Opinion paper

Dynamic analysis of subsidies for reducing farmers' grain storage losses

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Abstract: Large grain stocks held by rural households make reducing on-farm storage losses essential for strengthening food security. However, in the absence of government support, farmers lack sufficient incentives to invest in improved storage practices. To address this issue, this study adopted a dynamic perspective to construct and analyze three types of subsidy policies: the grain price subsidy, a new storage tool subsidy, and a hybrid subsidy combining both subsidies. Optimal control theory was employed to evaluate the effectiveness of each subsidy strategy. The results showed that all three subsidy types improve farmers' income and grain quality, with the hybrid subsidy outperforming the single-subsidy schemes in overall performance, particularly in achieving higher income gains, better grain quality, and more effective loss reduction. Specifically, the new storage tool subsidy showed greater effectiveness in improving grain quality, while the price subsidy contributed more significantly to increasing farmers' income. Furthermore, under high rates of grain quality degradation, the marginal benefits of all subsidies in improving quality declined markedly, indicating that the effectiveness of subsidy policies varies under different conditions.

1. Introduction

Grain is the material foundation for human survival and fundamental to ensuring people's livelihoods [1]. Currently, China's grain supply and demand dynamics will remain in a tight balance over the long term. Against the backdrop of increasing challenges in sustaining grain production growth, minimizing grain loss has become a critical pathway to safeguarding national food security [2]. Notably, smallholder farmers, who constitute over 98% of China's grain producers [3], account for 40% to 50% of grain storage [4] and serve as a stabilizer in the national grain reserve system. As the initial stage of the grain supply chain, on-farm grain storage is a decisive step in determining the quantity and quality

of post-harvest grain. However, constrained by limited infrastructure, smallholders typically rely on simple tools such as woven bags, brick silos, and pottery jars for grain storage [5]. These facilities are highly susceptible to pests, mold, and rodent damage, leading to significant losses in both quantity and quality. Studies indicate that post-harvest loss rates among smallholders reach 8–10% [6], while losses in enterprises with professional storage facilities are only about 1% [7]—a striking disparity. Therefore, promoting loss reduction and technological upgrading in smallholder grain storage has emerged as a key intervention point for enhancing national food security capabilities.

Although farmers have significant potential to reduce grain loss and safeguard national food security, the implementation of grain loss reduction often entails high upfront investment costs. In the absence of government support, farmers' motivation to spontaneously increase storage investments is difficult to sustain. Under these real-world constraints, the guiding and catalytic role of the government becomes increasingly prominent.

At the same time, under the strategic context of strengthening agriculture through national brands and empowering rural revitalization through digital technologies [8], some grain enterprises engage in grain quality management and loss-reduction incentives from the perspective of market competition and value appreciation. They adopt quality-based grading and screening as well as brand-building strategies to enhance product value-added [9], continuously releasing brand premium effects to form a differentiated competitive advantage. Regional public brands such as Jilin Rice, Wuchang Rice, Xinzhou Millet, and Yanjin Wheat have become iconic cases of China's grain industry branding development, offering a new pathway to reduce losses along the agricultural industrial chain while increasing revenues for supply-chain participants and boosting farmers' incomes.

In summary, the government's behavioral guidance for farmers in the grain storage stage and grain enterprises' investments in branding and market promotion both have far-reaching impacts on the overall operational performance of the grain supply chain. Given that these two types of actions usually evolve simultaneously with grain loss processes, this paper adopts a dynamic perspective along the time dimension, taking smallholder farmers as the core research subject. A differential game equation is constructed, and optimal control theory is applied to separately solve and characterize the evolution patterns of smallholder storage behavior and grain-marketing firm promotional behavior under price subsidy, storage-tool subsidy policy, and mixed subsidy policy that combines both interventions. On this basis, the study further explores the optimal decision-making strategies of supply-chain members to improve grain quality and supply-chain performance. The findings show that these policy instruments can not only significantly enhance grain quality, but also effectively increase farmers' economic returns.

The main innovations of this paper are as follows: 1) It characterizes, from a dynamic perspective, the evolving features of grain-quality deterioration, smallholder storage behavior, and grain enterprises' marketing strategies. Because grain quality declines over time, a time-based, dynamic depiction of quality, smallholders' storage decisions, firms' marketing actions, and the resulting payoffs of both farmers and enterprises is more appropriate. 2) Three subsidy models are developed to safeguard farmers' incomes and grain quality, while reducing grain losses through the dual pathways of incentive design and management capability enhancement. Specifically, on the one hand, well-structured incentive mechanisms are designed to encourage farmers to sell grain earlier, mitigating quality deterioration caused by prolonged storage. On the other hand, improvements in farmers' storage management practices help further reduce losses at the grain storage stage.

2. Literature review

Our research mainly focuses on grain storage loss reduction and agricultural loss reduction subsidies.

2.1. Research on post-harvest grain storage loss reduction

The issue of grain storage losses is becoming increasingly severe and has emerged as an important factor indirectly threatening national food security [10]. Academic research generally focuses on storage facilities, storage technologies, and storage management. Studies indicate that traditional grain storage facilities are prone to causing mold and pest problems during the storage process [11, 12], while adopting advanced storage equipment and technology can significantly reduce grain storage losses at the household level [13–15]. Nodin et al. [16] pointed out that strengthening post-harvest management and raising awareness of scientific grain storage can effectively reduce grain storage waste. Furthermore, a two-layer robust optimization model proposed by An and Ouyang [17] demonstrates that by optimizing the layout of grain processing and storage facilities and formulating reasonable procurement prices, food enterprises can not only maximize profits but also effectively reduce post-harvest losses. Existing studies have shown that improved storage technologies can effectively enhance grain quality and reduce storage losses. However, the potential role of motivating farmers to sell grain earlier in mitigating post-harvest losses has received insufficient attention in the current literature. To address this gap, this paper innovatively proposes the design of incentive mechanisms to guide farmers toward earlier grain sales, while simultaneously encouraging improvements in grain storage management, storage efficiency, and operational practices, thereby reducing losses during the storage stage.

