

Government Subsidy Strategy Considering Weather Options under Adverse Weather Conditions

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Abstract: Under the joint impact of adverse weather and demand uncertainty, fresh agricultural product supply chains (FAPSCs) face significant challenges, including yield volatility, quality deterioration, and price instability. To address these issues, this paper develops a two-echelon supply chain model consisting of an agricultural cooperative and a retailer. A weather index is introduced to capture the joint effects of weather conditions on both yield and product quality, while weather options are incorporated as financial instruments for risk hedging. We consider three policy scenarios: no government subsidy, subsidies to the agricultural cooperative, and subsidies to the retailer. A Stackelberg game framework is established to analyze the optimal decisions of supply chain members and evaluate their economic performance under different subsidy schemes. The results show that adverse weather reduces agricultural input investment and leads to higher wholesale and retail prices, thereby decreasing supply chain profits and social welfare. Government subsidies can effectively mitigate the negative impacts of weather uncertainty. Moreover, different subsidy schemes have heterogeneous effects, and subsidizing the agricultural cooperative is more effective in reducing wholesale prices, increasing input investment, and improving overall social welfare. In addition, weather options significantly enhance the supply chain's ability to hedge weather risks and improve system stability. This study provides theoretical insights for optimizing government subsidy policies and integrating financial derivatives into agricultural risk management.

Keywords: Agricultural product supply chain, adverse weather, weather index, weather options, government subsidies.

1. Introduction

Agricultural product supply chains (APSCs) are characterized by high perishability and strong dependence on natural conditions, making their operations highly vulnerable to various sources of uncertainty. Among these, adverse weather conditions represent one of the most critical exogenous risk factors. Extreme temperature, drought, cold waves, and abnormal precipitation not only reduce agricultural yield but also deteriorate product quality, thereby amplifying fluctuations in market supply and price instability. Under the joint effects of stochastic demand and weather shocks, both supply chain members' profitability and overall social welfare may be significantly affected.

To address these challenges, governments commonly intervene in agricultural production and distribution through fiscal subsidies to stabilize market supply. In recent years, with the development of financial derivatives in agricultural risk management, weather options have gained increasing attention as an effective hedging instrument. Weather options can transform non-tradable weather risk into tradable financial risk, thereby providing a practical mechanism for mitigating uncertainty faced by agricultural producers and retailers. However, due to their associated costs, reliance solely on market mechanisms may lead to insufficient participation, making the integration of government subsidies and weather options particularly meaningful.

Motivated by this context, this paper develops a two-echelon APSC consisting of an agricultural cooperative and a retailer under stochastic demand and weather uncertainty. We investigate optimal government subsidy strategies under two scenarios: subsidizing the agricultural cooperative or subsidizing the retailer. Meanwhile, weather options are introduced as a risk-hedging instrument. A Stackelberg game framework is employed to analyze optimal decisions, profit

outcomes, and social welfare under different policy schemes, and to compare the effectiveness of alternative subsidy mechanisms.

The main contributions of this paper are threefold. First, a weather index is introduced into the FAPSC model to jointly capture the impact of weather on both yield and quality. Second, a coordinated framework combining fiscal subsidies and weather options is developed to integrate governmental policy tools with financial risk hedging instruments. Third, a systematic comparison of subsidy schemes is conducted from a supply chain perspective, providing theoretical insights for optimizing agricultural risk management policies.

2. Literature Review

2.1. Agricultural Product Supply Chain under Uncertainty

Agricultural product supply chains (APSCs) have attracted extensive attention due to product perishability, short shelf life, and quality sensitivity to environmental conditions. Early studies focused on inventory management, pricing, and coordination mechanisms. For instance, Liu and Chen [1] developed an integrated production–distribution model, while Muriana [2] investigated optimal pricing strategies for perishable products under stochastic demand. However, most of these studies primarily focus on demand uncertainty, while neglecting environmental shocks, particularly weather-related risks.

2.2. Weather Risk in Agricultural Production

Weather uncertainty has been increasingly recognized as a critical factor in agricultural production. Sall [3] and Peng et al. [4] show that temperature and precipitation significantly affect crop yield. Kazaz et al. [5] introduce weather indices to quantify agricultural risk and incorporate them into

optimization models. However, most existing studies focus on production-side analysis and lack a systematic supply chain perspective.

