λ_2	λ_3		
$E_1(0,0,0)$	$C_{et} - C_{eg} + L_1 - R_e^{tt} + R_e^{gt}$	$C_{et} - C_{eg} + L_1 - R_e^{tt} + R_e^{gt}$	$M - C_{gs}$	$(s,s,+)$	Saddle point or unstable point
$E_2(1,0,0)$	$C_{eg} - C_{et} - L_1 - R_e^{gt} + R_e^{tt}$	$C_{ct} - C_{cg} + D_1 + L_1 + R_c^{gg} - R_c^{gt} + bC_{cg}$	$M - C_{gs} - S_e$	$(s,+,s)$	Saddle point or unstable point
$E_3(0,1,0)$	$C_{et} - C_{eg} + D_2 - D_1 + L_2 + R_e^{gg} - R_e^{tg} + aC_{eg}$	$C_{cg} - C_{ct} - D_2 - L_2 - R_c^{tg} + R_c^{tt}$	$M - C_{gs} - S_c$	$(+,s,s)$	Saddle point or unstable point
$E_4(0,0,1)$	$C_{et} - C_{eg} + L_1 + R_e^{gt} - R_e^{tt} + S_e$	$C_{ct} - C_{cg} + D_2 + L_2 - R_c^{tg} + R_c^{tt} + S_c$	$C_{gs} - M$	$(s,s,-)$	Saddle point or stable point
$E_5(1,1,0)$	$C_{eg} - C_{et} - D_2 + D_1 - L_2 - R_e^{gg} + R_e^{tg} - aC_{eg}$	$C_{cg} - C_{ct} - D_1 - L_1 - R_c^{gg} + R_c^{gt} - bC_{cg}$	$M - C_{gs} - S_e - S_c$	$(-,-,s)$	Saddle point or stable point
$E_6(1,0,1)$	$C_{eg} - C_{et} - L_1 - R_e^{gt} + R_e^{tt} - S_e$	$C_{ct} - C_{cg} + D_1 + L_1 + R_c^{gg} - R_c^{gt} + S_c - bC_{cg}$	$C_{gs} - M + S_e$	$(s,+,s)$	Saddle point or unstable point
$E_7(0,1,1)$	$C_{et} - C_{eg} + D_2 - D_1 + L_2 + R_e^{gg} - R_e^{tg} + S_e + aC_{eg}$	$C_{cg} - C_{ct} - D_2 - L_2 - R_c^{tg} + R_c^{tt} - S_c$	$C_{gs} - M + S_c$	$(+,s,s)$	Saddle point or unstable point
$E_8(1,1,1)$	$C_{et} - C_{eg} + D_2 - D_1 + L_2 + R_e^{gg} - R_e^{tg} - S_e + aC_{eg}$	$C_{cg} - C_{ct} - D_1 - L_1 - R_c^{gg} + R_c^{gt} - S_c - bC_{cg}$	$C_{gs} - M + S_c + S_e$	$(-,-,s)$	Saddle point or stable point



(**a**) (**b**) (**c**)

Figure 5. Evolution track of the system. (**a**) Evolution track of $E_4(0,0,1)$; (**b**) evolution track of $E_8(1,1,1)$; (**c**) evolution track of $E_5(1,1,0)$.

For example, China put forward the concept of agricultural green development in 2015. At the initial stage of agricultural green development, China allocated substantial funds to promote AGTIA. According to reports, China's fiscal agricultural science and technology funding increased from 281.90 billion yuan in 2015 to 379.65 billion yuan in 2020, which is used to support AGTIA, and the country's agricultural green development index has increased by 2.34 compared with 2015.

With the continuous refinement and enhancement of the government's subsidies and policies, agricultural green development will progressively enter into the developmental stage. The government will continue to choose strategy "S" to incentivize AGTIA. With the maturity of agricultural green technology and the guidance of government subsidy policies, the proportion of participants engaging in AGTIA increases. At this stage, many LAEs will select the "AGTI" strategy and cooperatives will opt for the "AGTA" strategy, and participants may opt to collaborate through ITISAs to reduce costs and increase incomes. Consequently, this stage corresponds to $E_8(1,1,1)$. We can establish Proposition 6 as follows.

Proposition 6. *When* $D_2 - D_1 + L_2 + S_e > R_e^{tg} - C_{et} - \left(R_e^{gg} - (1-a)C_{eg}\right)$, $S_c + D_1 + L_1 > \left(R_c^{gt} - C_{ct}\right) - \left(R_c^{gg} - (1-b)C_{cg}\right)$ *and* $M > C_{gs} + S_c + S_e$, $E_8(1,1,1)$ *is ESS at the developmental stage.*

Proposition 6 indicates that when the collaborative retained profits of LAEs and cooperatives exceed speculative retained profits with government subsidies, the system equilibrium is expected to result in $E_8(1,1,1)$, which means that the optimal strategies for LAEs, cooperatives, and the government are "AGTI", "AGTA", and "S", respectively. The findings from the simulation in Matlab support this conclusion, as depicted in Figure 5b. Proposition 6 suggests that, when the costs and benefits of AGTIA are difficult to change in the short term, AGTIA subsidies, as well as dividends and liquidated damages within ITISAs, are crucial factors influencing the green development of agriculture in the developmental stage. Therefore, the establishment of ITISAs between LAEs and cooperatives is the key at this stage. Thus, the government should actively encourage the formation of ITISAs, monitor their maturity, and appropriately reduce subsidies when the alliances are mature, relying on proactive innovation within ITISAs.

For example, to promote AGTIA, the United States incorporates organic farmers and farmers transitioning to organic farming in the Environmental Quality Incentives Program (EQIP), providing them with up to USD 20,000 per year or a total of USD 80,000 over six years in assistance. Led by the federal government and state agricultural departments, close collaboration has been established between organic farmers and enterprises to create a system of organic agriculture research collaboration and help organic farmers solve technological challenges in adopting agricultural green technology. Currently, the adoption rate of agricultural green technology in the United States exceeds 80%, with technological factors contributing over 75% to agricultural output.

When agricultural green development reaches its maturity, market demand increases, policy support is sufficient, cooperatives widely adopt green technology, and agricultural green development will enter a maturity stage. The governments will gradually withdraw from subsidies and choose the "NS" strategy. LAEs and cooperatives are the primary drivers of AGTIA, and they choose the "AGTI" and "AGTA" strategies, respectively. ITISAs have become increasingly prevalent at this stage. Therefore, this stage corresponds to $E_5(1,1,0)$. We then draw Proposition 7.

Proposition 7. *When* $R_e^{tg} - C_{et} - D_2 - L_2 < R_e^{gg} - (1-a)C_{eg} - D_1$, $R_c^{gt} - C_{ct} - L_1 - \left(R_c^{gg} - (1-b)C_{cg} + D_1\right) < 0$ *and* $M < C_{gs} + S_c + S_e$, $E_5(1,1,0)$ *is ESS at the maturity stage.*

Proposition 7 suggests that the ESS of the system will tend towards $E_5(1,1,0)$ when the collaborative retained profits of LAEs and cooperatives exceed speculative retained profits after the government ceases subsidies. This means that at the maturity stage, the optimal strategies for LAEs, cooperatives, and the government are "AGTI", "AGTA", and "NS", respectively. The simulation results in Matlab further substantiate the conclusion, as graphically demonstrated in Figure 5c. According to Proposition 7, as agricultural green development enters into the maturity stage, the government should gradually phase out subsidies for AGTIA and reallocate financial budgets to other projects. ITISAs formed by LAEs and cooperatives become the main bodies for AGTIA, autonomously engaging in AGTIA. At this stage, dividends and liquidated damages within ITISAs play a crucial role.