2.2. Government subsidy mechanisms in post-harvest grain loss reduction

To encourage farmers' active participation in grain loss reduction, many countries have implemented policy-level guidance and support for farmers' loss-reduction behaviors, introducing incentive measures across storage [8, 18], processing [19, 20], and harvesting [21, 22] stages to promote the reduction of grain losses. For instance, studies by Omotilewa et al. [23] and Chatterjee et al. [24] found that implementing subsidies for grain storage tools in developing countries significantly stimulates farmers' purchase intention, thereby reducing household grain storage losses by approximately 60%. Moreover, research by Yang et al. [25] and Liu et al. [26] demonstrated that minimum purchase price policies help enhance farmers' production motivation, optimize market supply-demand dynamics, stabilize yields, and increase profits. A comparative study by Liu and Zhang [27] further indicated that, under specific conditions, subsidies based on loss-reduction performance are more effective than input subsidies, while a hybrid subsidy model is more conducive to improving producer profitability. Existing research indicates that subsidy policies not only provide economic incentives to guide farmers and enterprises in improving storage and circulation practices, thereby effectively reducing post-harvest losses, but also facilitate the diffusion of agricultural storage technologies and the transformation and upgrading of industrial structures through institutional design. Nevertheless, most current studies focus on static decision-making and do not fully account for the dynamic impact of temporal factors on farmers' behavior and income. Moreover, specialized subsidy policies targeting farmers' storage loss reduction remain underexplored.

3. Problem description and modeling assumptions

3.1. Problem description

This paper constructs a two-tier supply chain composed solely of smallholders (F) and a grain enterprise (R). Given the high volatility of grain prices, many farmers—who rely on grain sales as their primary source of income—often choose to hoard their produce when prices are unfavorable, waiting for better returns [28]. However, due to limited on-farm storage capacity, farmers cannot store grain indefinitely; in other words, storage time is finite. Therefore, the sequence of decisions in all models of this paper is as follows:

1) Smallholders first determine their grain storage effort ($u(t)$).

2) The grain enterprise then decides on the grain purchase price (w) and marketing effort ($A(t)$). The symbols used in this paper and their meanings are listed in Table 1.

Table 1. Notations and descriptions.

Notation	Description
T	The cycle from grain harvesting to final sale for farmers
$u(t)$	Farmers' storage efforts at time t
$C_u(t)$	Farmers' storage cost at time t
b	Storage cost coefficient, $b > 0$
$v(t)$	Grain storage quality at time t, $v(0) = v_0 > 0$
k	Grain loss rate, $k > 0$
β	The impact coefficient of storage efforts on the grain loss rate, $0 < \beta < k$
$G(t)$	Product goodwill at time t, $G(0) = G_0 > 0$
λ	The coefficient of consumers' preference for grain quality, $\lambda > 0$
γ	The coefficient of consumers' preference for grain brands, $\gamma > 0$
$A(t)$	Grain enterprises' marketing effort at time t
θ	The impact coefficient of marketing on goodwill, $\theta > 0$
ω	Forgetting factor, $\omega > 0$
$C_A(t)$	Grain enterprises' marketing costs at time t
δ	Marketing cost coefficient, $\delta > 0$
$q(t)$	Grain demand at time t
a	Potential demand in the grain market, $a > 0$
α	Consumers' price-sensitivity coefficient, $\alpha > 0$
$p(t)$	The price of grain at time t
ρ	Discount factor
τ	The government's subsidy

3.2. Model assumptions

Assumption 1: Before the new grain harvest in the following year, farmers will sell their previously stored old grain to make room for the new grain. The time interval between the grain harvest and its final sale by farmers is T.

Assumption 2: During the storage period, farmers make efforts $u(t)$ to prevent the grain from acquiring mildew and insect infestation. The storage cost is $C_u(t) = \frac{b}{2}u(t)^2$, where b denotes the storage cost coefficient.

Assumption 3: During storage, grain is subject to a natural loss rate k. Referring to previous research [29], the quality of grain stored by farmers is denoted as $v'(t) = \beta u(t) - kv(t)$, where β is the influence coefficient of storage effort on grain quality decay. At $t = 0$, the initial quality of the grain is v_0.

Assumption 4: Drawing on De Giovanni [30], the goodwill of a grain brand is influenced by the advertising and marketing efforts of the grain enterprise. The Nerlove-Arrow classic goodwill model is adopted to characterize the trajectory of goodwill over time, i.e., $G'(t) = \theta A(t) - \omega G(t)$, where $A(t)$ represents the marketing effort level of the grain enterprise at time t, ω is the forgetting factor, and θ is the influence coefficient of marketing on goodwill. The advertising cost of the grain enterprise is $C_A(t) = \frac{\delta}{2}A(t)^2$, where δ is the advertising cost coefficient. At $t = 0$, the initial goodwill of the product is G_0.

Assumption 5: The demand for grain is related not only to price, but also to grain quality and grain brand reputation. Referring to the research by Liu et al. [31], the demand for grain at time t is $q(t) = (a - \alpha p(t))(\lambda v(t) + \gamma G(t))$, where a represents the potential demand in the grain market, α is the consumers' price sensitivity coefficient, $p(t)$ is the price of grain at time t, λ is the impact factor of grain quality on demand, and γ is the impact of product reputation on demand.

Assumption 6: To simplify the calculation, this paper assumes that the unit grain production cost of farmers and the unit management cost of grain enterprises are 0.

4. Model and equilibrium results

4.1. Traditional storage model (N)

In the traditional storage model, farmers and grain enterprises cannot obtain government subsidies. Then, the profit functions of farmers and grain enterprises are, respectively:

$$\max \ \pi_F^N = \int_0^T e^{-\rho t}(wq(t) - C_u(t)) \, dt, \tag{1}$$

$$\max \ \pi_R^N = \int_0^T e^{-\rho t}((p - w)q(t) - C_A(t)) \, dt. \tag{2}$$

Proposition 1: Under the traditional grain storage model, the optimal purchase price of grain is $w^{N*} = \frac{a}{2\alpha}$ and the optimal grain storage effort is $u^{N*} = \frac{\beta \lambda a^2}{8\alpha b(\rho+k)}$; the optimal sales price of grain is $p^{N*} = \frac{3a}{4\alpha}$ and the optimal marketing effort is $A^{N*} = \frac{\gamma \theta a^2}{16\alpha\delta(\rho+\omega)}$. At this point, the trajectory of grain storage quality by farmers and the trajectory of grain brand reputation are, respectively:

$$v(t)^{N*} = \left[v_0 - \frac{\beta^2 \lambda a^2}{8\alpha bk(\rho + k)} \right] e^{-kt} + \frac{\beta^2 \lambda a^2}{8\alpha bk(\rho + k)},$$

$$G(t)^{N*} = \left[G_0 - \frac{\theta^2 \gamma a^2}{16\alpha\delta\omega(\rho + \omega)} \right] e^{-\omega t} + \frac{\theta^2 \gamma a^2}{16\alpha\delta\omega(\rho + \omega)}.$$