2.3. Weather Derivatives and Agricultural Risk Management

Weather derivatives have emerged as important financial instruments for managing weather-related risks. Omkar and Palsule-Desai [6] provide a comprehensive framework for pricing weather derivatives, while Zheng et al. [7] analyze the effectiveness of weather futures in hedging agricultural risks. Yu and Sumner [8] further demonstrate that weather insurance and options can significantly reduce income volatility. Nevertheless, few studies integrate weather options into supply chain decision-making frameworks.

2.4. Government Subsidies and Supply Chain Coordination

Government subsidies play a crucial role in agricultural policy and supply chain coordination. Srivastava and Wood [9] study coordination mechanisms such as revenue-sharing contracts. Cheng et al. [10-12] investigate the impact of subsidies on agricultural supply chain efficiency and find that subsidies can improve production decisions. However, comparative analysis of subsidy allocation schemes between producers and retailers remains limited.

2.5. Research Gap

In summary, existing literature has explored supply chain management, weather risk modeling, financial derivatives, and government subsidy policies separately. However, several gaps remain: (1) lack of an integrated modeling framework incorporating weather indices in FAPSC; (2) insufficient integration of weather options into supply chain decision-making; (3) limited study on the interaction between government subsidies and financial hedging instruments; (4) lack of comparative analysis on subsidy allocation strategies and their welfare implications. To address these gaps, this paper develops a two-echelon FAPSC model integrating weather indices, weather options, and government subsidy mechanisms.

3. Problem Description and Assumptions

Agricultural production is highly susceptible to adverse weather conditions. Such unfavorable weather not only reduces the yield of agricultural products but also deteriorates their quality. To mitigate the losses incurred by supply chain members due to adverse weather, the government provides a series of fiscal subsidies to support agricultural production.

Under demand uncertainty, this paper considers the impact of adverse weather on both the yield and quality of agricultural products. We examine a two-echelon supply chain composed of an agricultural cooperative (F) and a retailer (R). The decision-making process is modeled as a two-stage sequential game. In the first stage, the agricultural cooperative determines the level of agricultural input investment I . In the second stage, the retailer decides the wholesale price w and purchases all agricultural products produced by the cooperative. Finally, the retailer sells the products to consumers (C) at a retail price p .

The government (G) provides weather option subsidies to both the agricultural cooperative and the retailer, aiming to

incentivize them to purchase weather options from external financial markets. This mechanism enables supply chain members to hedge against the risks and losses caused by adverse weather conditions.

In this paper, according to Fu et al [13], a weather index r is employed to characterize weather conditions, such as temperature, rainfall, and sunlight. Due to the relatively homogeneous nature of agricultural products, the suitable range of the weather index for crop growth is denoted as $r \in (\underline{r}, \bar{r}) \subset [\underline{r}, \bar{r}]$. All weather-related variables, including \underline{r} , \bar{r} , \underline{r} , \bar{r} are treated as exogenous. Specifically, \underline{r} and \bar{r} represent the lower and upper bounds of the weather index that are suitable for crop growth, respectively, while \underline{r} and \bar{r} denote the lower and upper bounds of non-catastrophic adverse weather conditions occurring in nature.

Basic Assumptions

The fundamental assumptions of this paper are as follows: Assumption 1.

(1) The analysis focuses on a specific region and a single type of agricultural product.

(2) All parties involved are rational and risk-neutral.

(3) The residual value of unsold agricultural products and the loss caused by stockouts are not considered.

(4) Information is assumed to be common knowledge among all parties.

Assumption 2.

Let I denote the level of agricultural input, where $I \in [0,1]$. The total production cost increases with the level of input and exhibits a marginally increasing trend. The total production cost incurred by the agricultural cooperative is given by $C(I) = cI^2$ where c is the cost coefficient. ($c > 0$).

Assumption 3.

Refereeing Tang et al [14], The yield of agricultural products is denoted by $Q(I, r) = Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}$, where Q_0 represents the maximum potential yield, and $Q(I, r) \in [0,1]$ is the yield factor affected by adverse weather conditions and the level of agricultural input. It is assumed that $Q(I, r) \in [0,1]$.

Assumption 4.

Refereeing Shi et al [15], The market demand for agricultural products is given by $D = \theta a p^{-b} \varepsilon$, ($a > 0, b > 1$), where a measures the market size and is assumed to be a constant, and b denotes the price elasticity of demand with respect to the retail price P . Let $\theta(I, r) = I^{\frac{1}{2}} t^{-\beta(r-\bar{r})}$ represent the quality factor, which is affected by adverse weather conditions and the level of agricultural input, where $0 \leq \theta \leq 1$. In addition, ε is a continuous random variable capturing demand uncertainty that is independent of the retail price and product quality. Its probability density function and cumulative distribution function are denoted by $g(x)$ and $G(x)$ respectively, where $g(x) > 0$ and $G(x) \in (0,1)$. Furthermore, the random variable x assumed to satisfy the Increasing Generalized Failure Rate (IGFR) property, i.e., $\frac{xg(x)}{G(x)}$ is increasing in x .