Since the 21st century, in order to reduce government expenditures, the federal government has made significant adjustments to its support mechanisms for agriculture, exerting macro-control over the progress of green agriculture and reducing direct subsidies to farmers. Market-oriented trends have become more apparent, with projects such as Direct Payment (DP) and Average Crop Revenue Election (ACRE) subsidies being canceled. The legislation also decided to eliminate the USD 5 billion Direct Payment subsidy program annually, leading to a trend of stabilization and reduction in the U.S. government's agricultural support budget. Although the U.S. government has not entirely withdrawn subsidies from green agriculture, the sector has matured significantly, with enterprises, farms, cooperatives, and so on autonomously engaging in AGTIA.

5. Simulation and Empirical Analysis

In this section, we use breeding technology as an example for simulation analysis. First, in Section 5.1, we explain how the initial values of each parameter are determined in the simulation experiments. In the following sections, we use Matlab to examine the effects of changes in participants' initial willingness, subsidies, dividends, and its difference between scenario II and III, and liquidated damages and the difference in liquidated damages between cooperatives and LAEs on participants' strategy choices.

5.1. Initial Parameters

Breeding, a crucial technology in modern agricultural production, significantly advances agricultural green development by boosting crop yield, enhancing disease resistance, and improving adaptability and quality. China has been consistently emphasizing the acceleration of the revitalization of the seed industry for several years, with a focus on improving collaborative research and adoption mechanisms. Various incentive policies have been introduced for this purpose. These include encouraging the formation of ITISAs to drive collaborative AGTIA, providing green innovation subsidies for LAEs to support innovation, and offering green adoption subsidies for cooperatives to increase the adoption of improved seeds. Therefore, the use of breeding as a case study in this research is highly relevant and appropriate. Henan, a major agricultural province in China, is also prominent in breeding, seed production, and seed utilization. The breeding industry chain in Henan agriculture has been formalized from basic research and technological development to product commercialization. Therefore, this paper selects LAEs in Henan Province and their collaborative cooperatives as a case study to calculate the initial values of parameters. This case study holds typical, demonstrative, and replicable significance for the implementation of AGTIA in China.

The initial values of the parameters in this article are obtained through three main channels and are shown in Table 5. Firstly, some parameters are set referring to government subsidy policies. The Finance Department of Henan Province encourages LAEs to increase their research and development efforts in breeding innovation by offering a maximum reward of CNY 5 million for LAEs that independently undertake key R&D projects. Cooperatives who use improved seeds of wheat, corn, peanuts, and other crops will be given a subsidy of CNY 10 per mu. Secondly, the initial values of some parameters are obtained through field research. As a representative and replicable case, we visited an ITISA formed by a seed LAE and its cooperatives. The costs of the LAE's breeding collaborating with cooperatives are approximately CNY 50 million, with a government subsidy of CNY 4 million and annual sales incomes of approximately CNY 55 million. The LAE produces about 3 million kilograms of improved seeds annually for its cooperatives, impacting around 200,000 mu of land. By using improved seeds, the adoption costs of cooperatives are about CNY 1550 per mu, with an income of around CNY 2000. The LAE and cooperatives sign a contract for collaboration, agreeing on a profit-sharing ratio of 30% of the increased incomes from collaboration and a penalty of 15% of the contract amount. Cooperatives incur the costs of approximately CNY 1200 per mu when they do not use improved seeds, while their incomes are around CNY 1800. If LAEs adhere to past traditional practices, their costs will be CNY 30 million, and their incomes will be CNY 42 million. The third approach is the combination of field research and classic literature. Other parameters, including the incomes and costs of LAEs and cooperatives after collaboration, refer to the research content of Audretsch et al. [76] and Ma et al. [77]. Audretsch et al. [76] believed that the technology spillover effect would increase income by 0.5–5%, and Ma et al. [77] considered that the collaboration would reduce costs by around 0.5–10%. In summary, the initial values of all the related parameters are shown in Table 6.

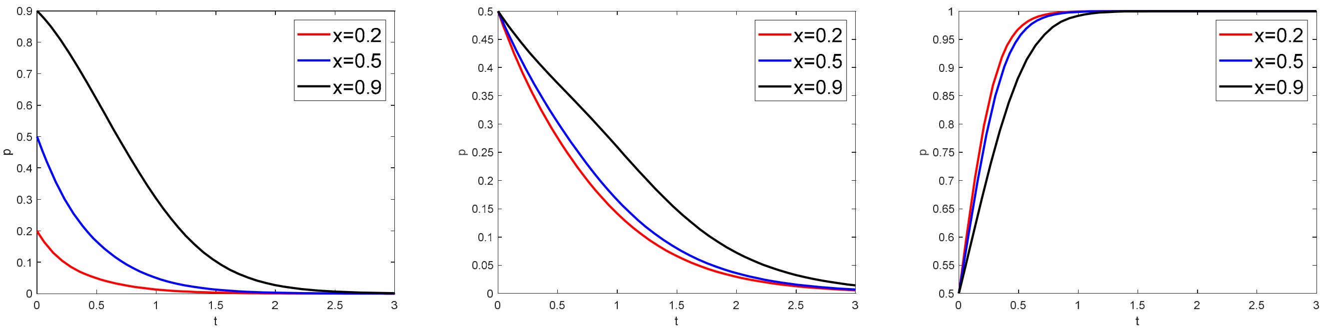
Table 6. Initial values of related parameters (unit: CNY, ten thousand yuan).

Symbol	R_e^{gg}	R_e^{gt}	R_e^{tg}	R_e^{tt}	C_{eg}	C_{et}	R_c^{gg}	R_c^{gt}	R_c^{tg}	R_c^{tt}	C_{cg}
Value	56	54	43	42	50	30	39	36	37	35.5	31
Symbol	a	b	L_1	L_2	D_1	D_2	M	C_{gs}	S_e	S_c	C_{ct}
Value	0.01	0.01	1	1.5	0.6	0.3	9	1	4	2	24

5.2. Impact of Participants' Initial Willingness

Based on Figures 6–8, the final equilibrium point remains $(0, 0, 1)$ at the initial stage, regardless of the magnitude of the initial probabilities. It means that the cooperatives choose the "ATPM" strategy, LAEs choose the "APTP" strategy, and the government chooses the "S" strategy. The changes in initial willingness do not lead to changes in the strategic choices of the participants, but rather affect the convergence rate of the system. Specifically, when the green innovation probability of LAEs increases, the probability of the cooperatives opting for the "AGTA" strategy also increases. Similarly, when cooperatives increase the green adoption probability, the probability of the LAEs selecting the "AGTI" strategy trends upwards. As the probability of the government adopting "S" strategy increases, the probabilities of LAEs choosing the "AGTI" strategy and cooperatives choosing "AGTA" strategy also increase.