By substituting the above optimal equilibrium solutions into the profit function, the optimal profits of smallholder farmers and grain enterprises under the traditional storage model can be obtained as follows:

$$\pi_F^{N*} = \frac{\lambda a^2}{8\alpha(\rho + k)} v_0 + \frac{\gamma a^2}{8\alpha(\rho + \omega)} G_0 + \frac{\beta^2 \lambda^2 a^4}{128\, b\, \alpha^2(\rho + k)^2} + \frac{\theta^2 \gamma^2 a^4}{128\, \delta\, \alpha^2(\rho + \omega)^2},$$

$$\pi_R^{N*} = \frac{\lambda a^2}{16\alpha(\rho + k)} v_0 + \frac{\gamma a^2}{16\alpha(\rho + \omega)} G_0 + \frac{\beta^2 \lambda^2 a^4}{128\, b\, \alpha^2(\rho + k)^2} + \frac{\theta^2 \gamma^2 a^4}{512\, \delta\, \alpha^2(\rho + \omega)^2}.$$

The proof is shown in the Appendix.

Corollary 1:

1) Under the traditional storage model, it can be known seen from $\frac{\partial u^{N*}}{\partial \lambda} > 0$ and $\frac{\partial A^{N*}}{\partial \gamma} > 0$ that farmers' storage efforts increase as consumers' preference for grain quality strengthens; when consumers' brand preference rises, the marketing efforts of grain enterprises will also increase accordingly.

2) Since $\frac{\partial u^{N*}}{\partial k} < 0$ and $\frac{\partial A^{N*}}{\partial \omega} < 0$, the farmer's storage effort is negatively correlated with the decay rate of grain quality, and the grain enterprise's marketing effort is negatively correlated with the forgetting rate of brand goodwill. Meanwhile, since $\frac{\partial u^{N*}}{\partial b} < 0$ and $\frac{\partial A^{N*}}{\partial \delta} < 0$, both storage effort and marketing effort are negatively correlated with their respective cost coefficients.

3) Since $\frac{\partial \pi_i^{N*}}{\partial \lambda} > 0$ and $\frac{\partial \pi_i^{N*}}{\partial \gamma} > 0$, the profits of both the farmer and the grain enterprise increase with the consumer's quality preference and brand preference. From $\frac{\partial \pi_i^{N*}}{\partial k} < 0$ and $\frac{\partial \pi_i^{N*}}{\partial \omega} < 0$, it can be seen that the profits of the farmer and the grain enterprise are negatively correlated with the decay rate of grain quality and the decay rate of brand goodwill, where $i = F, R$.

In summary, under the traditional storage model, farmers' storage efforts, grain enterprises' marketing efforts, as well as the profits of both farmers and grain enterprises, will increase with the enhancement of consumers' preferences for quality and brand. Conversely, they will decrease as the decay rate of grain quality and the decay rate of brand reputation increase. This indicates that if grain enterprises and farmers want to improve their own profits, they should continuously enhance grain storage efforts, improve grain quality, and build advantageous brands. However, if the costs are too high, farmers and grain enterprises will reduce their storage efforts and marketing efforts correspondingly.

4.2. Grain price subsidy model (M)

To ensure farmers' interest while incentivizing them to sell grain earlier to reduce losses during storage, the government provides a price subsidy to grain enterprises, enabling them to purchase grain from farmers at a higher price. If farmers sell grain to the enterprise within time $T_1(T_1 < T)$, the enterprise receives a unit subsidy $\tau_1(0 < \tau_1 < 1)$. Grain sold after T_1 receives no subsidy. Under this model, the profit functions of the farmer and the grain enterprise are, respectively:

$$\max \pi_F^M = \int_0^T e^{-\rho t}(wq(t) - C_u(t))\, dt, \tag{3}$$

$$\max \pi_R^M = \int_0^{T_1} e^{-\rho t}\big([(1 + \tau_1)p - w]q(t) - C_A(t)\big)\, dt + \int_{T_1}^T e^{-\rho t}((p - w)q(t) - C_A(t))\, dt. \tag{4}$$

Proposition 2: Under the grain price subsidy policy, the optimal purchase price of grain is

$$w^{M*} = \begin{cases} \dfrac{(1+\tau_1)a}{2\alpha}, & t \in [0, T_1], \\ \dfrac{a}{2\alpha}, & t \in (T_1, T]. \end{cases}$$

The optimal sales price of grain is

$$p^{M*} = \begin{cases} \dfrac{(3+2\tau_1)a}{2\alpha(2+\tau_1)}, & t \in [0, T_1], \\ \dfrac{3a}{4\alpha}, & t \in (T_1, T]. \end{cases}$$

The optimal grain storage effort of farmers is

$$u^{M*} = \begin{cases} \dfrac{\lambda\beta(1+\tau_1)a^2}{8\alpha b(\rho+k)}, & t \in [0, T_1], \\ \dfrac{\lambda\beta a^2}{8\alpha b(\rho+k)}, & t \in (T_1, T]. \end{cases}$$

The optimal marketing effort of grain enterprises is

$$A^{M*} = \begin{cases} \dfrac{\gamma\theta(1+\tau_1)a^2}{16\alpha\delta(\rho+\omega)}, & t \in [0, T_1], \\ \dfrac{\gamma\theta a^2}{16\alpha\delta(\rho+\omega)}, & t \in (T_1, T]. \end{cases}$$