Notation

The main notations used in this paper are defined as follows. Subscript F and R represent the agricultural cooperative and the retailer, respectively. Superscripts $i = \{N, A, S\}$ are used to distinguish different scenarios: N denotes the case without government subsidies, A represents the case where the government subsidizes the agricultural cooperative, and S

denotes the case where the government subsidizes the retailer.

4. Model Formulation

4.1. No Government Subsidy

In the supply chain, both the agricultural cooperative and the retailer aim to maximize their own profits. Given the dominant position of the agricultural cooperative in the market, the decision-making process is modeled as a two-stage sequential game. Specifically, the agricultural cooperative first determines the level of agricultural input I . Then, the retailer decides the wholesale price w and purchases all agricultural products produced by the cooperative. Finally, the retailer sells the products to consumers C at the retail price p .

Consumer surplus is defined as the difference between the maximum price that consumers are willing to pay for a given quantity of a product and the actual market price paid for that product.

Under the no-subsidy scenario, the expected profit of the agricultural cooperative, the expected profit of the retailer, consumer surplus, and the overall social welfare, denoted by π_F^N , π_R^N , CS^N and respectively, are given as follows:

$$\pi_F^N(I) = WQ_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} - cI^2$$

$$\pi_R^N(w, p) = pE \left\{ \min \left(Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}, I^{\frac{1}{2}} t^{-\beta(r-\bar{r})} a p^{-b} \varepsilon \right) \right. \\ \left. - WQ_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} \right\}$$

$$CS^N = \int_p^{+\infty} (x - p) \phi(x) dx$$

$$SW^N = \pi_F^N + \pi_R^N + CS^N$$

Here, $\phi(x) = I^{\frac{1}{2}} t^{-\beta(r-\bar{r})} a x^{-b} \varepsilon$ denotes the probability density function of demand. Under the constraint $0 < w < p$ both the agricultural cooperative and the retailer make decisions to maximize their respective profits. The above game model is solved using backward induction.

Furthermore, we define the inventory factor as $Z = \frac{Q_0}{ap^{-b}} \left(\frac{k}{t} \right)^{-\beta(r-\bar{r})}$. By selecting the optimal retail price p the problem can be equivalently transformed into choosing the optimal inventory factor Z . After this transformation,

substituting $p = \left(\frac{za}{Q_0 \left(\frac{k}{t} \right)^{-\beta(r-\bar{r})}} \right)^{\frac{1}{b}}$ into π_R^N and simplifying

yields: $\pi_R^N(z) = (za t^{-\beta(r-\bar{r})})^{\frac{1}{b}} (Q_0 k^{-\beta(r-\bar{r})})^{1-\frac{1}{b}} I^{\frac{1}{2}} (\bar{G}(z) + \int_0^z \frac{x}{z} g(x)) - WQ_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}$.

By analyzing $\frac{\partial \pi_R^N}{\partial z}$ and utilizing the Increasing Generalized Failure Rate (IGFR) property of ε , we obtain the following lemma.

Lemma 1.

The optimal z^* is uniquely determined by $\int_0^z (b-1)xg(x)dx = z(1-G(x))$.

Based on the result of Lemma 1, the above no-subsidy game model can be solved using backward induction, leading to the following theorem.

Theorem 1.

(1) The equilibrium decisions of the agricultural product supply chain are given by:

$$I^{N*} = \left(\frac{b\eta \bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})}}{4c(b-1)} \right)^{\frac{2}{3}}, \quad p^{N*} = \eta, \quad w^{N*} = \frac{b\eta \bar{G}(z^*)}{4(b-1)};$$

$$\text{Among them } \eta = \left(\frac{z^* a}{Q_0 \left(\frac{k}{t} \right)^{-\beta(r-\bar{r})}} \right)^{\frac{1}{b}}$$

