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Research on the optimization of supply chain decisions for green agricultural products based on farmers' risk preferences and disaster year subsidies

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A B S T R A C T

This study focuses on optimizing supply chain decisions under two scenarios: government subsidies during disaster years and farmers with varying risk preferences. An order-agriculture supply chain model is constructed, involving three parties: farmers, distributors, and insurance companies. Farmers cultivate agricultural products with varying levels of greenness. A three-stage game model is employed to derive the optimal planting scale for farmers, the optimal wholesale price for distributors, and the optimal premium rate for insurance companies. The results indicate that government disaster year subsidies directly increase the Conditional Value-at-Risk (CVaR) of farmers, although a maximum subsidy rate exists to prevent inequity. Enhancing the greenness of agricultural products has a positive impact on agricultural production. As the probability of disaster years increases, loan guarantee insurance becomes more effective in expanding farmers' planting scales, while yield guarantee insurance demonstrates superior performance in improving farmers' CVaR. The practical value of this study lies in providing farmers with optimal decision-making frameworks and profit calculations for loan guarantee insurance and yield guarantee insurance under varying disaster-year probability scenarios. Additionally, it explores the impact of government subsidies during disaster years, the greenness level of agricultural products, and the risk of crop failure on changes in farmers' value. These findings contribute to the optimization of farmers' decision-making processes, enhancement of their economic welfare, and the promotion of sustainable agricultural development, ultimately improving the livelihoods of farmers.

1. Introduction

With the increasing global emphasis on environmental protection and food safety, a growing number of consumers are prioritizing green agricultural products. According to data from Chinese App such as Hema and Alibaba, approximately 50% to 60% of consumers specifically consider whether food meets green, organic, and safety standards when making purchases, a trend that continues to rise annually. Green agricultural products are characterized by environmentally friendly production, health and safety benefits, and authoritative certification. However, the supply chain for green agricultural products faces several challenges. This study is of significant importance for understanding and addressing the decision-making processes within green agricultural product supply chains.

With the continuous expansion of farming operations, the supply chain for green agricultural products faces numerous unpredictable risks, such as climate disasters and pandemics. These events often lead to reduced crop yields and livestock losses, significantly impacting farmers' livelihoods and rural economies. To mitigate these issues, governments commonly implement natural disaster subsidy policies to alleviate farmers' financial pressures and improve production conditions. For example, following the 2019 super typhoon in southern Philippines, the local government provided affected farmers with cash subsidies and material assistance, including rice seeds, fertilizers, and feed, to help restore agricultural and livestock production. Since 2007, China has also incorporated agricultural insurance subsidies into its agricultural support and

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protection framework, developing insurance schemes based on international practices. However, frequent natural disasters continue to disrupt green agricultural product supply chains. While government subsidies help mitigate losses, they also introduce new challenges in coordinating farmers' supply chain decisions.

Despite their effectiveness in alleviating disaster impacts, government subsidies face limitations, such as fiscal constraints and insufficient funding inflows, making it difficult to fully compensate farmers for all losses. This highlights the urgent need to introduce market mechanisms, specifically commercial insurance, to share the risk burden faced by farmers. Among commercial insurance options, the most widely used and effective are loan guarantee insurance and yield guarantee insurance. Loan guarantee insurance, a mainstream product in China, compensates planting costs in cases where natural disasters or accidents result in agricultural losses. Globally, yield guarantee insurance is the dominant product in agricultural insurance, providing compensation for the difference between actual and target yields when natural disasters cause production shortfalls (Barnett, 2014).This study develops corresponding models to address farmers' adoption of loan guarantee insurance and yield guarantee insurance, providing insights into their roles in enhancing resilience within green agricultural product supply chains. Moreover, disasters significantly influence farmers' behavioral choices, with varying risk preferences among farmers becoming a focal point for both governments and the agricultural market. The presence of government disaster subsidies and commercial insurance further complicates farmers' risk preference behaviors, adding layers of complexity to their decision-making processes. This heightened uncertainty poses additional challenges to supply chain coordination. Therefore, conducting in-depth research on farmers with different risk preference types is essential for better informing the development and implementation of relevant policies. Such studies can enhance the resilience and efficiency of the overall supply chain, enabling it to better withstand and recover from the impacts of disasters.

There are some urgent research questions we need to investigate:

(1) What is the impact of disaster occurrence and farmers' risk preferences on the green agricultural product supply chain?
(2) How can the optimal planting scale, wholesale pricing, and insurance premium rates be determined under the interplay between government subsidies and commercial insurance?
(3) How do government subsidy rates, the level of greenness of agricultural products, bank loan interest rates, and the probability of disaster occurrence influence these optimal decisions?
(4) What are the systemic performance differences between loan guarantee insurance and yield guarantee insurance?

The practical significance of this study lies in clarifying the decision-making mechanisms of farmers under varying risk preferences and government subsidies. Based on probabilities of bumper years, normal years, and disaster years over the past decade, the study calculates the green agricultural production decisions and profits of farmers purchasing loan guarantee insurance and yield guarantee insurance. Furthermore, it examines the effects of government disaster subsidies, the level of greenness of agricultural products, and crop failure risks on the value of farmers' risk preferences. Addressing these issues enhances our understanding of the role of agricultural insurance in sustainable agricultural development and provides valuable policy recommendations for improving farmers' livelihoods and the agricultural economy. Moreover, the innovative aspects of this study are :

(1) It incorporates the joint effects of disaster-year subsidies and agricultural insurance.
(2) It identifies the performance differences between loan guarantee insurance and yield guarantee insurance, providing a basis for selecting insurance strategies.
(3) It quantitatively analyzes the impacts of greenness levels, disaster-year probabilities, bank interest rates, and government subsidy rates on optimal strategies.

The structure of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 constructs a three-party game model under loan guarantee insurance and yield guarantee insurance; Section 4 derives the optimal solutions of the model and conducts sensitivity analysis; Section 5 performs numerical simulations; and Section 6 summarizes the research findings and provides policy recommendations.

2. Literature Review and Motivation

2.1 Coordination of Agricultural Supply Chains Based on Risk Aversion

Understanding the role of risk aversion in supply chain management is critical for optimizing decision-making in various industries, including green innovation and agriculture. Recent studies have explored how risk-averse behavior influences supply chain performance, particularly under uncertainty. Zhong et al. (2024) investigate the impact of risk aversion in green innovation-led enterprises on the utilization of construction and demolition waste (CDW) resources, contributing to contingency theory through Stackelberg game models. Similarly, Bai and Jia (2022) analyze financing strategies for farmers, revealing how risk preferences and production uncertainty affect equilibrium outcomes in supply chains. Other works, such as Lin et al. (2024) highlight the challenges of balancing benefits for farmers and companies in agricultural supply chains through loan guarantees. The use of Conditional Value-at-Risk (CVaR) frameworks further deepens our understanding of risk-averse behaviors in contract farming under yield uncertainty (Shi et al., 2023; Peng & Pang, 2019; Amanullah et al., 2019). For instance, Liao and Lu (2024) demonstrate how game theory and CVaR can inform digital cooperation mechanisms, emphasizing the importance of price and investment decisions in contract farming.

2.2 Coordination of Agricultural Supply Chains Based on Government Agricultural Subsidies

Many countries implement agricultural subsidy policies to encourage production. As direct government subsidies for agricultural production increase, farmers significantly expand their planting scales, and their target total production correspondingly rises, further promoting agricultural development and enhancing food production capacity (Peng & Pang, 2019). Zhang et al. (2021) examine the impact of three subsidy schemes on an agricultural supply chain with low- and high-cost firms, incorporating factors such as cost, market structure, product differentiation, and competition. Findings suggest a hybrid subsidy combining output and innovation subsidies reduces pollution, boosts profits, and enhances consumer surplus, leading to greater social welfare. A moderate subsidy rate maximizes benefits for the government, firms, and consumers. Market structure does not affect the subsidy’s effectiveness. In China, the "Government-Bank-Insurance Collaboration" loan model has pioneered a financing mechanism involving government guidance, insurance, and bank participation. Through loan interest subsidies, the government mitigates farmers' financing difficulties and high costs, boosting banks' willingness to lend (Huang Jianhui and Lin Qiang, 2019). When farmers can opt for agricultural insurance, they often face additional costs that diminish their motivation to purchase insurance. Consequently, most countries subsidize insurance premiums to lower farmers' costs, encouraging participation in agricultural insurance and expanding agricultural risk management coverage (Yu & Sumner, 2018). In China, agricultural premium subsidies follow a multi-level mechanism, with the central government subsidizing part and provincial governments covering the rest.

When natural disasters occur, governments commonly compensate farmers to alleviate economic losses, restore agricultural production, and stabilize rural economies. Government disaster-year subsidies can increase consumer surplus and social welfare, while benefiting retailers through increased income (Huang et al., 2017). However, such disaster relief funds are also associated with insurance demand. The expectation of receiving government relief during catastrophic losses can reduce farmers' demand for insurance and their motivation for preventive measures (Philippi & Schiller, 2024).