At this point, the trajectory of grain storage quality for farmers and the trajectory of grain brand reputation are, respectively:

$$v(t)^{M*} = \begin{cases} \left[v_0 - \dfrac{\lambda\beta^2(1+\tau_1)a^2}{8\alpha bk(\rho+k)} \right] e^{-kt} + \dfrac{\lambda\beta^2(1+\tau_1)a^2}{8\alpha bk(\rho+k)}, & t \in [0, T_1], \\ \left[v_0 - \dfrac{\lambda\beta^2(1+\tau_1)a^2}{8\alpha bk(\rho+k)} \right] e^{-kt} + \dfrac{\beta^2\lambda a^2\tau_1}{8\alpha bk(\rho+k)} e^{-k(t-T_1)} + \dfrac{\beta^2\lambda a^2}{8\alpha bk(\rho+k)}, & t \in (T_1, T], \end{cases}$$

$$G(t)^{M*} = \begin{cases} \left[G_0 - \dfrac{\gamma\theta^2(1+\tau_1)a^2}{16\alpha\delta\omega(\rho+\omega)} \right] e^{-\omega t} + \dfrac{\gamma\theta^2(1+\tau_1)a^2}{16\alpha\delta\omega(\rho+\omega)}, & t \in [0, T_1], \\ \left[G_0 - \dfrac{\gamma\theta^2(1+\tau_1)a^2}{16\alpha\delta\omega(\rho+\omega)} \right] e^{-\omega t} + \dfrac{\gamma\theta^2\tau_1 a^2}{16\alpha\delta\omega(\rho+\omega)} e^{-\omega(t-T_1)} + \dfrac{\gamma\theta^2 a^2}{16\alpha\delta\omega(\rho+\omega)}, & t \in (T_1, T]. \end{cases}$$

By substituting the above optimal equilibrium solutions into the profit function, the optimal profits of smallholder farmers and grain enterprises under the grain price subsidy model can be obtained as follows:

$$\pi_F^{M*} = \left[\frac{\lambda a^2}{8\alpha(\rho+k)} v_0 + \frac{\gamma a^2}{8\alpha(\rho+\omega)T} G_0 \right] \frac{(1+\tau_1)(T+T_1)}{T}$$
$$+ \left[\frac{\beta^2\lambda^2 a^4}{128\, b\, \alpha^2(\rho+k)^2 T} + \frac{\theta^2\gamma^2 a^4}{128\, \delta\, \alpha^2(\rho+\omega)^2} \right] \frac{(1+\tau_1)^2(T+T_1)}{T}.$$

$$\pi_R^{M*} = \left[\frac{\lambda a^2}{16\alpha(\rho + k)} v_0 + \frac{\gamma a^2}{16\alpha(\rho + \omega)T} G_0 \right] \frac{(1 + \tau_1)(T + T_1)}{T}$$
$$+ \left[\frac{\beta^2 \lambda^2 a^4}{128\, b\, \alpha^2(\rho + k)^2 T} + \frac{\theta^2 \gamma^2 a^4}{512\, \delta\, \alpha^2(\rho + \omega)^2} \right] \frac{(1 + \tau_1)^2(T + T_1)}{T}.$$

The proof is shown in the Appendix.

Corollary 2:

1) Under the food price subsidy model, $\frac{\partial u^{M*}}{\partial \lambda} > 0, \frac{\partial A^{M*}}{\partial \gamma} > 0$, meaning that as consumers' preference for food quality increases, farmers' storage efforts will correspondingly rise; similarly, when consumers' brand preference strengthens, the marketing efforts of food enterprises will also intensify.

2) Since $\frac{\partial u^{M*}}{\partial k} < 0$, $\frac{\partial u^{M*}}{\partial b} < 0$, the storage efforts of farmers are negatively correlated with the decay rate of food quality and storage costs. Meanwhile, due to $\frac{\partial A^{M*}}{\partial \omega} < 0$, $\frac{\partial A^{M*}}{\partial \delta} < 0$, the faster the consumers' forgetting rate, the higher the marketing costs for enterprises, and the lower the marketing efforts exerted by food enterprises.

3) From $\frac{\partial \pi_i^{M*}}{\partial \lambda} > 0$, $\frac{\partial \pi_i^{M*}}{\partial \gamma} > 0$, it can be seen that the profits of farmers and grain enterprises will increase with the rise in consumers' quality preference and brand preference. Since $\frac{\partial \pi_i^{M*}}{\partial k} < 0$, $\frac{\partial \pi_i^{M*}}{\partial \omega} < 0$, the profits of farmers and food enterprises are negatively correlated with the decay rate of food quality and the decay rate of brand goodwill, where $i = F, R$.

4) When $t \in [0, T_1]$, we have $\frac{\partial w^{M*}}{\partial \tau_1} > 0$, $\frac{\partial p^{M*}}{\partial \tau_1} > 0$, $\frac{\partial A^{M*}}{\partial \tau_1} > 0$, $\frac{\partial u^{M*}}{\partial \tau_1} > 0$, meaning that as the food price subsidy increases, the optimal procurement price, selling price, promotional efforts, and storage efforts also increase. Moreover, $\frac{\partial \pi_i^{M*}}{\partial \tau_1} > 0$, $\frac{\partial \pi_i^{M*}}{\partial T_1} > 0$, indicating that as the intensity and duration of the food price subsidy increase, the profits of farmers and food enterprises show an upward trend, where $i = F, R$.

The proof is shown in the Appendix.

Corollary 3: Compared with the traditional storage model, the government's grain price subsidies can increase the optimal purchase price of grain, while also enhancing farmers' storage efforts and the marketing efforts of grain enterprises. Furthermore, after the government implements grain price subsidies, grain quality, grain brand reputation, and the profits of both farmers and grain enterprises are improved.

The proof is shown in the Appendix.

From the perspective of management practice, these phenomena may occur due to the following reasons: For grain enterprises, the government's price subsidies create a "price floor" effect on grain prices, making enterprises more willing to pay higher prices when purchasing grain from farmers. At the same time, the subsidy policy effectively reduces the sales risks faced by enterprises, thereby boosting their enthusiasm for brand promotion and market expansion. For farmers, grain price subsidies raise the purchase price of grain, leading to higher expectations of potential profits. This, in turn, encourages farmers to attach greater importance to storage management, enhance the standardization and initiative in their storage management practices, and thus improve the overall level of storage efforts.