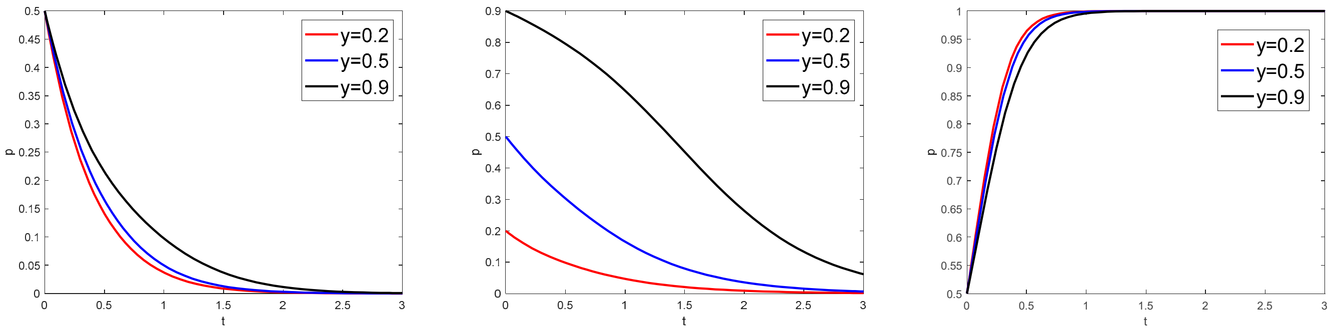
Observation 1. *Boosting the initial green innovation willingness of LAEs can drive cooperatives to adopt the "AGTA" strategy, and vice versa. Additionally, the evolutionary trajectory of cooperatives is more influenced by changes in the initial green innovation willingness of LAEs.*



(**a**) (**b**) (**c**)

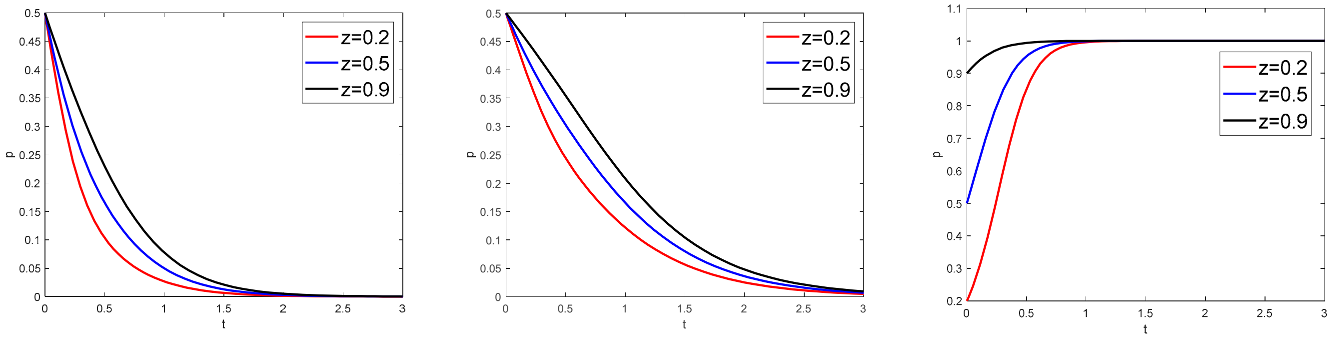
Figure 6. The effect of x on evolutionary stability strategies; (**a**) the evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives; (**c**) the evolutionary trajectory of the government.

This observation shows that LAEs play a crucial role in driving the green development of agriculture. By increasing the publicity efforts directed towards green agriculture, LAEs' enthusiasm and motivation in green innovation can be aroused. Additionally, the evolutionary trajectory of cooperatives is greatly influenced by the strategic choices of LAEs. In turn, the evolutionary trajectory of LAEs is influenced by the strategic choices of cooperatives, as the growing demand from cooperatives will stimulate LAEs to innovate agricultural green technology. Thus, active collaboration among partners is particularly important in promoting AGTIA. Strengthening collaboration between LAEs and cooperatives can facilitate effective AGTIA, which is crucial for the green development of agriculture.



(**a**) (**b**) (**c**)

Figure 7. The effect of y on evolutionary stability strategies. (**a**) The evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives; (**c**) the evolutionary trajectory of the government.



(**a**) (**b**) (**c**)

Figure 8. The effect of z on evolutionary stability strategies. (**a**) The evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives; (**c**) the evolutionary trajectory of the government.

5.3. Impact of Green Innovation Subsidies

We set the green innovation subsidies as 4, 6, 8, and 9, which means that the green innovation subsidies are 100%, 150%, 200%, and 225% of the original subsidy level, respectively. The simulation results are depicted in Figure 9. Figure 9a reveals that increasing green innovation subsidies within a certain range will increase LAEs' green innovation willingness, guiding them to shift from the "APTP" strategy to the "AGTI" strategy. In contrast, excessively high green innovation subsidies reduce LAEs' green innovation willingness, leading them to shift from "AGTI" strategy to "APTP" strategy. Figure 9b shows that increasing green innovation subsidies will augment the cooperatives' green adoption probability. Figure 9c shows that increasing green innovation subsidies will decrease government's subsidy probability.

When the green innovation subsidies are relatively low, LAEs' green innovation willingness is always 0. This means that LAEs will choose the "APTP" strategy when green innovation subsidies are not high enough to offset the high green innovation costs. LAEs' green innovation willingness will increase significantly when the subsidies have doubled from their original level. However, when the green innovation subsidies are increased to more than 225% of their original level, there will be a decrease in LAEs' green innovation willingness and government's subsidy willingness. The evolutionary trajectories of LAEs and the government fluctuate cyclically, and the speed of LAEs cyclical evolution is slower than that of the government evolution. This implies that when the green innovation subsidies for LAEs are higher than a threshold, i.e., increased to about 225% of the original level, it could result in a decrease in government's subsidy willingness due to the excessive financial burden. Therefore, the optimal green innovation subsidy level should be at a reasonable level, i.e., 200% and 225% of the original level in this case.

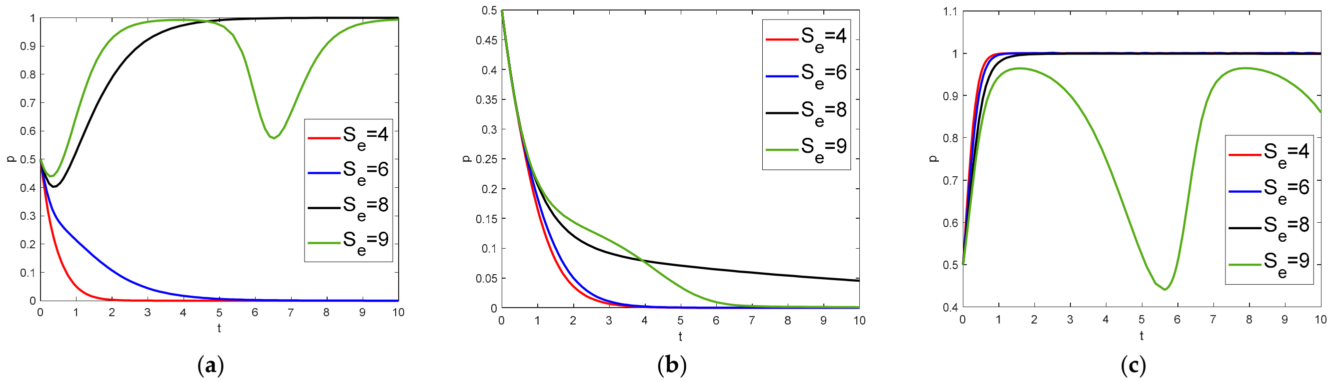


Figure 9. Impact of green innovation subsidies. (**a**) The evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives; (**c**) the evolutionary trajectory of the government.