2.3 Coordination of Agricultural Supply Chains Based on Agricultural Insurance

In recent years, accelerated climate change has made extreme weather events more frequent. Insurance has become an essential tool for preventing greater economic losses in agricultural production (Philippi & Schiller, 2024). Collaboration between banks and insurance companies serves as a critical mechanism to address farmers' financial crises and losses. The availability of insurance alters farmers' behavior, encouraging them to invest more in riskier but higher-yield crops (Cai, 2016). the factors influencing agricultural insurance adoption in Nigeria, surveying 1,080 farming households across diverse regions. Results show that low awareness, affordability, and trust issues hinder adoption. Key drivers include education, herd size, bank access, and weather information. (Madaki et al., 2023) Raising awareness and enhancing institutional support are essential for a functional insurance market. Hazell and Varangis (2020) explore the advantages and challenges of agricultural insurance subsidies, emphasizing issues such as inefficient design, operational shortcomings, and potential environmental consequences. It calls for the implementation of "smart" subsidies that are cost-efficient, minimize negative incentives, and ensure the availability of necessary public goods to facilitate well-functioning insurance markets. Economic development has driven the proliferation of insurance, yet a major challenge for the insurance market remains: when insurance is not mandated or subsidized, farmers show low demand for it. To promote insurance adoption among farmers, insurance companies and governments must implement measures to influence purchasing behavior.

Traditional agricultural insurance includes price insurance, revenue insurance, and income insurance. Currently, loan guarantee insurance is gaining popularity in the market, though yield insurance remains the preferred choice for most agricultural producers (Shi et al., 2023). Crop insurance is a crucial measure to reduce economic losses and protect agricultural production. Additionally, insurance policies can decrease the use of agricultural chemicals, thereby reducing environmental pollution (Mishra et al., 2005). Agricultural insurance can also encourage farmers to adopt green agricultural technologies, thereby improving agricultural green total factor productivity (Fang et al., 2021). After post-disaster insurance compensation, insurance companies maintain their credibility and strengthen their access to credit markets (Collier & Babich, 2019). Governments worldwide have been striving to increase premium subsidies for farmers and identify appropriate subsidy rates. Despite this progress, research remains limited in comprehensively analyzing the combined impacts of government disaster-year subsidies and insurance mechanisms on supply chains. Comparisons of different insurance product types are also scarce, yet such analyses are crucial for understanding how various insurance forms influence farmers' decisions. Based on the above literature, agricultural insurance is vital for agricultural production as it reduces losses for multiple stakeholders and relates closely to farmers' risk-averse behaviors. Further research is needed to explore farmers' behaviors under different risk preferences. This paper introduces government disaster-year subsidies, considers the conditional value-at-risk for risk-averse farmers growing green agricultural products, and constructs a contract farming supply chain involving financially constrained farmers, wholesalers, and insurance companies. The paper solves for the optimal planting scale, wholesale price, and insurance premium rate. Numerical simulations analyze the effects of government subsidy rates, loan interest rates, greenness levels, and disaster-year probabilities on equilibrium decisions, farmers' CVaR, and wholesalers' profits.

Table 1
Summary of related previous research studies

Key Related Studies	Risk Aversion	Government Agricultural Subsidies	Agricultural Insurance	Agricultural Supply Chains
Shi et al., 2023	✓		✓	
Peng & Pang, 2019	✓	✓		✓
Philippi and Schiller, 2024		✓	✓	
Yan et al., 2024	✓			
Huang and Lin Qiang, 2019		✓		✓
Mishra et al., 2005			✓	
Yu and Sumner, 2018		✓		
Huang and Lin Qiang, 2019		✓		
Current Article	✓	✓	✓	✓

3. Model Setup

The green agricultural product supply chain considered in this study consists of financially constrained farmers and well-capitalized distributors. Farmers produce green agricultural products, which are entirely purchased by distributors. Distributors process and package the products for sale to consumers. The government insures farmers' production. This paper analyzes agricultural supply chain models under two types of insurance: loan guarantee insurance and yield guarantee insurance. Subscripts i=1 and i=2 represent the loan guarantee insurance and yield guarantee insurance models, respectively, while f, m and g denote farmers, distributors, and insurance companies, respectively.

3.1 Assumpsions

Agricultural production is subject to weather conditions and other factors, causing variations in crop yields at harvest. The random yield x represents the yield per unit of land. Three types of years are assumed: bumper years, normal years, and disaster years. Farmers face no bankruptcy in bumper and normal years but go bankrupt in disaster years. Farmers harvest x_H in bumper years, x_N in normal years, and a low yield x_L in disaster years. The probabilities of these years occurring are k_H, k_N, and k_L, respectively. The expected yield is $\mu = k_H x_H + k_N x_N + k_L x_L$, and the expected squared yield is $E\left(x^2\right) = \sigma^2$, $\sigma^2 = k_H x_H^2 + k_N x_N^2 + k_L x_L^2$.

Following Huang and Lin (2019) and Alizamir et al. (2019), the production cost of ordinary agricultural products is modeled as a quadratic cost function. Quadratic functions indicate increasing marginal costs of production. For example, Peterson (1997) showed that as farm size increases, the long-term average total cost curve of farms in the U.S. Corn Belt exhibits diseconomies of scale. In certain traditional crops (e.g., rice, wheat), expanding production beyond a certain scale leads to significantly higher marginal costs due to resource constraints and increased management complexity.

The production cost function is defined as $c_1 q^2$, where c_1 is the effort cost coefficient representing all inputs and effort required to cultivate q units of ordinary agricultural products. Producing green agricultural products incurs additional costs, which depend on the greenness level g of the products. These additional costs increase with g and are denoted as $\frac{1}{2}c_2 g^2$. Thus, the total production cost for green agricultural products is $c_1 q^2 + \frac{1}{2}c_2 g^2$, where q is the farmer's decision variable. For simplicity, g is treated as an exogenous variable, and sensitivity analyses are used to evaluate its impact on decision variables.

The scale of cultivation is q, and the harvested output at the end of the season is qx. Distributors purchase the green agricultural products at a wholesale price w, process them, and sell them to consumers at a retail price p. The retail price is determined by the total output Q and the greenness level g through the inverse demand function:

$$p = a - bQ + \lambda g,$$

where $Q = qx$, a is the price ceiling, b is the price elasticity coefficient indicating the sensitivity of price to supply, and λ represents consumers' sensitivity to the greenness level of agricultural products. Linear demand functions and the impact of greenness on product prices have been extensively studied (Peng & Pang, 2019; Li et al., 2021)

3.2 Modeling

We take Sugarcane farmers in Zhanjiang City, Guangdong Province as an example. Initially, the farmer has zero capital. The farmer pledges the order contract signed with the distributor as collateral to the bank for a loan, with the loan amount covering the insurance premium and production costs. farmers have zero initial capital and pledge order contracts with distributors as collateral to obtain bank loans. Loan amounts cover the production costs and insurance premiums. Banks decide on loan approval based on the collateral value of the contracts. Generally, the collateral value exceeds the required loan amount due to the low production cost of agriculture. Banks provide loans to farmers at an interest rate r. Agricultural insurance provides timely economic compensation to insured farmers following disasters covered by the policy. Therefore, to maintain their creditworthiness in the event of a disaster, farmers purchase agricultural insurance in advance. When farmers are unable to repay loans, the insurance company compensates the bank, thereby reducing credit risk. To encourage lending, the government covers the cost of farmers' insurance premiums. Taking the 2021 Henan Province flood as an example, the government subsidized disaster-affected farmers. In disaster years, farmers go bankrupt and cannot repay loans. The insurance company compensates the bank, while the government subsidizes farmers' production costs, including loan interest, at a bankruptcy subsidy rate s_i. The upper limit of the subsidy rate is determined by the profit in normal years, ensuring that the sum of disaster year profit and government subsidy does not exceed normal year profit. We considers the Sugarcane farmers bought the two types of insurance: loan guarantee insurance and yield guarantee insurance. Assuming a perfectly competitive insurance market (Shi et al., 2023), insurance premiums β are determined based on the zero-expected-profit principle.

This paper considers two scenarios for comparison: loan guarantee insurance and yield guarantee insurance. The Zhanjiang city's insurance companies evaluate various risks associated with agricultural products and calculate the corresponding insurance premiums. In the two-tier supply chain consisting of distributors and farmers, distributors hold the leadership position, while farmers act as followers. The decision sequence is as follows: first, the insurance company determines the insurance premium rates β for the two types of insurance. Next, the distributor decides the wholesale price w. Finally, the farmer determines the cultivation scale q.

3.3 Farmer Risk Analysis

Farmers are typically risk-averse with limited risk tolerance. Hence, they must also consider loss risk. Building on the work of Peng and Pang (2019) and Ye et al. (2020) this paper uses CVaR (Conditional Value-at-Risk) to evaluate farmers' risk-averse behavior.

$$CVaR_{1-\eta}\left(\pi_f\left(q\right)\right)=\max_{v\in R}\left\{v+\frac{1}{1-\eta}E\left[\min\left(\pi_f-v,0\right)\right]\right\}$$

Based on Shi et al. (2023), farmers' risk aversion levels are categorized into three types: $\eta\in\left[1-k_L,1\right)$: high risk aversion. $\eta\in\left[k_H,1-k_L\right)$: medium risk aversion. $\eta\in\left[0,k_H\right)$: low risk aversion.