4.3. Subsidy model for new storage tools (S)

To promote the adoption of new grain storage tools, the government provides subsidies to farmers who utilize such tools [15, 32]. When farmers adopt new storage technologies, the government offers scientific storage training and provides a subsidy amount τ_2 to alleviate the financial burden associated

with purchasing new storage equipment, where $0 < \tau_2 < 1$. The profit functions for farmers and grain enterprises are as follows:

$$\max \pi_F^S = \int_0^T e^{-\rho t} \left[wq(t) - (1 - \tau_2)C_u(t) \right] dt. \tag{5}$$

$$\max \pi_R^S = \int_0^T e^{-\rho t} \left[(p - w)q(t) - C_A(t) \right] dt, \tag{6}$$

Proposition 3: Under the storage tool subsidy model, the optimal purchase price of grain is $w^{S*} = \frac{a}{2\alpha}$ and the optimal grain storage effort is $u^{S*} = \frac{\beta \lambda a^2}{8\alpha b(1 - \tau_2)(\rho + k)}$; the optimal sales price of grain is $p^{S*} = \frac{3a}{4\alpha}$ and the optimal marketing effort is $A^{S*} = \frac{\gamma \theta a^2}{16\alpha \delta(\rho + \omega)}$. At this point, the trajectory of farmers' grain storage quality and the trajectory of grain brand reputation are, respectively as follows:

$$\begin{cases} v(t)^{S*} = \left[v_0 - \dfrac{\beta^2 \lambda a^2}{8\alpha bk(1 - \tau_2)(\rho + k)} \right] e^{-kt} + \dfrac{\beta^2 \lambda a^2}{8\alpha bk(1 - \tau_2)(\rho + k)}, \\[2mm] G(t)^{S*} = \left[G_0 - \dfrac{\theta^2 \gamma a^2}{16\alpha \delta \omega(\rho + \omega)} \right] e^{-\omega t} + \dfrac{\theta^2 \gamma a^2}{16\alpha \delta \omega(\rho + \omega)}. \end{cases}$$

Substituting the above optimal equilibrium solution into the profit functions, the optimal profits for smallholder farmers and grain enterprises under the storage tool subsidy model can be derived as follows:

$$\pi_F^{S*} = \frac{\lambda a^2}{8\alpha(\rho + k)} v_0 + \frac{\gamma a^2}{8\alpha(\rho + \omega)} G_0 + \frac{\beta^2 \lambda^2 a^4}{128\, b\, \alpha^2 (1 - \tau_2)(\rho + k)^2} + \frac{\theta^2 \gamma^2 a^4}{128\, \delta\, \alpha^2 (\rho + \omega)^2},$$

$$\pi_R^{S*} = \frac{\lambda a^2}{16\alpha(\rho + k)} v_0 + \frac{\gamma a^2}{16\alpha(\rho + \omega)} G_0 + \frac{\beta^2 \lambda^2 a^4}{128\, b\, \alpha^2 (1 - \tau_2)(\rho + k)^2} + \frac{\theta^2 \gamma^2 a^4}{512\, \delta\, \alpha^2 (\rho + \omega)^2}.$$

Corollary 4:

1) Under the storage tool subsidy model, $\frac{\partial u^{S*}}{\partial \lambda} > 0$, $\frac{\partial u^{S*}}{\partial \tau_2} > 0$, meaning that farmers' storage efforts increase with the rise in consumers' quality preference and government subsidies. From $\frac{\partial u^{S*}}{\partial b} < 0$, $\frac{\partial u^{S*}}{\partial k} < 0$, it can be seen that farmers' storage efforts are inversely proportional to storage costs and the food quality decay rate.

2) Because $\frac{\partial A^{S*}}{\partial \gamma} > 0$, $\frac{\partial A^{S*}}{\partial \omega} < 0$, the marketing efforts of grain enterprises will increase with the rise in consumers' brand preference, but will decrease due to the increase in the brand forgetting factor.

3) Since $\frac{\partial \pi_i^{S*}}{\partial \lambda} > 0$ and $\frac{\partial \pi_i^{S*}}{\partial \gamma} > 0$, the profits of farmers and grain enterprises will increase with the rise in consumers' quality preference and brand preference; it can be inferred from $\frac{\partial \pi_i^{S*}}{\partial k} < 0$ and $\frac{\partial \pi_i^{S*}}{\partial \omega} < 0$ that the profits of farmers and grain enterprises are negatively correlated with the grain quality decay rate and the brand reputation decay rate, where $i = F, R$.

4) Since $\frac{\partial \pi_i^{S*}}{\partial \tau_2} > 0$, the income of farmers and grain enterprises will increase with the growth of the intensity of storage tool subsidies, where $i = F, R$.

Corollary 5: Compared with traditional storage models, the government's subsidy for farmers' procurement of new storage tools does not alter the optimal procurement price, selling price, or the

brand promotion efforts of enterprises. However, it enhances grain quality and increases the profits of both farmers and grain enterprises.

By lowering storage costs, however, the subsidy effectively incentivizes farmers to increase storage efforts, thereby improving grain quality. Although the subsidy does not directly target enterprises, they benefit from obtaining higher-quality raw materials from farmers, which significantly enhances efficiency and value in subsequent processing, storage, transportation, and sales processes, ultimately boosting corporate profits. Therefore, while the subsidy does not alter market price mechanisms, it indirectly expands the overall profit margins for both farmers and grain enterprises by improving storage efficiency and product quality. Proof: See the Appendix.

Corollary 6:

1) Under the storage tool subsidy model, the optimal purchase price, optimal selling price, and the advertising efforts of grain enterprises have not improved compared to the grain price subsidy model.

2) Compared with grain price subsidies, although the new storage tool subsidies bring lower direct economic benefits, farmers invest more in grain storage under this subsidy model, which can effectively improve the quality of stored grain. The proof is provided in the Appendix.

Under the storage tool subsidy model, since the subsidies are mainly targeted at farmers and do not directly interfere with the market price mechanism, the optimal purchase price of grain and the advertising efforts of grain enterprises are both lower than those in the price subsidy model. Grain price subsidies directly enhance enterprises' profit expectations by subsidizing them, thereby incentivizing enterprises to increase the purchase price and expand brand investment. In contrast, storage tool subsidies mainly take reducing farmers' storage costs and improving grain quality as the core approaches. Although enterprises indirectly benefit from the improvement of raw material quality, they lack clear price incentive signals.

As a result, their enthusiasm in pricing and marketing is relatively weak. This reflects the essential differences between the two types of subsidies in terms of incentive paths and market function mechanisms.

5. Extension: hybrid model (H) of grain price subsidies and storage tool subsidies

From the comprehensive analysis above, it can be concluded that grain price subsidies have a more significant effect on increasing farmers' income, while the new storage tool subsidies perform better in improving grain quality. Therefore, a reasonable combination of these two types of subsidy policies is expected to better achieve the dual goals of "increasing farmers' income" and "improving grain quality". Based on this, this paper extends the original model by assuming that the government not only subsidizes farmers for purchasing new storage tools but also provides corresponding subsidies to grain enterprises. This is intended to encourage enterprises to purchase grain stored by farmers at a higher price, thereby synergistically improving both grain quality and farmers' income.