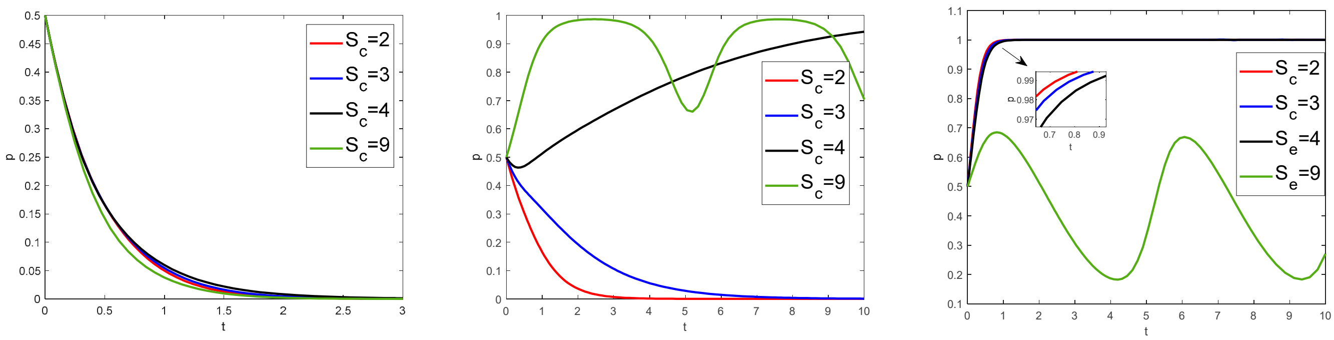
Observation 2. *Green innovation subsidies can fundamentally change LAEs' strategic choices. An increase in LAEs' green innovation probability enhances cooperatives' green adoption probability. However, excessive green innovation subsidies may decrease the likelihood of government subsidy provision.*

This observation implies that green innovation subsidies have profound implications for the strategic choices of LAEs. Subsidies can reduce the green innovation costs for LAEs, driving the active participation of LAEs in green innovation. However, it is important to note that excessive green innovation subsidies may increase LAEs' reliance on subsidies, reducing their motivation for independent green innovation. Additionally, excessive subsidies can increase the government's financial burden, reducing the sustainability and feasibility of providing subsidies. Therefore, to encourage LAEs' active participation in green innovation, green innovation subsidies should be maintained at a moderate level, i.e., 200% and 225% of the original level in this case.

5.4. Impact of Green Adoption Subsidies

We set the green adoption subsidies as 2, 3, 4, and 9, which means that the green adoption subsidies are 100%, 150%, 200%, and 450% of the original subsidy level, respectively, and the simulation results are illustrated in Figure 10. Figure 10a suggests that increasing green adoption subsidies will slightly increase LAEs' green innovation willingness. Figure 10b implies that increasing the green adoption subsidies within a certain range will increase the cooperatives' green adoption willingness. Figure 10c shows that increasing green adoption subsidies will slightly reduce the government's subsidy willingness.

When the green adoption subsidies are lower than 200% of the original level, LAEs select the "APTP" strategy and cooperatives opt for the "APTM" strategy. When the green adoption subsidies have been doubled from its original level, cooperatives' green adoption willingness will rise to be 1, but the green innovation probability of LAEs only increases slightly. When green adoption subsidies are excessively high, the green adoption willingness of cooperatives will fluctuate due to the fluctuation in the government's subsidy willingness. This implies that the government should increase the green adoption subsidies to about 200% of the original level, as it can help motivate cooperatives to adopt agricultural green technology.



(**a**) (**b**) (**c**)

Figure 10. Impact of green adoption subsidies. (**a**) The evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives; (**c**) the evolutionary trajectory of the government.

Observation 3. *In the process of the evolutionary game system converging towards a stable point, as green adoption subsidies increase, there is a growing tendency for cooperatives to choose the "AGTA" strategy, while the probability of the government providing green adoption subsidies decrease.*

Cooperatives' green adoption costs can be effectively reduced through green adoption subsidies, shifting their strategic choices from "ATPM" to "AGTA". However, as the level of subsidies increases, the likelihood of the government providing adoption subsidies decrease. Therefore, green adoption subsidies should also be maintained at an appropriate level. Moderately allocated subsidies can incentivize cooperatives to adopt agricultural green technology, while minimizing financial burden.

5.5. Impact of Dividends in ITISAs

Figure 11 shows the impact of the difference in dividends between scenario II (D_1) and III (D_2) on the evolutionary trajectories of LAEs and cooperatives when D_1 is 0.6. From Figure 11a,b, it can be observed that as the difference increases, both the green innovation willingness of LAEs and the green adoption willingness of cooperatives decrease. This implies that increasing D_2 will increase LAEs' green innovation willingness and the green adoption willingness of cooperatives. For LAEs, an increased dividend in scenario III means that the costs they incur for not engaging in AGTIA will also rise. On the other hand, for cooperatives, even if the LAEs default, the cooperatives can still receive higher dividends. However, the LAEs and cooperatives will still choose the "APTP" and "APTM" strategy. Additionally, we set the dividends of ITISAs in scenario II (D_1) as 0.6, 1.2, and 2, respectively, to explore the impact of D_1 on the participants' evolution trajectory when the difference ($D_1 - D_2$) is 3. The simulation results are shown in Figure 12. From Figure 12a, it can be seen that the increase in D_1 has a minimal impact on the willingness to engage in green innovation in LAEs. From Figure 12b, it is apparent that increasing D_1 will increase the green adoption willingness of cooperatives. However, LAEs will choose the "APTP" strategy, and cooperatives will choose the "APTM" strategy.

Observation 4. *Changes in* D_1, D_2, *and the difference between them will not alter the direction of the system's evolution; dividends within the ITISAs are not determining factors but only influencing factors at the initial stage. Dividends should be within a suitable range, neither too high nor too low, because* D_1 *has the opposite effect on the strategic choices of LAEs and cooperatives.*

Observation 4 suggests that higher dividend payouts may attract more cooperatives to form ITISAs, enabling cooperatives to adopt agricultural green technology. However, for LAEs, excessively high dividends may lead to resource over-allocation, weakening their potential for growth and long-term sustainability. Conversely, lower dividend levels may reduce cooperatives' interest in collaboration, hindering the establishment of ITISAs. Maintaining dividends at optimal levels can help mitigate potential conflicts arising from the differing preferences of LAEs and cooperatives, fostering collaboration between LAEs and cooperatives.

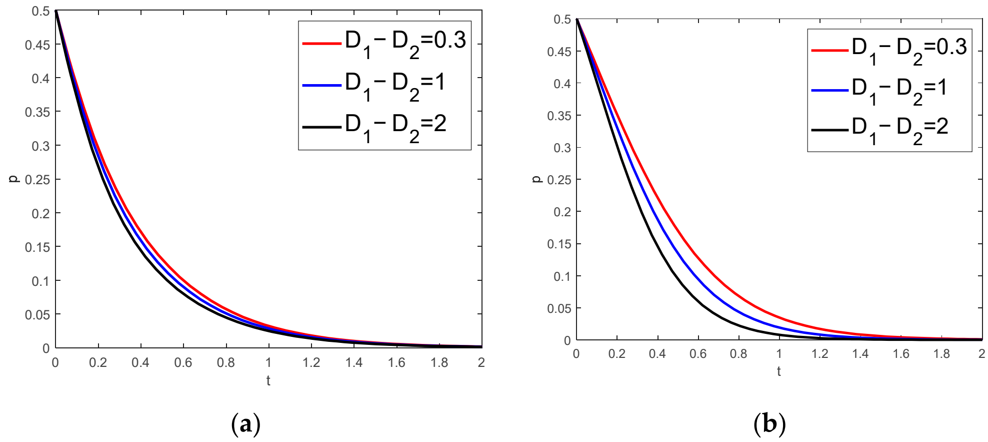


Figure 11. Impact of the difference of D_1 and D_2 on evolution trajectory when $D_1 = 0.6$; (**a**) the evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives.