The symbols used in this paper are shown in Table 1:

Table 1
Model Notations

Symbols	Explanation
x_H, x_N, x_L	Per-unit yield in bumper, normal, and disaster years
k_H, k_N, k_L	Probabilities of bumper, normal, and disaster years
μ , σ^2	Expected yield x and its square x^2
q, g	Farmers' cultivation scale and product greenness
η	Farmers' risk aversion level
c_1, c_2	Cost coefficients for green agricultural products
a, b, λ	Demand curve intercept, slope, and greenness impact
w	Wholesale price of green agricultural products
p	The retail price of green agricultural products
x_0	The yield level under yield guarantee insurance
s_i , r	Bankruptcy subsidy rate and loan interest rate
β_i	Insurance premium rate
π_f, π_m, π_g	The profits of farmers, distributors, and insurance companies

4. Optimal Strategy and Sensitivity Analysis

This section considers two scenarios to explore the optimal solutions for the supply chain under loan guarantee insurance and yield guarantee insurance. The supply chain consists of farmers, distributors, and insurance companies. Following the method of Huang and Lin（2019）, It is assumed that the Chinese government covers the insurance premiums, according to the Ministry of Finance of China, as disclosed on the 29th, the national and local governments collectively provided a total of 60.3 billion yuan in agricultural insurance premium subsidies in 2023. Insurance companies provide compensation in disaster years. As farmers are financially constrained, they borrow production costs from banks at an interest rate *r*, while the insurance premium rate is β.

4.1 Optimal Strategy under Loan Guarantee Insurance

We still use Sugarcane farmers in Zhanjiang City, Guangdong Province as an example, at the beginning of the period, the farmers borrow production costs $c_1q_1^2+\frac{1}{2}c_2g^2$ from banks. Since the government covers all insurance premiums $\beta_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$, farmers do not need to borrow for the insurance portion. At the end of the period, farmers repay the loan $(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$. In disaster years, farmers are unable to repay all debts, and insurance companies bear part of the bank's loan losses $(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)-w_1q_1x_L$. The government provides subsidies $s_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$ to farmers. The expected profit of farmers is given by:

$$\max \pi_{f1}(q_1)=\max_{q_1} E\left[w_1q_1x-(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)\right]^+ +k_Ls_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right) \tag{1}$$

where $y^+=max(y,0)$. The goal of the agricultural distributor is to determine the optimal wholesale price www to maximize its profit:

$$\max_{w1} \pi_{m1}=E\left[(a-bq_1x+\lambda g)q_1x-w_1q_1x\right]=(a-w_1+\lambda g)q_1\mu-bq_1^2\sigma^2 \tag{2}$$

Under perfect competition, the insurance company sets the premium rate β based on the zero-expected-profit principle:

$$\pi_{g1}=\beta_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)-k_L\left[(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)-w_1q_1x_L\right] \tag{3}$$

Using backward induction, the following results are derived.

Proposition 1: For loan guarantee insurance, the optimal cultivation scale q_1^*, wholesale price w_1^*, and premium rate $\beta_1^*$are given by:

$$q_1^*=\frac{(a+\lambda g)\mu}{2\left(b\sigma^2+\frac{\mu}{A_1}\right)} \tag{4}$$

$$w_1^*=\frac{(a+\lambda g)\mu}{2(b\sigma^2A_1+\mu)} \tag{5}$$

$$\beta_1^*=k_L\left[1-\frac{A_1w_1^{*2}x_L}{(1+r)\left(c_1A_1^2w_1^{*2}+\frac{1}{2}c_2g^2\right)}\right] \tag{6}$$

Here, β contains w^* to simplify notation, as expressing it directly in terms of A_1 becomes overly complex but does not alter the decision-making sequence.

$$A_1=\begin{cases}\dfrac{x_N}{c_1(1+r)} & 1-k_L\leqslant\eta<1;\ in\,0\leqslant\eta<1-k_L:s_1\geqslant\dfrac{1-\eta-k_L}{k_L}\\ \dfrac{(1-\eta-k_L)x_N}{2c_1(1+r)\left[1-\eta-k_L(1+s_1)\right]} & k_H\leqslant\eta<1-k_L:s_1<\dfrac{1-\eta-k_L}{k_L}\\ \dfrac{(1-\eta-k_L)x_H-k_N(x_H-x_N)}{2c_1(1+r)\left[1-\eta-k_L(1+s_1)\right]} & 0\leqslant\eta<k_H:s_1<\dfrac{1-\eta-k_L}{k_L}\end{cases}\tag{7}$$

The optimal CVaR value for farmers and the distributor's profit are obtained by substituting (5) and (6) into the CVaR and profit functions:

$$CVaR_{1-\eta}\left(\pi_{f1}^*\right)=\begin{cases}s_1(1+r)\left(c_1q_1^{*2}+\dfrac{1}{2}c_2g^2\right) & 1-k_L\leqslant\eta<1\\ \dfrac{1-\eta-k_L}{1-\eta}w_1^*q_1^*x_N-\dfrac{1-\eta-k_L(1+s_1)}{1-\eta}(1+r)\left(c_1q_1^{*2}+\dfrac{1}{2}c_2g^2\right) & k_H\leqslant\eta<1-k_L\\ \dfrac{(1-\eta-k_L)x_H-k_N(x_H-x_N)}{1-\eta}w_1^*q_1^*-\dfrac{1-\eta-k_L(1+s_1)}{1-\eta}(1+r)\left(c_1q_1^{*2}+\dfrac{1}{2}c_2g^2\right) & 0\leqslant\eta<k_H\end{cases}\tag{8}$$

$$\pi_{m1}^*=\frac{(a+\lambda g)\mu}{2}q_1^*\tag{9}$$

In normal years, the farmer's income exceeds the bank's loan repayment amount, subject to a maximum yield condition $w_1q_1x_N-(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)\geqslant 0$. To calculate $q_{\max}$. Approximately simplified as $q_{\max}=\frac{w_1x_N}{c_1(1+r)}$, That is, when the subsidy rate exceeds a certain threshold, farmers will choose to produce at the maximum output level.

4.2 Optimal Strategy under Yield Guarantee Insurance

At the beginning of the period, the Sugarcane farmers borrow production costs from banks under yield guarantee insurance is $c_1q_1^2+\frac{1}{2}c_2g^2$. The guaranteed yield level is $x_0\in(x_L,x_N)$, the guarantee amount is $w_2q_2x_0$, and the government subsidizes the insurance premium $\beta_2w_2q_2x_0$. At the end of the period, farmers repay the loan $(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$ at interest rate *r*. If the yield *x* per unit of land is below x_0, the insurance company compensates the farmer at the wholesale price w_2. The compensation amount is $w_2q_2(x_0-x_L)$. It is assumed that the guaranteed yield covers the bank loan principal and interest: $w_2q_2x_0\geqslant(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$.

The farmer's profit under yield guarantee insurance is given by:

$$\pi_{f2}=\begin{cases}w_2q_2x_0-(1-s)(1+r)\left(c_1q_2^2+\dfrac{1}{2}c_2g^2\right), & bad\ year\\ w_2q_2x_N-(1+r)\left(c_1q_2^2+\dfrac{1}{2}c_2g^2\right), & normal\ year\\ w_2q_2x_H-(1+r)\left(c_1q_2^2+\dfrac{1}{2}c_2g^2\right), & good\ year\end{cases}\tag{10}$$

The distributor's profit is:

$$\max_{w2}\pi_{m2}=E\left[(a-bq_2x+\lambda g)q_2x-w_2q_2x\right]=(a-w_2+\lambda g)q_2\mu-bq_2^2\sigma^2\tag{11}$$

The insurance company's profit is:

$$\pi_{g2}=\beta_2w_2q_2x_0-k_L\left(w_2q_2x_0-w_2q_2x_L\right)\tag{12}$$

Using a similar solution approach as in the loan guarantee insurance case, the equilibrium strategy is derived as follows:

Proposition 2: For yield guarantee insurance, the optimal cultivation scale q_2^*, wholesale price w_2^*, and premium rate β_2^* are given by:

$$q_2^* = \frac{(a+\lambda g)\mu}{2\left(b\sigma^2 + \dfrac{\mu}{A_2}\right)} \tag{13}$$

$$w_2^* = \frac{(a+\lambda g)\mu}{2\left(b\sigma^2 A_2 + \mu\right)} \tag{14}$$

$$\beta_2^* = \frac{k_L(x_0 - x_L)}{x_0} \tag{15}$$

$$A_2 = \begin{cases} \dfrac{x_0}{2c_1(1+r)(1-s_2)} & 1-k_L \leqslant \eta < 1 \\ \dfrac{(1-\eta)x_N - k_L(x_N - x_0)}{2c_1(1+r)\left[(1-\eta) - s_2 k_L\right]} & k_H \leqslant \eta < 1-k_L \\ \dfrac{(1-\eta)x_H - k_L(x_H - x_0) - k_N(x_H - x_N)}{2c_1(1+r)\left[(1-\eta) - s_2 k_L\right]} & 0 \leqslant \eta < k_H \end{cases} \tag{16}$$