(2) The equilibrium expected profit of the agricultural cooperative, the equilibrium expected profit of the retailer, consumer surplus, and social welfare are given by:

$$\pi_F^{N*} = \frac{(b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})} - 4c(b-1))}{8(b-1)} \gamma$$

$$\pi_R^{N*} = \frac{3b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{8(b-1)} \gamma$$

$$CS^{N*} = \frac{b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{2(b-1)^2} \gamma$$

$$SW^{N*} = \frac{b^2 \bar{G}(z^*) \eta Q_0 k^{-\beta(r-\bar{r})} - c(b-1)^2}{2(b-1)^2} \gamma$$

$$\text{Where, } \gamma = \left[\frac{2b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{c(b-1)} \right]^{\frac{1}{3}}$$

4.2. Government Subsidy for the Agricultural Cooperative

To incentivize the agricultural cooperative to purchase weather options from financial markets and thereby mitigate losses caused by adverse weather conditions such as high temperature, drought, and cold waves, the government provides a per-unit weather option subsidy for each unit of agricultural product produced by the cooperative.

The cost of purchasing a unit weather option from the financial market is denoted by λ . Within the contractual arrangement, if the average temperature experienced during production exceeds a threshold level \bar{r} , the agricultural cooperative receives a subsidy. For each unit increase in average temperature above this threshold, the cooperative obtains a subsidy of λ with an upper bound on the per-unit subsidy of $\hat{\lambda}$. Therefore, the net benefit obtained by the agricultural cooperative from purchasing weather options is given by $n_F \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - \lambda \}$, where n_F represents the quantity of weather options purchased by the agricultural cooperative.

The agricultural cooperative plays a dominant role in the market. The decision-making process is modeled as a two-stage Stackelberg game. First, based on the government's announced subsidy policy, the agricultural cooperative determines its level of agricultural input investment and purchases weather options from financial markets to hedge against losses caused by adverse weather conditions in agricultural production. Second, the retailer maximizes its own profit by determining the wholesale price and retail price.

Under the scenario of government subsidies to the agricultural cooperative, the expected profit of the agricultural cooperative, the expected profit of the retailer, consumer surplus, social welfare, and government expenditure, respectively, are given as follows:

$$\pi_F^A(I) = (W + \Gamma_F) Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} - cI^2 \\ + n_F E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - \lambda \}$$

$$\begin{aligned}\pi_R^A(w, p) &= pE_\varepsilon \left\{ \min \left(Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}, I^{\frac{1}{2}} t^{-\beta(r-\bar{r})} a p^{-b} \varepsilon \right) \right. \\ &\quad \left. - W Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} \right\} \\ CS^A &= \int_p^{+\infty} (x - p) \phi(x) dx \\ SW^A &= \pi_F^A + \pi_R^A + CS^A \\ GS^A &= \Gamma_F Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}\end{aligned}$$

Based on the result of Lemma 1, the above game model under the no-government-subsidy scenario can be solved using backward induction, yielding the following theorem.

Theorem 2.

(1) The equilibrium decisions of the agricultural product supply chain are given by:

$$I^{A*} = \frac{\xi^2}{4}, \quad p^{A*} = \eta, \quad w^{A*} = \frac{b\bar{G}(z^*)}{4(b-1)};$$

(2) The equilibrium expected profit of the agricultural cooperative, the equilibrium expected profit of the retailer, consumer surplus, social welfare, and government expenditure are given by:

$$\begin{aligned}\pi_F^{A*} &= \frac{Q_0 k^{-\beta(r-\bar{r})} (b\bar{G}(z^*)\eta + 4\Gamma_F(b-1)) - 4c(b-1)}{8(b-1)} \xi \\ &\quad + n_R E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \} \\ \pi_R^{A*} &= \frac{3b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{8(b-1)} \xi \\ CS^{A*} &= \frac{b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{2(b-1)^2} \xi \\ SW^{A*} &= \frac{Q_0 k^{-\beta(r-\bar{r})} (b^2\bar{G}(z^*)\eta + \Gamma_F(b-1)^2)}{2(b-1)^2} \xi \\ &\quad + n_R E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \} \\ GS^{A*} &= \frac{Q_0 k^{-\beta(r-\bar{r})} \Gamma_F}{2} \xi \\ \text{Where } \xi &= \left[\frac{2Q_0 k^{-\beta(r-\bar{r})} (b\bar{G}(z^*)\eta + 4\Gamma_F(b-1))}{c(b-1)} \right]^{\frac{1}{3}}\end{aligned}$$

4.3. Government Subsidy for the Retailer

Adverse weather conditions not only affect the yield of agricultural products but also deteriorate their quality, thereby influencing the retailer's ability to sell these products in the market. To incentivize the retailer to purchase weather options from financial markets and hedge against such risks, the government provides financial subsidies to the retailer.