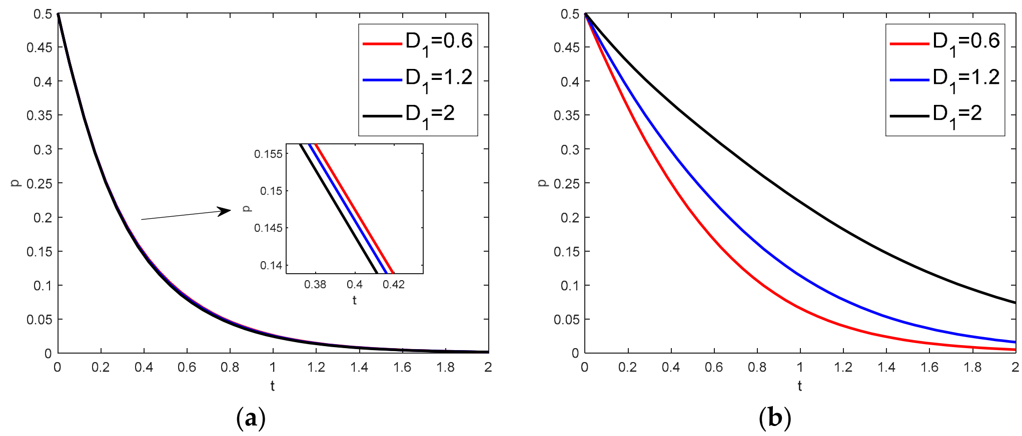
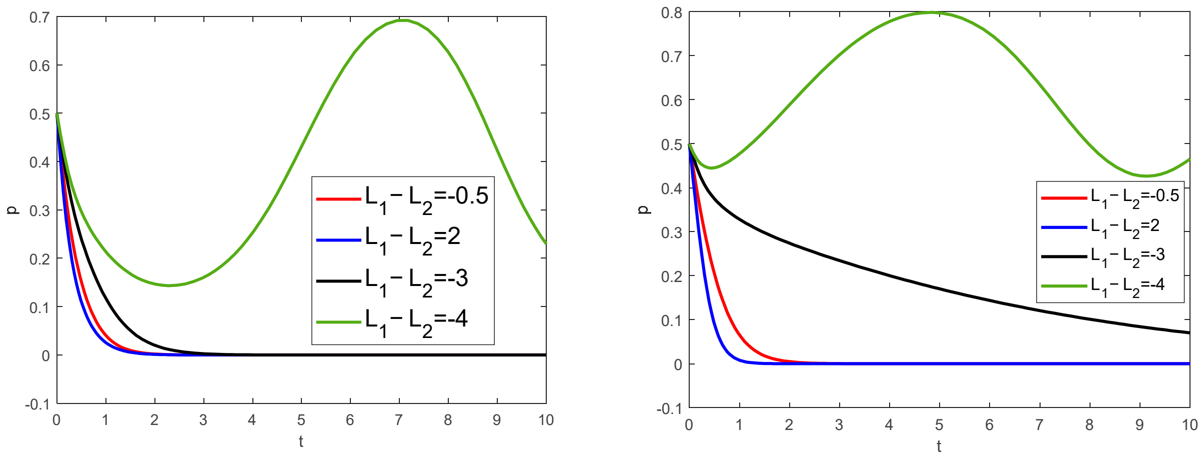


Figure 12. Impact of the D_1 on evolution trajectory when $D_1 - D_2 = 0.3$; (**a**) the evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives.

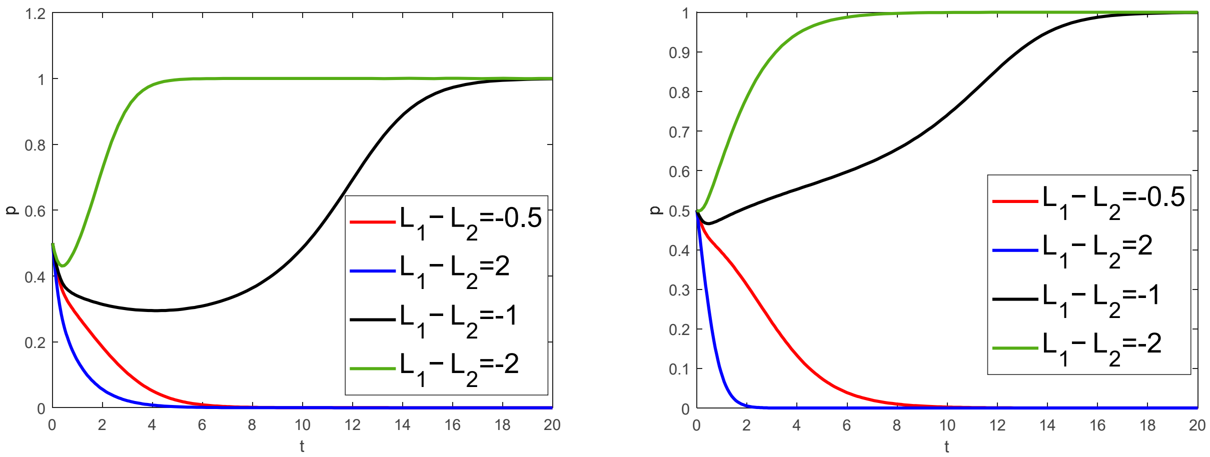
5.6. Impact of Liquidated Damages in ITISAs

We separately simulated the impact of the difference between liquidated damages of cooperatives (L_1) and LAEs (L_1) on the evolution stabilization strategies when liquidated damages in cooperatives are low and high, respectively. As shown in Figure 13, when the liquidated damages of cooperatives (L_1) is low, with an increasing difference between the liquidated damages of cooperatives and LAEs, the likelihoods of LAEs and cooperatives participating in the AGTIA correspondingly increase. Despite this trend, both LAEs and cooperatives ultimately choose not to execute the AGTIA. Furthermore, when the difference in liquidated damages is significant, the evolution trajectories of LAEs and cooperatives may exhibit periodic fluctuations. This is due to the imbalance and uncertainty introduced within the ITISAs when one party faces higher liquidated damages. Figure 14 shows that when the liquidated damages of cooperatives are high, with an increasing difference, the strategies of LAEs and cooperatives shift from "APTP" and "APTM" to "AGTI" and "AGTA" strategies. Therefore, there exists a threshold between L_1 and L_2 where lower liquidated damages do not affect the drive of LAEs and cooperatives towards AGTIA. When the liquidated damages exceed the critical value, x, y, and z converge to $(1, 1, 1)$.



(**a**) (**b**)

Figure 13. Impact of the difference of L_1 and L_2 on evolution trajectory when $L_1 = 1$; (**a**) the evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives.



(**a**) (**b**)

Figure 14. Impact of the difference of L_1 and L_2 on evolution trajectory when $L_1 = 3$; (**a**) the evolutionary trajectory of LAEs; (**b**) the evolutionary trajectory of cooperatives.

Observation 5. *Only when LAEs and cooperatives face heightened liquidated damages will they likely consider collaboration for AGTIA.*

This is because, when both parties are subject to similar punitive measures, they are more likely to be encouraged to make stable strategic choices in ITISA. And beyond that, LAEs and cooperatives will choose between speculative incomes and liquidated damages. Speculative behaviors of LAEs and cooperatives can be deterred when the liquidated damages are higher than a certain threshold. This indicates that liquidated damages, to some extent, can ensure the stable execution of ITISAs and deter free-rider behavior. Notably, cooperatives exhibit greater sensitivity to changes in liquidated damages.