By substituting (14) and (15) into the CVaR and profit equations, the optimal CVaR values for farmers and the distributor's profits are obtained.

$$CVaR_{1-\eta}\left(\pi_{f2}^*\right) = \begin{cases} w_2^* q_2^* x_0 - (1-s_2)(1+r)\left(c_1 q_2^{*2} + \dfrac{1}{2}c_2 g^2\right) & 1-k_L \leqslant \eta < 1 \\ \dfrac{(1-\eta)x_N - k_L(x_N - x_0)}{1-\eta} w_2^* q_2^* - \dfrac{(1-\eta) - s_2 k_L}{1-\eta}(1+r)\left(c_1 q_2^{*2} + \dfrac{1}{2}c_2 g^2\right) & k_H \leqslant \eta < 1-k_L \\ \dfrac{(1-\eta)x_H - k_L(x_H - x_0) - k_N(x_H - x_N)}{1-\eta} w_2^* q_2^* - \dfrac{(1-\eta) - s_2 k_L}{1-\eta}(1+r)\left(c_1 q_2^{*2} + \dfrac{1}{2}c_2 g^2\right) & 0 \leqslant \eta < k_H \end{cases} \tag{17}$$

$$\pi_{m2}^* = \frac{(a+\lambda g)\mu}{2} q_2^* \tag{18}$$

4.3 Sensitivity Analysis

Proposition 1

$$\begin{cases} \dfrac{dq_1^*}{ds_1} = 0, \dfrac{dw_1^*}{ds_1} = 0, \dfrac{d\beta_1^*}{ds_1} = 0, \dfrac{d\pi_{m1}^*}{ds_1} = 0 & 1-k_L \leqslant \eta < 1; in\ 0 \leqslant \eta < 1-k_L : s_1 \geqslant \dfrac{1-\eta-k_L}{k_L} \\ \dfrac{dq_1^*}{ds_1} > 0, \dfrac{dw_1^*}{ds_1} < 0, \dfrac{d\pi_{m1}^*}{ds_1} > 0 & 0 \leqslant \eta < 1-k_L : s_1 < \dfrac{1-\eta-k_L}{k_L} \end{cases} \quad \frac{dq_2^*}{ds_2} > 0, \frac{dw_2^*}{ds_2} < 0, \frac{d\beta_2^*}{ds_2} = 0, \frac{d\pi_{m2}^*}{ds_2} > 0$$

Proposition 1 demonstrates the following scenarios under loan guarantee insurance: First Scenario: When farmers exhibit high risk aversion $\eta \in [1-k_L, 1)$ or low-to-medium risk aversion $\eta \in [0, 1-k_L)$, while considering the government disaster-year subsidy rate $s_1 \geqslant \dfrac{1-\eta-k_L}{k_L}$, the farmers' optimal production scale remains at the maximum input level, and it will not increase further. In this case, the government disaster-year subsidy rate does not affect q_1^*, the distributor's optimal purchasing price, or the distributor's profit. However, if the government disaster-year subsidy rate is $s_1 = 0$, highly risk-averse farmers will have zero end-period profits and will choose not to produce.

Second Scenario: When farmers exhibit low-to-medium risk aversion $\eta \in [0, 1-k_L)$ and the government subsidy rate $s_1 < \dfrac{1-\eta-k_L}{k_L}$, both farmers' and distributors' optimal decision variables (q_1^*, w_1^*) are influenced by the subsidy level. As the government disaster-year subsidy rate increases, farmers expand their production scale, leading to higher anticipated sales by distributors at the end of the period. This results in a lower end-period retail price p, a reduction in the agreed wholesale price w, and, ultimately, an increase in distributor profits.

Under yield guarantee insurance, regardless of farmers' risk aversion levels, the optimal decision variables (q_2*,w_2*) of both farmers and distributors vary with the government disaster-year subsidy rate. This scenario is similar to the second case under loan guarantee insurance. However, the premium rate β_2 is independent of the government disaster-year subsidy rate. This is because the premium for yield insurance primarily depends on the predefined yield level, disaster-year probability, and disaster-year yield, rather than the government subsidy rate.

Proposition 2

$$\frac{dq_1^*}{dr} < 0, \frac{dw_1^*}{dr} > 0, \frac{d\pi_{m1}^*}{dr} < 0$$
$$\frac{dq_2^*}{dr} < 0, \frac{dw_2^*}{dr} > 0, \frac{d\beta_2^*}{dr} = 0, \frac{d\pi_{m2}^*}{dr} < 0$$

Proposition 2 indicates that an increase in bank loan interest rates reduces farmers' optimal production scale under both loan guarantee insurance and yield guarantee insurance. This is because higher loan interest rates directly raise farmers' financial costs, increasing end-period repayment amounts. When borrowing costs rise, farmers reduce their cultivation scale, as higher interest rates increase borrowing expenses and ultimately reduce farmers' net income.

As farmers' production scales decrease, the total output of agricultural products also declines. According to economic principles, with other conditions unchanged, a reduction in supply leads to an increase in market prices for agricultural products. To prevent a further decrease in farmers' production scales, distributors may raise wholesale prices and transfer a portion of their profits to farmers. Consequently, distributors' profits decrease as bank loan interest rates increase.

Similar to the discussion above, under yield guarantee insurance, the insurance premium rate does not change with variations in bank loan interest rates.

Proposition 3

$$\frac{dq_1^*}{dg} > 0, \frac{dw_1^*}{dg} > 0, \frac{d\pi_{m1}^*}{dg} > 0$$
$$\frac{dq_2^*}{dg} > 0, \frac{dw_2^*}{dg} > 0, \frac{d\beta_2^*}{dg} = 0, \frac{d\pi_{m2}^*}{dg} > 0$$

Proposition 3 can be observed that increasing the greenness level of agricultural products leads to an expansion in farmers' planting scale, a rise in the wholesale price of agricultural products, and an improvement in distributors' profits. Enhancing the greenness level of agricultural products implies adopting more environmentally friendly and health-conscious production methods. As public awareness of ecological balance, sustainable development, and personal health continues to grow, the demand for green agricultural products shows a significant upward trend. Green agricultural products align more closely with market demands for healthy and safe food, earning greater trust and loyalty from consumers, who are often willing to pay premium prices. Consequently, as the greenness level increases, distributors raise wholesale prices to encourage farmers to cultivate more green agricultural products. Farmers, in turn, achieve higher profits and expand their planting scale, while distributors' profits also see continuous growth. Moreover, under yield-guarantee insurance, the insurance premium rate remains unaffected by fluctuations in bank loan interest rates.

Proposition 4

$$\frac{d\beta_2^*}{dk_L} > 0$$

Proposition 4 shown that as the probability of disaster years increases, the insurance premium rate under yield-guarantee insurance also rises. Under yield-guarantee insurance, the amount covered by the insurance company is not influenced by random yield fluctuations but is solely determined by the yield guarantee level and the probability of disaster years. As the frequency of disaster years increases, the insurance company is required to make more payouts. Therefore, based on the principle of expected profit being zero, the insurance company must raise premiums to increase its revenue.

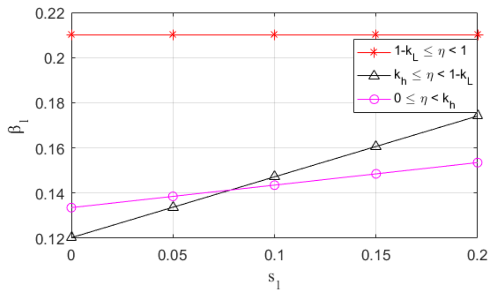
5. Discussions and numerical illustrations

The numerical illustrations in this paper are based on a fundamental principle: after government subsidies, farmers' profits in disaster years should not exceed those in normal years. This aligns with the idea that losses from disasters outweigh the aid provided, as government subsidies aim to alleviate economic pressure rather than enrich farmers. If farmers' total profits in disaster years surpass those in normal years, it could lead to inefficient resource allocation, dissatisfaction among farmers in non-disaster areas, and a lack of fairness. This condition ensures policy equity and market competitiveness.

This section examines how the insurance premium rate s_i, interest rate r, greenness level g, and disaster year probability k_L influence the equilibrium decisions under loan guarantee insurance and yield guarantee insurance. The parameters are selected based on real-world data of sugarcane production in Zhanjiang, Guangdong Province, referencing existing literature. The values are set as follows: a=1000, b=1.2, λ=20, c_1=90, c_2=60, $g_1 = g_2$=1, r=0.1, k_H=0.3, k_N=0.4, k_L=0.3, $s_1 = s_2$=0.1, x_H=14, x_N=10, x_L=3, x_0=7.Farmers' risk aversion levels η are set to three values: 0.2, 0.5, and 0.8. (The data x_H、 x_N、 x_L、 x_0, as well as k_H、 k_N、 k_L are derived from long-term statistical data of sugarcane farmers in the Zhanjiang region of Guangdong Province over the past decade. Historical yield data are used to calculate the per-acre yield and probability distributions for different years. The parameter x_0 is based on the yield guarantee standards specified in local policy agricultural insurance. Parameters s_1、 s_2 and r which are related to agricultural loans and subsidies, are determined by consulting relevant experts and aligning with bank loan policies.)