The government provides a per-unit weather option subsidy Γ_R for each unit of agricultural product purchased by the retailer. The cost of purchasing a unit weather option from the financial market is denoted by A .

Within the contractual arrangement, if the average temperature experienced during the production process exceeds a threshold level \bar{r} , the retailer receives a subsidy. For each unit increase in average temperature above this threshold, the retailer obtains a subsidy of λ , with a maximum per-unit subsidy cap of $\hat{\lambda}$. Therefore, the final net benefit obtained by the retailer from purchasing weather options is given by $n_R \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \}$. where n_R represents the quantity of weather options purchased by the retailer.

Under the scenario of government subsidies to the retailer, the expected profit of the agricultural cooperative, the expected profit of the retailer, consumer surplus, social welfare, and government expenditure respectively are given as follows:

$$\begin{aligned}\pi_F^S(I) &= W Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} - cI^2 \\ \pi_R^S(w, p) &= (p + \Gamma_R) E \left\{ \min \left(Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}, I^{\frac{1}{2}} t^{-\beta(r-\bar{r})} a p^{-b} \varepsilon \right) \right. \\ &\quad \left. - W Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})} + n_R E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \} \right\} \\ CS^S &= \int_p^{+\infty} (x - p) \phi(x) dx \\ SW^S &= \pi_F^S + \pi_R^S + CS^S \\ GS^S &= \Gamma_R E \left\{ \min \left(Q_0 I^{\frac{1}{2}} k^{-\beta(r-\bar{r})}, I^{\frac{1}{2}} t^{-\beta(r-\bar{r})} a p^{-b} \varepsilon \right) \right\}\end{aligned}$$

The above game model is solved using backward induction, yielding the following theorem.

Theorem 3.

(1) The equilibrium decisions of the agricultural product supply chain are given by:

$$I^{S*} = \left(\frac{(\eta + \Gamma_R) b \bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})}}{4c(b-1)} \right)^{\frac{2}{3}}, \quad p^{S*} = \eta, \quad w^{S*} = \frac{b\bar{G}(z^*)}{4(b-1)} (\eta + \Gamma_R);$$

(2) The equilibrium expected profit of the agricultural cooperative, the equilibrium expected profit of the retailer, consumer surplus, social welfare, and government expenditure are given by:

$$\begin{aligned}\pi_F^{S*} &= \frac{(\eta + \Gamma_R) b \bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})} - 4c(b-1)}{8(b-1)} \psi \\ \pi_R^{S*} &= \frac{3(\eta + \Gamma_R) b \bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})}}{8(b-1)} \psi \\ &\quad + n_R E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \} \\ CS^{S*} &= \frac{b\bar{G}(z^*)\eta Q_0 k^{-\beta(r-\bar{r})}}{2(b-1)^2} \psi \\ SW^{S*} &= \frac{b\bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})} [b(\eta + \Gamma_R) - \Gamma_R]}{2(b-1)^2} \psi \\ &\quad + n_R E_r \{ \min(\hat{\lambda}, \lambda(r-\bar{r})^+) - A \} \\ GS^{S*} &= \frac{b\bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})} \Gamma_R}{2(b-1)} \psi\end{aligned}$$

$$\text{Where } \psi = \left[\frac{2(\eta + \Gamma_R) b \bar{G}(z^*) Q_0 k^{-\beta(r-\bar{r})}}{c(b-1)} \right]^{\frac{1}{3}}.$$

5. Conclusion

This paper develops a two-echelon APSC consisting of an agricultural cooperative and a retailer under stochastic demand and weather uncertainty. We investigate optimal government subsidy strategies under two scenarios: subsidizing the agricultural cooperative or subsidizing the retailer. Meanwhile, weather options are introduced as a risk-hedging instrument. A Stackelberg game framework is employed to analyze optimal decisions, profit outcomes, and social welfare under different policy schemes, and to compare the effectiveness of alternative subsidy mechanisms. The

main contributions of this paper are follows. (1) Adverse weather conditions lead the agricultural cooperative to reduce its level of agricultural input investment, which in turn results in higher wholesale and retail prices, lower profits for both the agricultural cooperative and the retailer, and a decline in overall social welfare. (2) Government subsidies are effective in mitigating the negative impacts of adverse weather conditions on the supply chain. (3) Whether the government subsidizes the agricultural cooperative or the retailer, the retail price remains unchanged. (4) Compared with subsidizing the retailer, subsidizing the agricultural cooperative is more effective in reducing the wholesale price, increasing the level of agricultural input investment, and improving overall social welfare.

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