6. Extension

Static subsidies refer to fixed amounts of subsidies provided by the government to participants. Under the static subsidy mechanism, the government does not adjust the subsidy rate according to the choice of participants' behavioral strategies, which can result in high subsidy expenditures and reduced subsidy efficiency. In contrast, dynamic subsidies can offer more precise adjustments based on participants' innovation and adoption willingness. This dynamic subsidy mechanism changes with the strategic choices of participants.

Therefore, the dynamic subsidy mechanism might serve as a more effective policy tool at distinct stages of agricultural green development. Therefore, to improve the efficiency of government subsidies and accelerate agricultural green development, we further examine the performance of dynamic subsidy mechanisms at distinct stages of agricultural green development: the initial stage, the developmental stage, and the maturity stage.

Under the dynamic subsidy model, the tripartite dynamic replication equations are as follows:

$$\begin{cases} F(x) = x(1-x)\left(C_{et} - C_{eg} + L_1 + R_e^{gt} - R_e^{tt} + y\left(D_2 - D_1 - L_1 + L_2 + R_e^{gg} - R_e^{gt} - R_e^{tg} + R_e^{tt} + aC_{eg}\right) + zS_e(x)\right) \\ F(y) = y(1-y)\left(C_{ct} - C_{cg} + D_2 + L_2 + R_c^{tg} - R_c^{tt} + x\left(D_1 - D_2 + L_1 - L_2 + R_c^{gg} - R_c^{gt} - R_c^{tg} + R_c^{tt} + bC_{cg}\right) + zS_c(y)\right) \\ F(z) = z(1-z)\left(M - C_{gs} - xS_e(x) - yS_c(y)\right) \end{cases}$$

6.1. Dynamic Subsidy Mechanisms at the Initial Stage

As indicated by the earlier analysis, government subsidies played the most important role in guiding LAEs and cooperatives in AGTIA at the initial stage. Therefore, at this stage, we have designed dynamic subsidy mechanisms that assume both green innovation and green adoption subsidies are supposed to be positively correlated to the willingness of participants to engage in AGTIA; i.e., $S_e(x) = (1+x)S_e$ and $S_c(y) = (1+y)S_c$, S_e, and S_c are lower bound values for subsidies. To better compare the static subsidy mechanisms and dynamic subsidy mechanisms, we conducted simulations using MATLAB R2023a. Parameter values for the initial stage are the same as in Section 5. In the following figures, red, blue, and black lines represent the evolutionary trajectory of LAEs, cooperatives, and the government, respectively. Solid lines denote the static subsidy scenario, while dotted lines represent the dynamic subsidy scenario.

Figure 15a shows that at the initial stage, LAEs and cooperatives are reluctant to engage in AGTIA regardless of whether the government implements static or dynamic subsidy mechanisms when the lower bound of green innovation subsidies S_e and adoption subsidies S_c are four and two, respectively. However, the willingness of LAEs and cooperatives to engage in AGTIA is relatively higher under dynamic subsidy mechanisms. In order to promote AGTIA, the lower bound of government subsidies should be increased. Figure 15b,c shows that with the increase of S_e, fluctuation in LAE strategy choice increases under the dynamic subsidy mechanism. When S_e increases to eight, LAEs shift from the “APTP” strategy to “AGTI” strategy under the static subsidy mechanism. Figure 15d shows that when S_c increased to three, the cooperatives will opt “AGTA” strategy when the government provide a dynamic green adoption subsidy mechanism.

Observation 6. *At the initial stage of agricultural green development, the government should provide LAEs with static green innovation subsidies and cooperatives with dynamic green adoption subsidies that increase as the green adoption willingness increases. This combined static and dynamic subsidy mechanism can promote AGTIA more effectively and improve the efficiency of subsidization at the initial stage.*

Observation 6 indicates that at the initial stage of agricultural green development, to incentivize green innovation in LAEs, the government should provide stable green innovation subsidies for LAEs. In contrast, cooperatives are more sensitive to the changes in government subsidies. Therefore, the government can give lower subsidies to cooperatives at the beginning, and as the willingness of cooperatives to engage in AGTIA increases, the government should increase green adoption subsidies accordingly to better serve as an incentive.

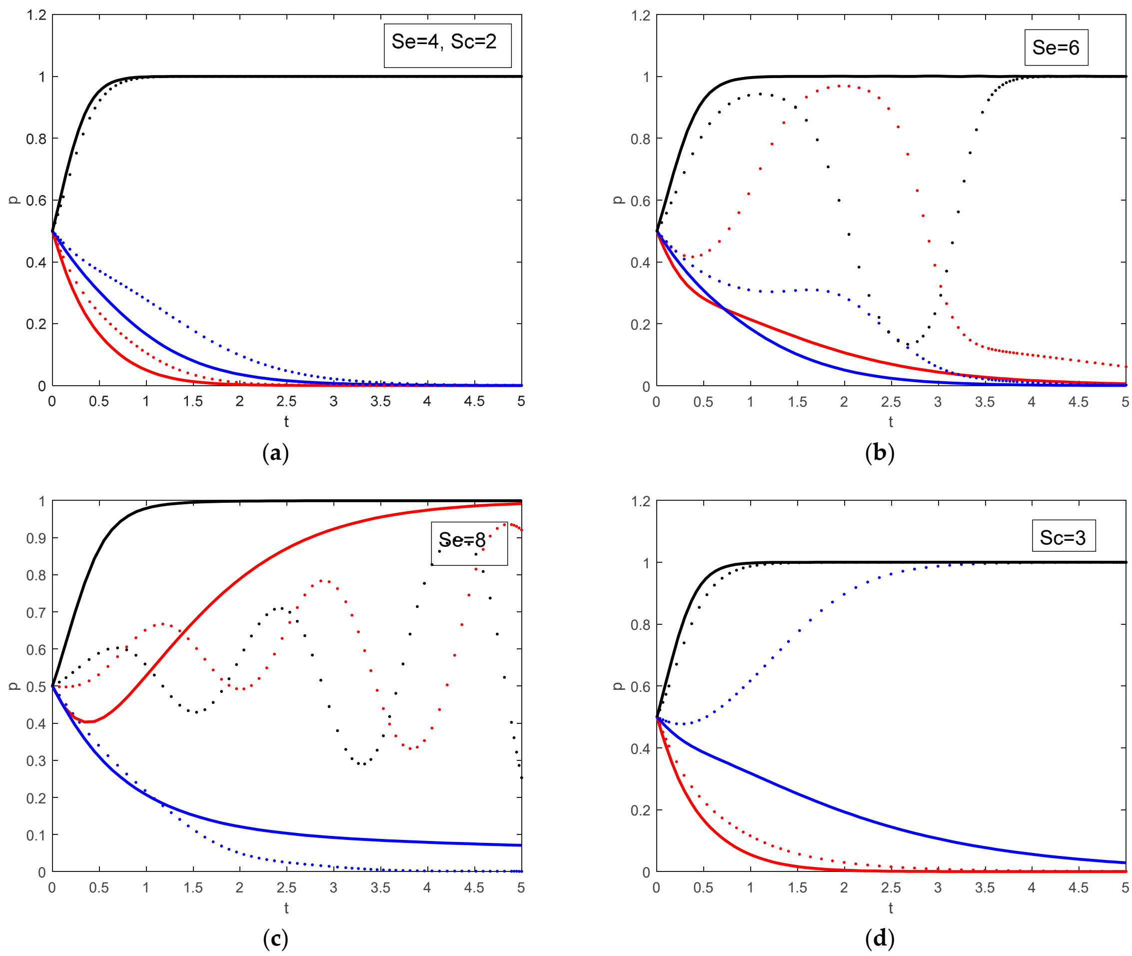


Figure 15. Comparison of game results under a dynamic subsidy mechanism and a static subsidy mechanism at the initial stage; (**a**) $S_e = 4, S_c = 2$; (**b**) $S_e = 6, S_c = 2$; (**c**) $S_e = 8, S_c = 2$; (**d**) $S_e = 4, S_c = 3$.