5.1 Impact of Government Subsidy Rates

Due to the complexity of the model, it is difficult to derive the impact of government disaster-year subsidy rates on insurance premiums and farmers' CVaR values. Therefore, numerical simulations are used to analyze the effects of government disaster-year subsidy rates. Figure 1 shows that under loan guarantee insurance: When $\eta \in [1-k_L, 1)$, the insurance premium rate does not change with the government disaster-year subsidy rate. When $\eta \in [0, 1-k_L)$, the insurance premium rate increases as the government disaster-year subsidy rate rises because farmers' production scales also expand, which increases the risks borne by insurance companies. Regarding farmers' CVaR values, government disaster-year subsidies directly increase farmers' CVaR values. For any risk aversion level, government disaster-year subsidies are always an additional source of income. Figure 2 demonstrates a similar impact under yield guarantee insurance: Government disaster-year subsidies also directly increase farmers' CVaR values. However, as the subsidy level increases, the growth rate of CVaR values gradually decreases. For highly risk-averse farmers, their CVaR values may even decrease. This is because the agreed yield level with the insurance company leads to higher production scales, which causes profits to be squeezed due to declining wholesale prices, ultimately reflecting as reduced CVaR values. From the figures, the maximum government disaster-year subsidy rate is 0.2 under loan guarantee insurance and 0.6 under yield guarantee insurance. When the subsidy rate exceeds the maximum value, farmers' profits in normal years become lower than in disaster years, leading to dissatisfaction among farmers in other regions. The difference in maximum subsidy rates arises from differences in insurance types. Under loan guarantee insurance, farmers' production scales are much larger than those under yield guarantee insurance. Thus, with the same subsidy rate, the actual subsidy amount under loan guarantee insurance is significantly higher than that under yield guarantee insurance.



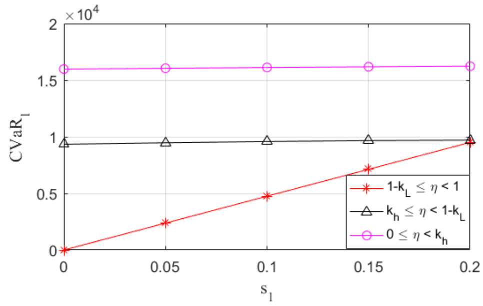


Fig. 1. Impact of Government Subsidies on Premium Rates and Farmers' CVaR under Loan Guarantee Insurance

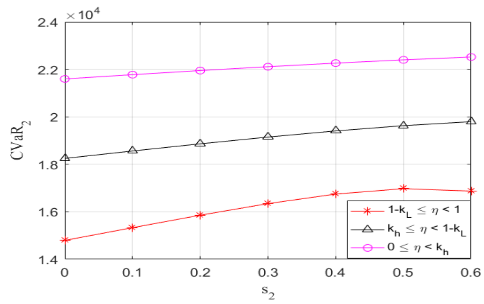


Fig. 2. Impact of Government Subsidies on Farmers' CVaR under Yield Guarantee Insurance

5.2 Impact of Bank Loan Interest Rates

In Fig. 3, as the interest rate r changes, β_1 gradually increases, albeit at a modest rate. According to the model, interest rate changes reduce farmers' cultivation scales but simultaneously increase their production costs. Wholesale prices also rise as cultivation scales decrease. Under these combined effects, the increase in farmers' profits is smaller than the increase in their costs, leading to a slight increase in insurance premium rates.

In Fig. 3 and Fig. 4, as interest rates rise, farmers' CVaR values generally decrease, except for highly risk-averse farmers under loan guarantee insurance. This observation aligns with intuition, as higher interest rates increase farmers' costs, reducing their CVaR values. However, in the case of highly risk-averse farmers under loan guarantee insurance, the situation differs. Here, the farmers' CVaR values derive from government subsidies. Higher costs result in larger government subsidy amounts, enabling farmers to benefit more from high interest rates.

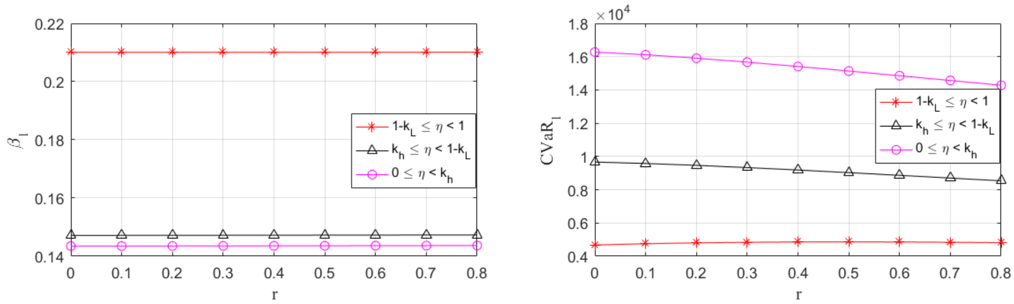


Fig. 3. Impact of Interest Rates on Premium Rates and Farmers' CVaR under Loan Guarantee Insurance

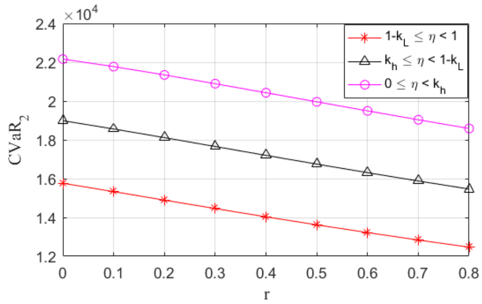


Fig. 4. Impact of Interest Rates on Farmers' CVaR under Yield Guarantee Insurance

5.3 Impact of Agricultural Product Greenness Levels

Proposition 5 indicates that increasing the greenness level of agricultural products leads to an increase in farmers' cultivation scale, higher wholesale prices for agricultural products, and enhanced distributor profits. Improving the greenness level of agricultural products means adopting more environmentally friendly and health-conscious production methods. As public awareness of ecological balance, sustainable development, and personal health grows, the demand for green agricultural products has risen significantly. Green agricultural products align better with market demand for healthy and safe food, earning consumers' trust and loyalty. Consumers are often willing to pay higher prices for green products. As the greenness level increases, distributors raise wholesale prices, encouraging farmers to cultivate more green agricultural products. This results in higher profits for farmers, increased cultivation scales, and rising distributor profits. Similarly, under yield guarantee insurance, the premium rate does not change with variations in bank loan interest rates.

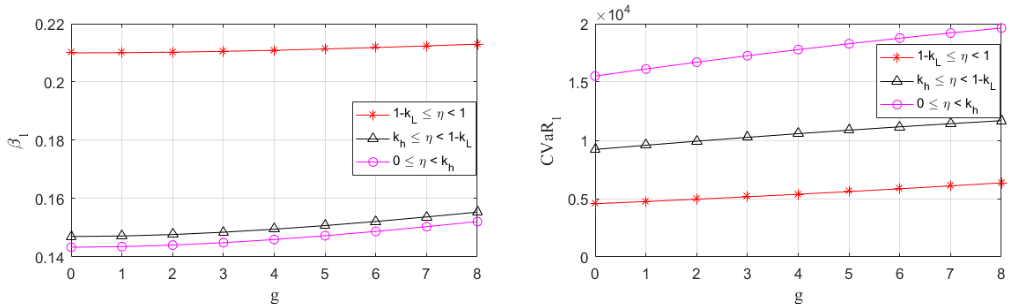


Fig. 5. Impact of Agricultural Product Greenness Levels on Premium Rates and Farmers' CVaR under Loan Guarantee Insurance

Fig. 5 and Fig. 6 illustrate that an increase in the greenness level of agricultural products leads to higher insurance premiums and CVaR values for farmers. For insurance companies, higher greenness levels increase both the farmers' potential profits and associated risks. When farmers incur losses, the insurance company must compensate higher amounts compared to regular agricultural products, prompting the insurance company to charge higher premiums to offset the risk. In this study, it is assumed that insurance costs are borne by the government. Therefore, the increase in insurance premiums does not raise farmers' costs. In all cases, as the greenness level increases, farmers' cultivation scales, wholesale prices, and profits rise significantly, leading to higher CVaR values for farmers.