When farmers adopt new storage tools, the government provides them with a subsidy τ_3 to alleviate the financial burden of purchasing new grain storage equipment (where $0 < \tau_3 < 1$), along with scientific storage technology training. Additionally, within a limited time period $T_2(T_2 \leq T)$, the government offers grain enterprises a certain price subsidy $\tau_4(0 < \tau_4 < 1)$, to encourage them to purchase stored grain from smallholders at a higher price. The profit functions for farmers and grain enterprises are as

follows:

$$\max \pi_F^H = \int_0^T e^{-\rho t}[wq(t) - (1 - \tau_3)C_u(t)] \, dt, \tag{7}$$

$$\max \pi_R^H = \int_0^{T_2} e^{-\rho t}\Big([(1 + \tau_4)p - w]q(t) - C_A(t)\Big) \, dt + \int_{T_2}^T e^{-\rho t}((p - w)q(t) - C_A(t)) \, dt. \tag{8}$$

Proposition 4: Under the hybrid subsidy model, the optimal grain procurement price is

$$w^{H*} = \begin{cases} \dfrac{(1 + \tau_4)a}{2\alpha}, & t \in [0, T_2], \\ \dfrac{a}{2\alpha}, & t \in (T_2, T], \end{cases}$$

and the optimal grain selling price is $p^{H*} = \frac{3a}{4\alpha}$. The optimal grain

storage effort by farmers is $u^{H*} = \begin{cases} \dfrac{\lambda\beta(1 + \tau_4)a^2}{8\alpha b(1 - \tau_3)(\rho + k)}, & t \in [0, T_2], \\ \dfrac{\lambda\beta a^2}{8\alpha b(1 - \tau_3)(\rho + k)}, & t \in (T_2, T], \end{cases}$ and the optimal marketing effort

by grain enterprises is $A^{H*} = \begin{cases} \dfrac{\gamma\theta(1 + \tau_4)a^2}{16\alpha\delta(\rho + \omega)}, & t \in [0, T_2], \\ \dfrac{\gamma\theta a^2}{16\alpha\delta(\rho + \omega)}, & t \in (T_2, T]. \end{cases}$ The trajectories of grain quality and brand

goodwill are given, respectively by: $v(t)^{H*} =$

$$\begin{cases} \left[v_0 - \dfrac{\lambda\beta^2(1 + \tau_4)a^2}{8\alpha bk(1 - \tau_3)(\rho + k)}\right]e^{-kt} + \dfrac{\lambda\beta^2(1 + \tau_4)a^2}{8\alpha bk(1 - \tau_3)(\rho + k)}, & t \in [0, T_2], \\ \left[v_0 - \dfrac{\lambda\beta^2(1 + \tau_4)a^2}{8\alpha bk(1 - \tau_3)(\rho + k)}\right]e^{-kt} + \dfrac{\beta^2\lambda a^2\tau_4}{8\alpha bk(1 - \tau_3)(\rho + k)}e^{-k(t-T_2)} + \dfrac{\beta^2\lambda a^2}{8\alpha bk(1 - \tau_3)(\rho + k)}, & t \in (T_2, T], \end{cases}$$

$$G(t)^{H*} = \begin{cases} \left[G_0 - \dfrac{\gamma\theta^2(1 + \tau_4)a^2}{16\alpha\delta\omega(\rho + \omega)}\right]e^{-\omega t} + \dfrac{\gamma\theta^2(1 + \tau_4)a^2}{16\alpha\delta\omega(\rho + \omega)}, & t \in [0, T_2], \\ \left[G_0 - \dfrac{\gamma\theta^2(1 + \tau_4)a^2}{16\alpha\delta\omega(\rho + \omega)}\right]e^{-\omega t} + \dfrac{\gamma\theta^2\tau_4 a^2}{16\alpha\delta\omega(\rho + \omega)}e^{-\omega(t-T_2)} + \dfrac{\gamma\theta^2 a^2}{16\alpha\delta\omega(\rho + \omega)}, & t \in (T_2, T]. \end{cases}$$

Substituting the above optimal equilibrium solutions into the profit functions, the optimal profits for smallholder farmers and grain enterprises under the grain price subsidy model can be derived as follows:

$$\pi_F^{H*} = \left[\frac{\lambda a^2}{8\alpha(\rho + k)}v_0 + \frac{\gamma a^2}{8\alpha(\rho + \omega)T}G_0\right]\frac{(1 + \tau_4)(T + T_2)}{T}$$
$$+ \left[\frac{\beta^2\lambda^2 a^4}{128\, b\, \alpha^2(1 - \tau_3)(\rho + k)^2} + \frac{\theta^2\gamma^2 a^4}{128\, \delta\, \alpha^2(\rho + \omega)^2}\right]\frac{(1 + \tau_4)^2(T + T_2)}{T},$$

$$\pi_R^{H*} = \left[\frac{\lambda a^2}{16\alpha(\rho + k)}v_0 + \frac{\gamma a^2}{16\alpha(\rho + \omega)T}G_0\right]\frac{(1 + \tau_4)(T + T_2)}{T}$$
$$+ \left[\frac{\beta^2\lambda^2 a^4}{128\, b\, \alpha^2(1 - \tau_3)(\rho + k)^2} + \frac{\theta^2\gamma^2 a^4}{512\, \delta\, \alpha^2(\rho + \omega)^2}\right]\frac{(1 + \tau_4)^2(T + T_2)}{T}.$$

Corollary 7: When the subsidy intensity is the same, the optimal grain quality achieved under the hybrid subsidy model is significantly better than that under the single storage tool subsidy model; when the duration of grain price subsidies is consistent, the hybrid subsidy model has a significant advantage in increasing farmers' income compared with the model where only price subsidies are implemented.

The proof is provided in the Appendix.

The mechanism behind this is that when the subsidy intensity and duration are consistent, farmers are more inclined to optimize their storage management under the incentive of storage subsidies, which in turn improves grain quality. Meanwhile, grain enterprises are more motivated to strengthen market promotion and sales due to price subsidies, thereby driving the improvement of overall market efficiency. The synergistic effect of the hybrid subsidy not only improves grain quality but also increases farmers' income levels.