6.2. Dynamic Subsidy Mechanisms at the Developmental Stage

During the developmental stage, the rising consumer preference for green agricultural products leads to an increase in the price premium of such products, and the incomes of LAEs and cooperatives engaging in AGTIA increased correspondingly [53]. This trend drives LAEs and cooperatives to actively participate in AGTIA with the support of government subsidies. Therefore, at this stage, we assume $R_e^{gg} = 59, R_e^{gt} = 58, R_c^{gg} = 41,\ R_c^{tg} = 40$. We also assume that under the dynamic subsidy mechanisms at this stage the government would reduce green innovation (adoption) subsidies as the green innovation (adoption) willingness increases; i.e., $S_e = (1-x)S_e$, $S_c = (1-y)S_c$, where S_e and S_c are upper bound value for subsidies.

As shown in Figure 16, LAEs and cooperatives will opt for the "AGTI" and "AGTA" strategies when the government provides static green innovation and adoption subsidies. However, under the dynamic subsidy mechanisms, the proportion of both LAEs and cooperatives engaging in AGTIA will decline.

Observation 7. *Dynamic subsidy mechanisms reduce the willingness of LAEs and cooperatives to engage in AGTIA. The government should provide static green innovation and static green adoption subsidies at the developmental stage.*

Observation 7 shows that the government should still provide stable subsidies to both LAEs and cooperatives at the developmental stage rather than scale down subsidies. Premature curtailment of subsidies would reduce the incentives for LAEs and cooperatives to engage in AGTIA. Therefore, a static subsidy mechanism is preferable to a dynamic one at this stage.

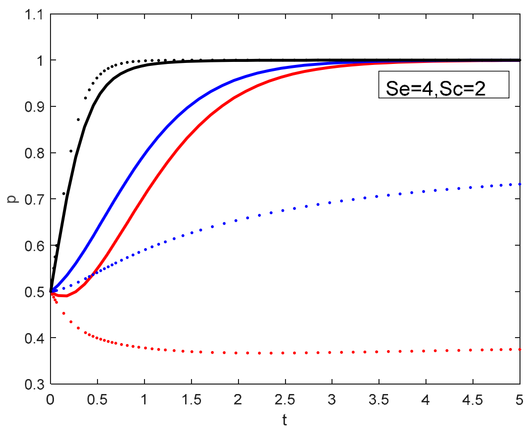


Figure 16. Game results under a dynamic subsidy mechanism and static subsidy mechanism at the developmental stage.

6.3. Dynamic Subsidy Mechanisms at the Maturity Stage

As agricultural green technologies mature, the AGTIA costs for LAEs and cooperatives will significantly decrease, and the profits from AGTIA will substantially increase [78,79]. We set the parameter values of green incomes and costs at this stage as follows: $R_e^{gg} = 60, R_e^{gt} = 58, C_{eg} = 48, R_c^{gg} = 42, R_c^{tg} = 40, C_{cg} = 30$. We assume that the government gradually reduces subsidies as the green innovation (adoption) willingness increases to reduce the dependence on subsidies by LAEs and cooperatives. Therefore, we have designed the following dynamic subsidy mechanism: $S_e = (1-y)S_e$, $S_c = (1-x)S_c$, where S_e and S_c are upper bound values for subsidies.

Figure 17a depicts the evolutionary trajectories of LAE, cooperatives, and the government under static and dynamic subsidy mechanisms, with green innovation and adoption subsidies set at 4 and 2, respectively. It can be obtained from Figure 17a that LAEs and cooperatives will choose the "AGTI" strategy and "AGTA" strategy under both static subsidy mechanisms and dynamic subsidy mechanisms. However, under dynamic subsidy mechanisms, both the LAEs' and the cooperatives' evolutionary game trajectories converge to 1 at a slower rate. In Figure 17b, the solid lines represent the evolutionary trajectories of the three parties under static subsidies when the government directly reduces green innovation and adoption subsidies to 0. The dotted lines illustrate the trajectories when the government sets green innovation and adoption subsidies as dynamic subsidies negatively correlated with the willingness for green innovation and adoption. From Figure 17b, it is evident that under both static and dynamic subsidy mechanisms, all trajectories tend towards 1, with the solid lines taking significantly longer to converge compared to the dotted lines. This indicates that LAEs and cooperatives will ultimately opt for the "AGTI" and "AGTA" strategies. However, when green innovation and adoption subsidies are held constant at 0, the time taken for LAEs and cooperatives to engage in AGTIA will substantially increase.

Observation 8. *The government can adopt dynamic subsidy mechanisms that decrease with the increasing probability of AGTIA to reduce subsidy expenditures and accelerate the progress of agricultural green development at the maturity stage.*

Observation 8 indicates that since LAEs and cooperatives have already established stable partnerships through ITISA at the maturity stage, the government can gradually reduce their subsidies. At this stage, ITISAs have played a more important role in promoting AGTIA than government subsidies. At the maturity stage, although LAEs and cooperatives can proactively engage in AGTIA without relying on government subsidies, a direct reduction in government subsidies to 0 would result in a prolonged period for participants to proactively pursue AGTIA. If the government continues to provide fixed government subsidies, it will escalate government expenditure. Implementing a dynamic subsidy mechanism at the maturity stage that is negatively correlated with the willingness of LAEs and cooperatives to engage in green innovation and adoption can reduce government expenditure and expedite the progress of agricultural green development.

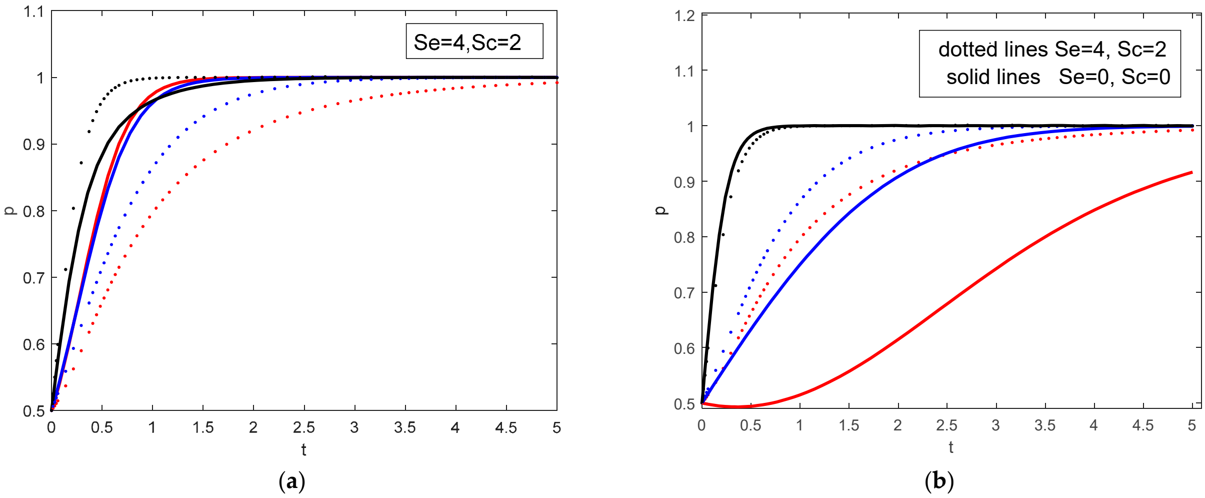


Figure 17. Game results under dynamic subsidy mechanisms and static subsidy mechanisms at the maturity stage; (**a**) $S_e = 4$. $S_c = 2$ under static subsidy mechanisms; (**b**) $S_e = 0$. $S_c = 0$ under static subsidy mechanisms.