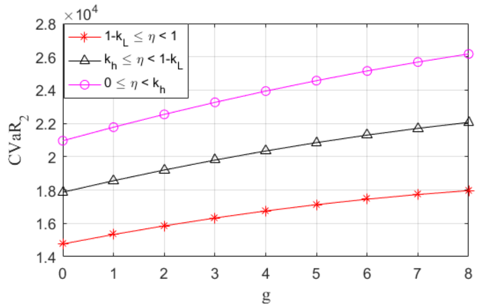
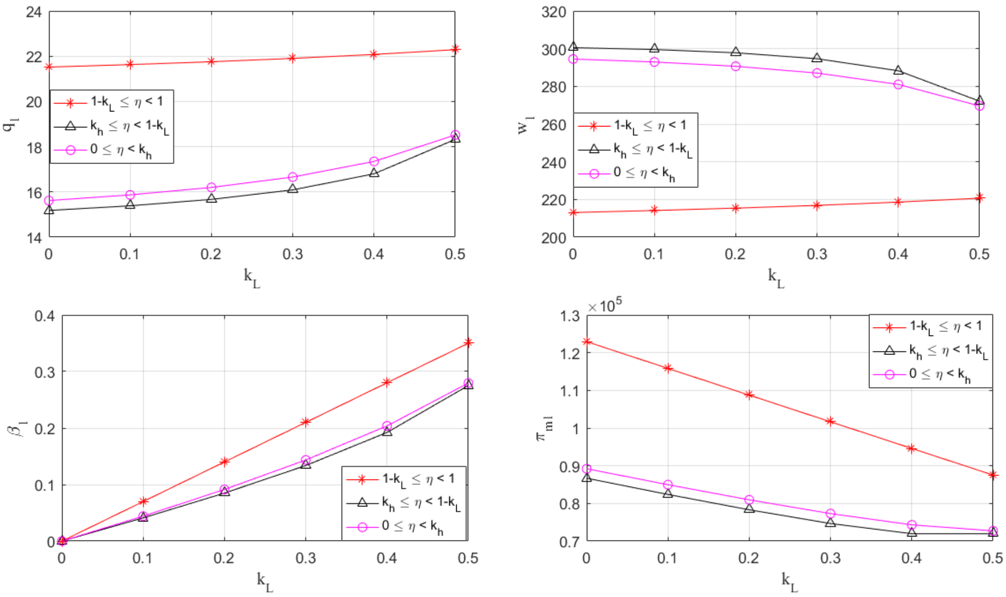


Fig. 6. Impact of Agricultural Product Greenness Levels on Farmers' CVaR under Yield Guarantee Insurance

5.4 Impact of Disaster-Year Probability

This section simulates disaster-year probabilities ranging from [0,0.7], while fixing k_H =0.3. To reflect moderate risk aversion $\eta \in [k_H, 1-k_L)$ among farmers, the risk aversion parameter η is set to 0.3.

In Fig. 7 under loan guarantee insurance: As the disaster-year probability k_L increases, farmers' cultivation scales also increase. Changes in k_L affect the expectations of yield μ and its square σ^2. Even if A_1 in Eq. (7) remains unchanged, variations in μ and σ^2 result in changes in q. Ultimately, this leads to increased cultivation scales for highly risk-averse farmers. Another factor contributing to the increased cultivation scale under loan guarantee insurance is that government subsidies and loan guarantee insurance provide a safety net for disaster years. For distributors, wholesale prices exhibit two opposing trends: On one hand, μ and σ^2 influence wholesale prices to increase. On the other hand, as farmers' cultivation scales expand, market prices for agricultural products decline, causing wholesale prices to drop. Distributors' profits are negatively impacted by the reduced expected yield μ. For farmers' CVaR values: As the disaster-year probability increases, the cultivation scale q of highly risk-averse farmers grows, and government subsidies rise. For other risk aversion levels, the decline in wholesale prices reduces CVaR values. If the disaster-year probability continues to rise, farmers' cultivation scales expand further, and wholesale prices fall more rapidly. The increase in k_L negatively affects farmers' normal-year profits, potentially turning them negative. When normal-year profits are lower than disaster-year profits, the government must intervene, or farmers should consider switching to alternative crops.



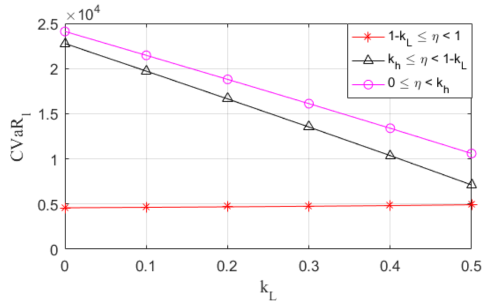


Fig. 7. Impact of Disaster-Year Probability on Loan Guarantee Insurance

Fig. 8 under yield guarantee insurance shows that farmers with high risk aversion levels exhibit an increasing trend in cultivation scale as disaster-year probabilities rise. This is also due to changes in μ (expected yield) and σ^2 (variance of yield). For farmers with other risk aversion levels, optimal production scales decrease as disaster-year probabilities increase, which aligns with common expectations. Similarly, wholesale prices move inversely to cultivation scales, resulting in reduced distributor profits. Regarding farmers' CVaR values: For highly risk-averse farmers, the presence of yield guarantee insurance increases their CVaR values as disaster-year probabilities rise. For farmers with lower risk aversion levels, CVaR values decrease with rising disaster-year probabilities.

From Fig. 7 and Proposition 4, it can be observed that insurance premium rates increase in line with disaster-year probabilities. As disaster years occur more frequently, both the probability and the magnitude of payouts by insurance companies increase. To maintain profitability, insurance companies raise premiums accordingly.

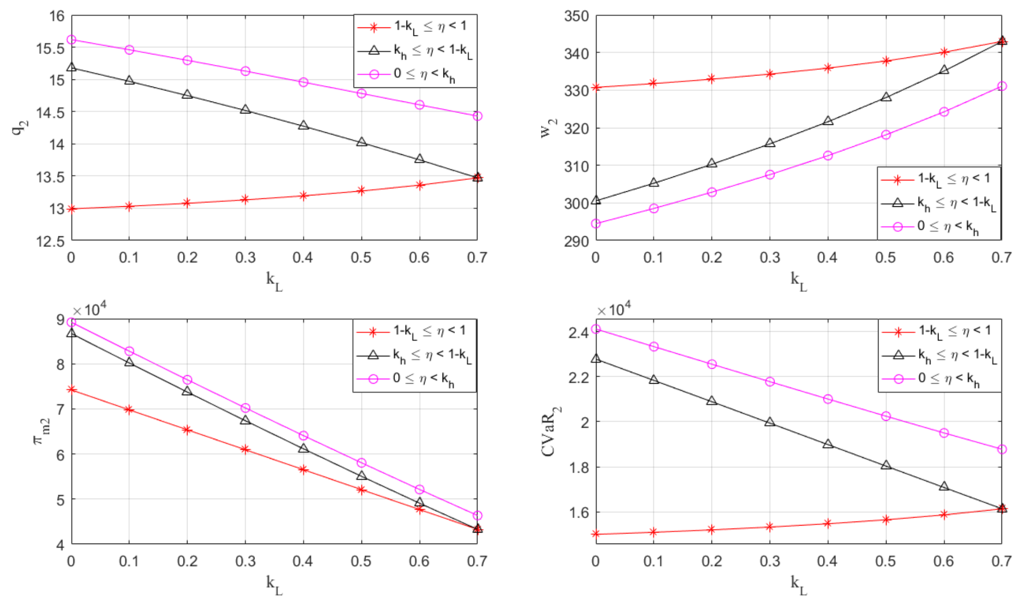


Fig. 8. Impact of Disaster-Year Probability on Yield Guarantee Insurance

5.5 Comparison of Loan Guarantee Insurance and Yield Guarantee Insurance

A key concern for farmers is determining which type of insurance to choose under different conditions. This section compares the efficiency of the two insurance types under varying disaster-year probabilities.This study evaluates the differences in optimal cultivation scale (Δq_i) and farmers' CVaR ($\Delta CVaR_i$) resulting from changes in disaster-year probabilities, where i=1,2.

From Fig. 9, it is evident that regardless of farmers' risk aversion levels, the increase in the optimal cultivation scale is always greater under loan guarantee insurance compared to yield guarantee insurance as disaster-year probabilities rise. In contrast, Figure 10 shows that the changes in CVaR values are more favorable under yield guarantee insurance. Thus, loan guarantee insurance is more effective in increasing farmers' cultivation scales, while yield guarantee insurance is better at improving farmers' CVaR values.

For policymakers, greater emphasis should be placed on minimum purchase price policies during disaster years. Such measures can help ensure higher returns for farmers who opt for loan guarantee insurance.