6. Numerical analysis

This section employs numerical simulation to provide a more intuitive exploration of how storage time affects grain storage quality, brand reputation, and supply chain performance under three model scenarios. Following the studies of Li et al. [33] and Liu et al. [29], let $k = 0.2$, $\omega = 0.2$, $\rho = 0.1$, $\beta = 0.1$, $\theta = 0.1$, $\alpha = 1$, $v_0 = 100$, $G_0 = 100$, $b = 800$, $\delta = 800$, $\lambda = 0.2$, $\gamma = 0.1$. Taking wheat demand as an example, and based on the 2024 grain output data announced by the National Bureau of Statistics [34], we set $a = 3000$, $T_1 = 2$, $\tau_1 = 0.3$, $\tau_2 = 0.3$, $T = 12$.

6.1. Comparative analysis of the impacts of price subsidies and storage tool subsidies
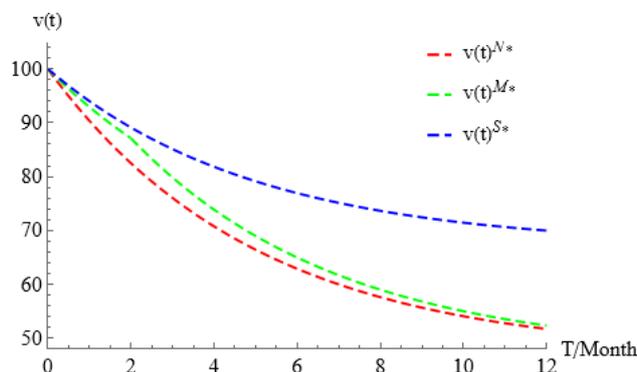
Figure 1. Comparison of Grain storage quality by farmers.
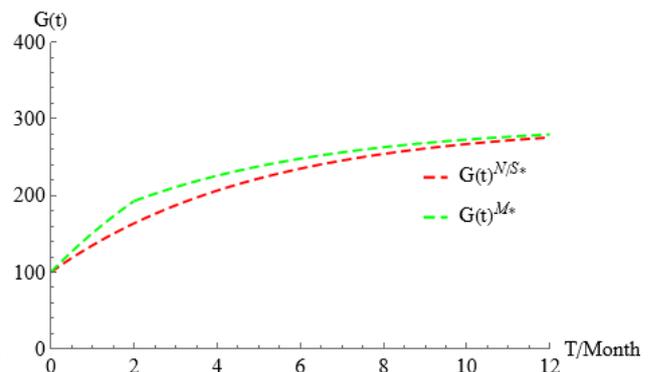

Figure 2. Comparison of grain enterprises' marketing efforts.

According to Figure 1, both grain price subsidies and storage tool subsidies contribute to improving the overall quality of farmers' grain storage. However, the quality enhancement effect of storage tool subsidies is more pronounced. This may be because storage tool subsidies directly improve farmers' storage conditions, reducing quality losses caused by mold, pests, and other factors, thereby safeguarding grain quality at the source. In contrast, although grain price subsidies can also indirectly incentivize farmers to supply higher-quality grain, their effectiveness is often constrained by enterprises' ability to identify grain quality, making the quality improvement relatively limited.

Figure 2 shows that the grain price subsidy significantly enhances the marketing efforts of grain enterprises. By leveraging the increased profit margins from subsidies, enterprises may allocate more resources to advertising in order to boost brand awareness and market share. In contrast, the storage tool subsidy does not exhibit a noticeable incentivizing effect on enterprises' advertising and marketing efforts. This discrepancy can be explained as follows: Price subsidies directly improve enterprises' profit

expectations, motivating them to expand market presence; whereas storage tool subsidies primarily target farmers and do not directly enhance enterprises' revenue, thus providing little impetus for increased promotional activities.
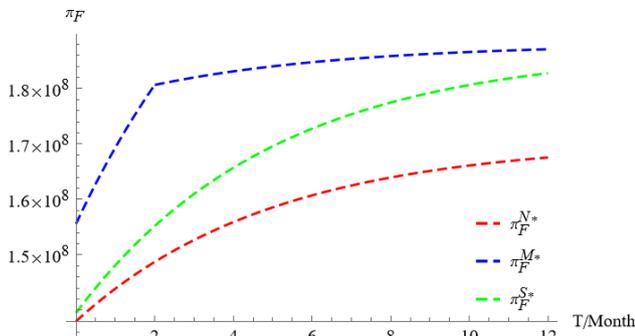

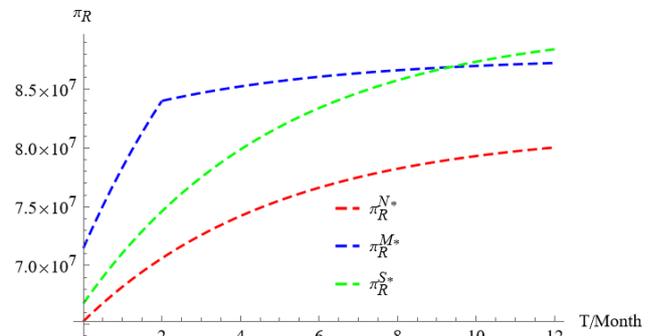**Figure 3(a).** Comparison of farmers' income.

Figure 3(b). Comparison of grain enterprises' income.

Figure 3. The impact of price subsidies and storage tool subsidies on income.

As can be seen from Figure 3, whether grain price subsidies or storage tool subsidies are adopted, they can both increase the income of farmers and grain enterprises to a certain extent. Among them, grain price subsidies have a more significant effect on boosting farmers' profits. Specifically, grain price subsidies directly increase farmers' income by raising the purchase price of grain, so their role in improving farmers' income is particularly prominent.

For grain enterprises, in the early stage of the policy, grain price subsidies can bring a relatively high increase in income. This is because enterprises can use government subsidies to increase investment in advertising and marketing, thereby rapidly expanding their market share in the short term. However, as time goes by, high marketing expenditures compress the profit margins of enterprises, and the growth rate of their income gradually slows down—even lower than the benefits brought by storage tool subsidies. In contrast, although storage tool subsidies are mainly targeted at farmers and have a limited direct incentive effect on enterprises, they improve grain quality and the stability of market supply. As a result, they bring more sustained and steady income growth to enterprises in the later stage.
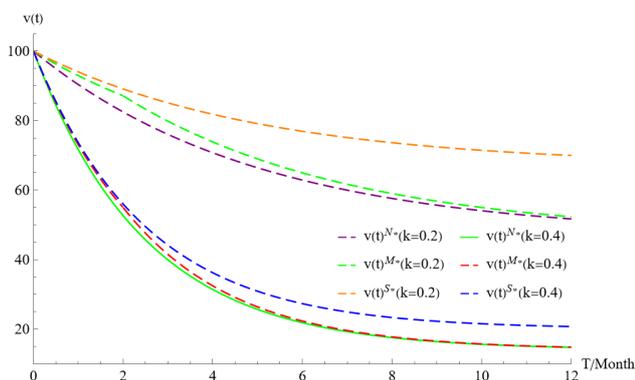