7. Conclusions and Implications

7.1. Conclusions

This paper developed a tripartite evolutionary game composed of the government, LAEs, and cooperatives, considering the government's AGTIA subsidies, ITISAs, consisting of LAEs and cooperatives, the spillover effect of agricultural green technology and price premiums of green agricultural products, to research the paths towards realizing agricultural green development. According to industry life cycle theory, we found three possible ESSs existing in our evolutionary game. The key factors that affect LAEs and cooperatives' engagement in AGTIA are different at distinct stages, and the formation of each ESS depends mainly on the trade-off between costs and incomes for each participant. We found that the government can offer different combinations of static and dynamic subsidy mechanisms at distinct stages of agricultural green development. The government can implement a static green innovation subsidy mechanism for LAEs and a dynamic green adoption subsidy mechanism for cooperatives to efficiently promote AGTIA at the initial stage. At the developmental stage, it is essential for the government to ensure stable subsidies for LAEs and cooperatives, while at the maturity stage the government can gradually reduce both green innovation and green adoption subsidies. We carried out a simulation analysis to further analyze the influence of different parameters on the evolution results at the initial stage to better identify the factors that promote the green transformation of agriculture. We found that LAEs and cooperatives will gradually become willing to engage in AGTIA with an increase in AGTIA subsidies. However, subsidies for AGTIA do not follow the "more is better" principle. Beyond a certain threshold, their stability diminishes due to fluctuations in the government's subsidy willingness. Therefore, subsidies for AGTIA should be within a reasonable range. In addition, the dividends in the ITISAs within the appropriate range are not decisive factors, but only affect evolutionary speed. There is a threshold for liquidated damages, though higher liquidated damages facilitate a durable ITISAs' development and can discourage free-rider behavior. But LAEs and cooperatives can only mutually promote AGTIA in the ITISAs when the difference in liquidated damages minus the difference in dividends falls within a certain range.

In the existing research, several studies have addressed topics similar to those in our research, specifically concerning government subsidies or multi-party collaboration to promote agricultural green production. Omotilewa et al. [55], Akkaya et al. [14], Ray et al. [56], and Laborde et al. [15] have explored the topic of government subsidies. However, most existing studies have only considered subsidy mechanisms for single entities, farmers, or LAEs. Their research results indicate that appropriate subsidies provided by the government can enhance the innovation or adoption rates of green technologies. In contrast, our research adopted a more comprehensive framework by simultaneously considering both green innovation subsidies and green adoption subsidies, while also evaluating various static and dynamic subsidy mechanisms at distinct stages of agricultural green development. Our findings showed that suitable green innovation subsidies and green adoption subsidies can directly or indirectly promote the willingness of cooperatives and LAEs to engage in green practices, and the government should offer different combinations of static and dynamic subsidy mechanisms tailored to the distinct stages of agricultural green development. Additionally, while certain aspects of the research conducted by Liu et al. [22], Luo et al. [27], and Chen et al. [28] share thematic similarities with our focus on ITISAs, our study diverges in its specific emphasis. Our study primarily emphasizes the mutual influence between ITISAs members and the breach of contract between members. Thus, this study not only examined the roles of government, LAEs, and cooperatives in AGTIA from a holistic perspective, but also enriched the application of evolutionary game theory in the field of green agriculture, providing insights for the future development of agriculture in China. In summary, this research offered solutions to the difficulties faced by agricultural green development in China. Additionally, forming ITISAs to address the issue of multi-party collaborative development in AGTIA is a novel approach. This serves as a model for agricultural green development in many developing countries around the world and holds significant importance for the sustainable development of the global economy.

7.2. Managerial Implications

(1) Government subsidies play different roles at distinct stages of agricultural green development. The government is the advocate and leader of AGTIA at the initial stage, and the government should offer AGTIA subsidies, including static green innovation and dynamic green adoption subsidies, to guide cooperatives and LAEs to mutually promote AGTIA. Based on the research findings, it is evident that China's agricultural green development is still at its initial stage; the government should actively guide agricultural entities to innovate and adopt agricultural green technology by providing static subsidies for LAEs and dynamic subsidies for cooperatives to reduce the costs of AGTIA. In addition, the government should also encourage LAEs to lead in the formation of ITISAs to establish stable collaborative relationships, thereby improving the efficiency of government subsidies.

(2) Participants' initial willingness affects the system stability rate. To expedite AGTIA, the government should increase awareness efforts to ensure that agricultural participants fully recognize the role of AGTIA, cultivate a green production mindset, and fundamentally drive the sustainable development of agriculture. For example, China's fertilizer consumption per unit of sown area was 350 kg/hm^2 in 2019, with an annual growth rate of 1.6%. This consumption surpasses the environmental safe upper limit of 225 kg per hectare set by many developed countries [80]. To promote chemical fertilizer reduction, the government can enhance dissemination and education efforts by organizing specialized promotional activities and establishing information-sharing platforms aimed at increasing the awareness and acceptance of innovative technology among farmers and other institutions. Additionally, offering professional guidance and training services in fertilizer reduction can assist agricultural enterprises and cooperatives in elevating their technological proficiency and application capabilities.

(3) These research findings indicate that liquidated damages in ITISAs, government subsidies, costs, and incomes are the key factors influencing the decision-making strategies of participants at the initial stage of agricultural green development. In terms of reducing the costs and improving the benefits of AGTIA, ITISAs can integrate resources and enhance the efficiency of innovation transformation. The government should actively encourage and promote LAEs and cooperatives to form ITISAs by designating long-term support policies and establishing incentive mechanisms. It is essential to improve government support policies and create a market environment conducive to alliance development. Furthermore, it is imperative for the government to enhance oversight and management processes to ensure the effective implementation and operation of ITISAs, while safeguarding against breaches of contract. For agricultural entities such as LAEs, they can draw inspiration from the concept of Bayer's Farm Adoption Program, and proactively recruit cooperatives and other organizations to engage in innovative partnerships.

(4) At the developmental stage of agricultural green development, stable subsidies are still necessary for promoting AGTIA. Stable government subsidies can assist LAEs and cooperatives in maintaining continuous investment, fostering innovation practices, mitigating risks, and thus motivating them to achieve sustained outcomes in the field of AGTIA. The government needs to gradually delegate power but maintain control over the market at the macroscopic level at the maturity stage. At this stage, collaboration between LAEs and the cooperative solidified as ITISAs stabilized. Thus, the government can gradually reduce subsidy expenditures, allowing the ITISAs to carry out AGTIA proactively. The government should offer dynamic subsidy mechanisms that are inversely correlated with the willingness of LAEs and cooperatives to engage in AGTIA to reduce fiscal expenditure.

7.3. Future Research Directions

Our work has some limitations that suggest several interesting questions for future research. First, by considering participants' asymmetric attitudes towards potential losses and incomes, prospect theory makes decision models more reflective of real human behavior, enabling better explanations and predictions of individual decision-making results. As a result, in future research, prospect theory can be integrated with evolutionary game theory [65]. Second, the research in this paper is only carried out from the perspective of the supply side of green agricultural products, ignoring the role of the demand side, so more stakeholders (e.g., consumers) or factors related to the demand side (e.g., the technology treadmill effect) could also be taken into account in the model [27,62]. Third, this paper only considers the government subsidy policies. Future studies may consider some non-financial solutions.

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