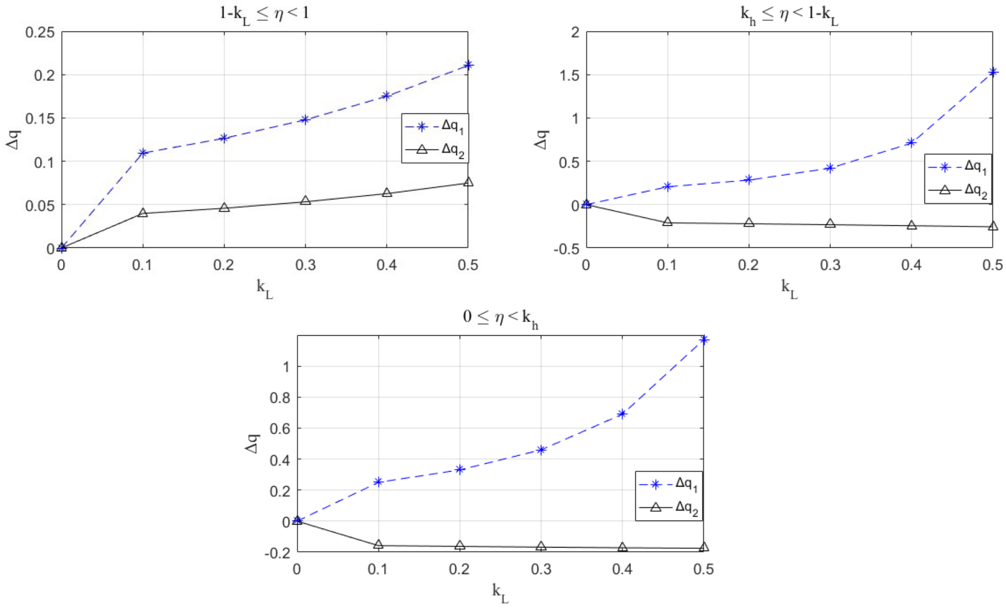


Fig. 9. Impact of Disaster-Year Probability on Changes in Cultivation Scale

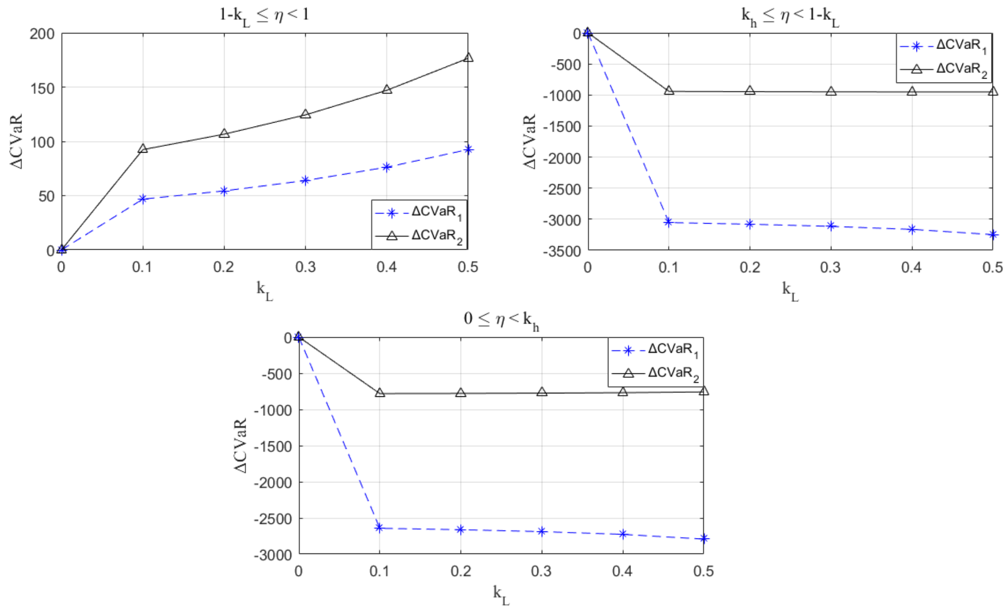


Fig. 10. Impact of Disaster-Year Probability on Changes in CVaR

6. Conclusions and Recommendations

This study examines a three-tier contract supply chain consisting of financially constrained farmers, distributors, and insurance companies. It considers the uncertainties in the output of green agricultural products and the behaviors of farmers with different risk aversion levels under loan guarantee insurance and yield guarantee insurance. The analysis focuses on the impacts of government subsidy rates, loan interest rates, greenness levels, and disaster-year probabilities on equilibrium decisions, farmers' CVaR, and distributors' profits. The main findings are as follows:

(1) Under specific conditions of loan guarantee insurance, farmers' optimal production scale remains at the maximum input level and does not increase further.
(2) Government disaster-year subsidies directly increase farmers' CVaR values. However, there is a maximum subsidy rate beyond which inequities may arise.
(3) Increasing the greenness level of agricultural products benefits farmers' production.
(4) For loan guarantee insurance: an increase in disaster-year probability affects normal-year farmers' profits, potentially causing them to become negative. The government may need to intervene or encourage farmers to switch crops. For yield guarantee insurance: while the insurance mechanism increases the value of highly risk-averse farmers with higher disaster probabilities, it decreases the value for others.
(5) As the disaster-year probability increases, loan guarantee insurance is more effective in expanding farmers' production

scales, while yield guarantee insurance better improves farmers' CVaR values.
Challenges also exist within agricultural supply chains. Farmers, as part of the supply chain, often rely on distributors for wholesale sales of their products. However, factors such as market demand and distributors' unilateral decision-making power can lead to distributors setting wholesale prices that squeeze farmers' profits, which are far below market retail prices. To ensure fair and reasonable profits for farmers, it is necessary to change the current practice of distributors determining wholesale prices, empowering farmers in the process. This would lead to more equitable profit distribution and improve the efficiency and sustainability of the entire agricultural supply chain.

The model presented in this paper has some limitations. Firstly, it does not fully account for distributors' sales, transportation, and storage costs, which may lead to overestimation of distributors' profits. Secondly, it does not incorporate product loss rates and perishability, creating some discrepancies between the model and real-world scenarios. Future research should integrate distributors' costs and agricultural product characteristics to improve the accuracy and practicality of supply chain models.

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Appendix

Loan Guarantee Insurance

First, let's discuss the farmer's profits. The profit in a disaster year is given by: $s_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$,

The profit in a normal year is: $w_1q_1x_N-(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$,

The profit in a bumper year is: $w_1q_1x_H-(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$.

In reality, the government subsidy will not exceed the farmer's normal-year profit, so the condition is: $w_1q_1x_N-(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)>s_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$

Condition: $\dfrac{w_1q_1x_N}{(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)}>1+s_1$

Let $g(q_1,v)=v+\dfrac{1}{1-\eta}E\left[\min\left(\pi_{f1}-v,0\right)\right]$

$$g(q_1,v)=\begin{cases} v, v\leqslant v_1 \\ v-\dfrac{k_L}{1-\eta}\left[v-s_1(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right], & v_1<v\leqslant v_2 \\ v-\dfrac{k_L}{1-\eta}\left[v-s_1(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right] \\ -\dfrac{k_N}{1-\eta}\left[v-w_1q_1x_N+(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right], & v_2<v\leqslant v_3 \\ v-\dfrac{k_L}{1-\eta}\left[v-s_1(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right] \\ -\dfrac{k_N}{1-\eta}\left[v-w_1q_1x_N+(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right] \\ -\dfrac{k_H}{1-\eta}\left[v-w_1q_1x_H+(1+r)\left(c_1q_1^2+\dfrac{1}{2}c_2g^2\right)\right], & v>v_3 \end{cases}$$

where $v_1=s_1(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$, $v_2=w_1q_1x_N+(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$, $v_3=w_1q_1x_H+(1+r)\left(c_1q_1^2+\frac{1}{2}c_2g^2\right)$.

$$\frac{\partial g(q_1,v)}{\partial v}=\begin{cases} 1, & v\leqslant v_1 \\ 1-\dfrac{k_L}{1-\eta}, & v_1<v\leqslant v_2 \\ 1-\dfrac{k_L+k_N}{1-\eta}, & v_2<v\leqslant v_3 \\ 1-\dfrac{1}{1-\eta}, & v>v_3 \end{cases}$$

When $k_N + k_H \leqslant \eta < 1$, $1-\eta > 0$, $1-\frac{k_L}{1-\eta} \leqslant 0$, $1-\frac{k_L+k_N}{1-\eta} < 0$, and $1>0$, Thus $v^* = v_1$. When $k_H \leqslant \eta < k_H + k_N$, $1-\frac{k_L}{1-\eta} > 0$, $1-\frac{k_L+k_N}{1-\eta} < 0$, Thus $v^* = v_2$. When $0 \leqslant \eta < k_H$, $1-\frac{k_L}{1-\eta} > 0$, $1-\frac{k_L+k_N}{1-\eta} > 0$, and $1-\frac{1}{1-\eta} < 0$, Thus $v^* = v_3$.

$$g\left(q_1, v^*\right) = \begin{cases} s_1\left(1+r\right)\left(c_1 q_1^2 + \frac{1}{2}c_2 g^2\right), & 1-k_L \leqslant \eta < 1 \\ w_1 q_1 x_N - \left(1+r\right)\left(c_1 q_1^2 + \frac{1}{2}c_2 g^2\right) - \frac{k_L}{1-\eta}, & k_H \leqslant \eta < 1-k_L \\ w_1 q_1 x_H - \left(1+r\right)\left(c_1 q_1^2 + \frac{1}{2}c_2 g^2\right) - \frac{k_L}{1-\eta}\left(w_1 q_1 x_H - \left(1+s_1\right)\left(1+r\right)\left(c_1 q_1^2 + \frac{1}{2}c_2 g^2\right)\right) & \\ -\frac{k_N}{1-\eta}\left[w_1 q_1\left(x_H - x_N\right)\right], & 0 \leqslant \eta < k_H \end{cases} \quad 1-k_L \leqslant \eta < 1,$$

$\frac{dg\left(q_1, v^*\right)}{dq_1} = 2s_1\left(1+r\right)c_1 q_1$, $\frac{dg\left(q_1, v^*\right)^2}{dq^2} = 2s_1\left(1+r\right)c_1 > 0$, $\frac{dg\left(q_1, v^*\right)}{dq_1} > 0$, is an increasing function, $q_1^* = q_{\max}$.

When $k_H \leqslant \eta < 1-k_L$:

$\frac{dg\left(q_1, v^*\right)}{dq_1} = \frac{w_1 x_N\left(1-\eta-k_L\right) - 2c_1 q_1\left(1+r\right)\left[1-\eta-k_L\left(1+s_1\right)\right]}{1-\eta}$, $\frac{dg\left(q_1, v^*\right)^2}{dq_1^2} = -\frac{2c_1\left(1+r\right)\left[1-\eta-k_L\left(1+s_1\right)\right]}{1-\eta}$, When $s_1 < \frac{1-\eta-k_L}{k_L}$, $\frac{dg\left(q_1, v^*\right)^2}{dq_1^2} < 0$, Let $\frac{dg\left(q_1, v^*\right)}{dq_1} = 0$, $q_1^* = \frac{\left(1-\eta-k_L\right)w_1 x_N}{2c_1\left(1+r\right)\left[1-\eta-k_L\left(1+s\right)\right]}$

When $s_1 \geqslant \frac{1-\eta-k_L}{k_L}$, $\frac{dg\left(q_1, v^*\right)}{dq_1} > 0$, $q_1^* = q_{\max}$.

$0 \leqslant \eta < k_H$, the result is similar to the case above. $k_H \leqslant \eta < 1-k_L$.

When $s_1 < \frac{1-\eta-k_L}{k_L}$, $q_1^* = \frac{\left(1-\eta-k_L\right)w_1 x_H - k_N w_1\left(x_H - x_N\right)}{2c_1\left(1+r\right)\left[1-\eta-k_L\left(1+s\right)\right]}$,

If $s_1 \geqslant \frac{1-\eta-k_L}{k_L}$, $\frac{dg\left(q_1, v^*\right)}{dq_1} > 0$, $q_1^* = q_{\max}$.

Now, we seek to determine that $q_{\max}$, in this paper, it is assumed that farmers will go bankrupt in disaster years, but not in normal years. Therefore, $q_{\max}$ the condition is satisfied:

$$w_1 q_1 x_N - \left[\left(1+r\right)\left(c_1 q_1^2 + \frac{1}{2}c_2 g^2\right)\right] \geqslant 0,$$

$$q_{\max} = \frac{w_1 x_N + \sqrt{\left(w_1 x_N\right)^2 - 2c_1 c_2 g^2\left(1+r\right)^2}}{2c_1\left(1+r\right)},$$

to calculate the optimal solution w for the distributor in the next section, we ignore $c_1 c_2 g^2\left(1+r\right)^2$ certain factors, thus: $q_{\max} = \frac{w_1 x_N}{c_1\left(1+r\right)}$

For the distributor, the objective is: $\frac{\partial \pi_{m1}}{\partial w_1} = -q_1\mu + \left(a - w_1 + \lambda g\right)\mu\frac{\partial q_1}{\partial w_1} - 2b\sigma^2 q_1\frac{\partial q_1}{\partial w_1}$, While $q_1 = A_1 w_1$.

$$\frac{\partial \pi_{m1}^2}{\partial w_1^2} = -2A_1\mu - 2b\sigma^2 A_1^2 < 0, \quad \text{Thus } w_1^* = \frac{\left(a+\lambda g\right)\mu}{2\left(b\sigma^2 A_1 + \mu\right)}.$$

For the insurance company's optimal solution:

$\pi_{g1} = 0$ get the optimal premium

Yield Guarantee Insurance

$$v_1 = w_2 q_2 x_0 - (1-s_2)(1+r)\left(c_1 q_2^2 + \frac{1}{2}c_2 g^2\right),$$

The farmer's profit in a disaster year is:

$$v_2 = w_2 q_2 x_N - (1+r)\left(c_1 q_2^2 + \frac{1}{2}c_2 g^2\right),$$

The profit in a normal year is:

$$v_3 = w_2 q_2 x_H - (1+r)\left(c_1 q_2^2 + \frac{1}{2}c_2 g^2\right).$$

The profit in a bumper year is:

$$v_3 = w_2 q_2 x_H - (1+r)\left(c_1 q_2^2 + \frac{1}{2}c_2 g^2\right).$$

$$g(q_2, v) = \begin{cases} v, & v \leqslant v_1 \\ v - \dfrac{k_L}{1-\eta}\left[v - w_2 q_2 x_0 + (1-s_2)(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right], & v_1 < v \leqslant v_2 \\ v - \dfrac{k_L}{1-\eta}\left[v - w_2 q_2 x_0 + (1-s_2)(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right] \\ -\dfrac{k_N}{1-\eta}\left[v - w_2 q_2 x_N + (1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right], & v_2 < v \leqslant v_3 \\ v - \dfrac{k_L}{1-\eta}\left[v - w_2 q_2 x_0 + (1-s_2)(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right] \\ -\dfrac{k_N}{1-\eta}\left[v - w_2 q_2 x_N + (1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right] \\ -\dfrac{k_H}{1-\eta}\left[v - w_2 q_2 x_H + (1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right], & v > v_3 \end{cases}$$

Similar to the loan guarantee insurance proof:, $v^* = v_1, v_2, v_3$,

$$g(q_2, v^*) = \begin{cases} w_2 q_2 x_0 - (1-s_2)(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right), & 1-k_L \leqslant \eta < 1 \\ w_2 q_2 x_N - (1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right) \\ -\dfrac{k_L\left[w_2 q_2 (x_N - x_0) - s_2(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right]}{1-\eta}, & k_H \leqslant \eta < 1-k_L \\ w_2 q_2 x_H - (1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right) \\ -\dfrac{k_L\left[w_2 q_2 (x_H - x_0) - s_2(1+r)\left(c_1 q_2^2 + \dfrac{1}{2}c_2 g^2\right)\right]}{1-\eta} \\ -\dfrac{k_N\left[w_2 q_2 (x_H - x_N)\right]}{1-\eta}, & 0 \leqslant \eta < k_H \end{cases}$$

When $1-k_L \leqslant \eta < 1$:

$$\frac{\partial g(q_2, v^*)}{\partial q_2} = w_2 x_0 - 2(1-s_2)(1+r)c_1 q,$$

$$\frac{\partial g(q_2, v^*)^2}{\partial q_2^2} = -2c_1(1-s_2)(1+r) < 0, \quad q_2^* = \frac{w_2 x_0}{2c_1(1+r)(1-s_2)}$$

When $k_H \leqslant \eta < 1-k_L$:

$$\frac{\partial g\left(q_2,v^*\right)}{\partial q_2}=w_2x_N-2\left(1+r\right)c_1q_2-\frac{k_L\left[w_2\left(x_N-x_0\right)-2s_2c_1q_2\left(1+r\right)\right]}{1-\eta} \\ =\frac{\left(1-\eta\right)w_2x_N-k_Lw_2\left(x_N-x_0\right)-2\left[\left(1-\eta\right)-s_2k_L\right]c_1q_2\left(1+r\right)}{1-\eta}$$

$$\frac{\partial g\left(q_2,v^*\right)^2}{\partial q_2^2}=-\frac{2c_1\left[1-\eta-s_2k_L\right]\left(1+r\right)}{1-\eta}<0$$

$$q_2^*=\frac{\left(1-\eta\right)w_2x_N-k_Lw_2\left(x_N-x_0\right)}{2c_1\left(1+r\right)\left[1-\eta-s_2k_L\right]}$$

When $0 \leqslant \eta < k_H$:

$$\frac{\partial g\left(q_2,v^*\right)}{\partial q_2}=w_2x_H-2c_1q_2\left(1+r\right)-\frac{k_L\left[w_2\left(x_H-x_0\right)-2c_1q_2s_2\left(1+r\right)\right]}{1-\eta} \\ -\frac{k_N\left[w_2\left(x_H-x_N\right)\right]}{1-\eta}$$

$$\frac{\partial g\left(q_2,v^*\right)^2}{\partial q_2^2}=-\frac{2c_1\left[1-\eta-s_2k_L\right]\left(1+r\right)}{1-\eta}<0;$$

$$q_2^*=\frac{\left(1-\eta\right)w_2x_H-k_Lw_2\left(x_H-x_0\right)-k_Nw_2\left(x_H-x_0\right)}{2c_1\left(1+r\right)\left[1-\eta-s_2k_L\right]}.$$

For the distributor:

$$\frac{\partial \pi_{m2}}{\partial w_2}=-q_2\mu+\left(a-w_2+\lambda g\right)\mu\frac{\partial q_2}{\partial w_2}-2b\sigma^2q_2\frac{\partial q_2}{\partial w_2}, \text{While } q_2=A_2w_2 。$$

$$\frac{\partial \pi_{m2}^2}{\partial w_2^2}=-2A_2\mu-2b\sigma^2A_2^2<0, \quad \text{Thus } w_2^*=\frac{\left(a+\lambda g\right)\mu}{2\left(b\sigma^2A_2+\mu\right)}.$$

Similarly, the insurance company's optimal premium rate $\pi_{g2}=0$ is derived accordingly.