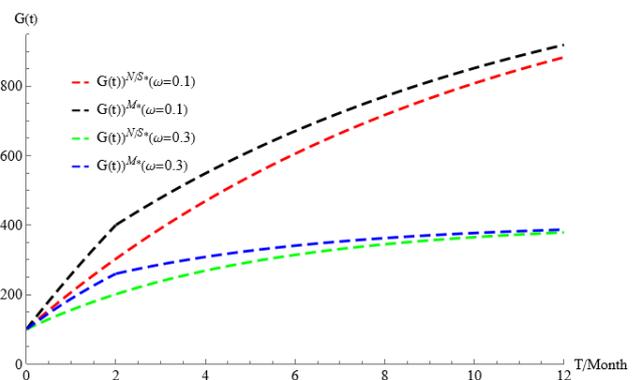**Figure 4.** Impact of grain decay rate on grain quality.

Figure 5. Impact of forgetting rate on marketing efforts.

As can be seen from Figure 4, the quality of grain decreases significantly as the grain loss rate increases. Meanwhile, both grain price subsidies and storage tool subsidies become less effective in

improving grain quality under these conditions. Particularly when the storage period is extended, the impact of grain price subsidies on enhancing grain quality is not significant. This indicates that in high-loss environments, the marginal effect of subsidy policies is somewhat constrained, making it difficult to fully achieve the intended goal of safeguarding grain quality.

Figure 5 shows that as the forgetting rate increases, the marketing efforts of grain enterprises show a downward trend. Meanwhile, the rise in the forgetting rate also weakens the incentive effect of grain price subsidies on enterprises' marketing enthusiasm. This indicates that the rapid loss of consumers' memory of promotional content will limit the ability of enterprises to obtain market returns through advertising investment, thereby reducing their motivation to respond to subsidy policies.
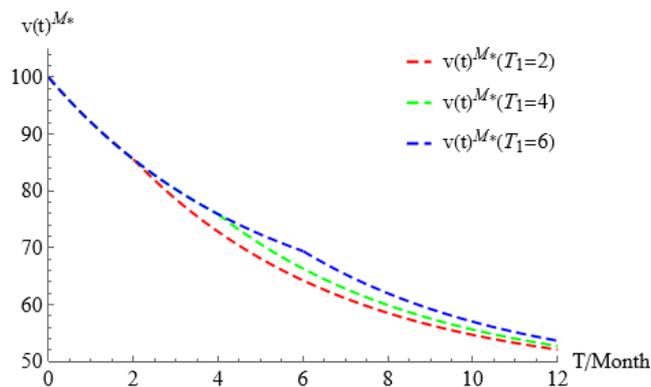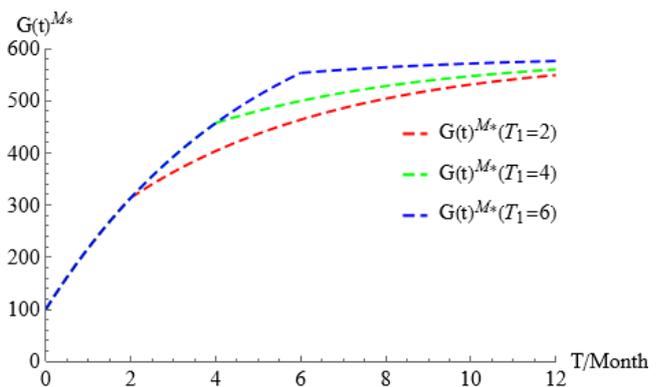

Figure 6(a). Impact on grain quality.
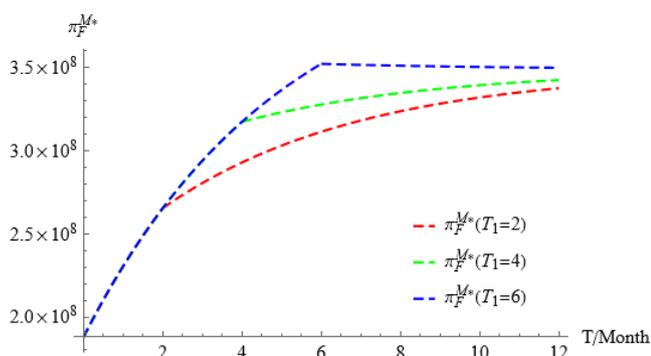
Figure 6(b). Impact on marketing efforts.

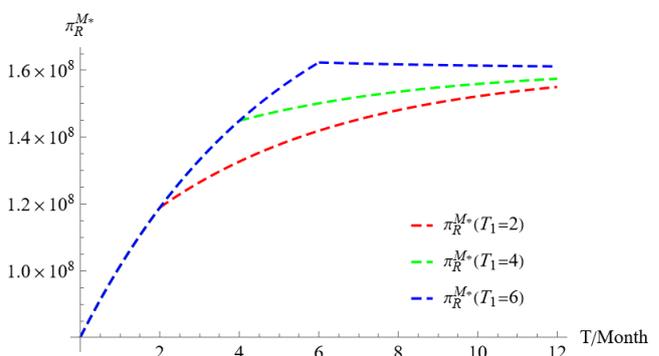**Figure 6(c).** The Impact on farmers' income.

Figure 6(d). The impact on grain enterprises' income.

Figure 6. The impact of grain price subsidy timing.

Figure 6 show that as the duration of grain price subsidies extends, grain quality, marketing investments by grain enterprises, and the profits of both farmers and enterprises all demonstrate an upward trend. For farmers, longer-term price subsidies mean that higher grain purchase prices can be sustained, which enhances their motivation to improve grain quality and encourages them to invest more effort in early storage to reduce grain losses. Furthermore, the expectation of price stability brought by long-term subsidies helps farmers maintain higher profit levels amid significant market price fluctuations. For grain enterprises, the extension of subsidy duration secures their investment in marketing activities, enabling them to enhance brand recognition and market share. Based on continuously improving grain quality, sustained marketing efforts help enterprises gain a competitive advantage in an increasingly fierce market environment.
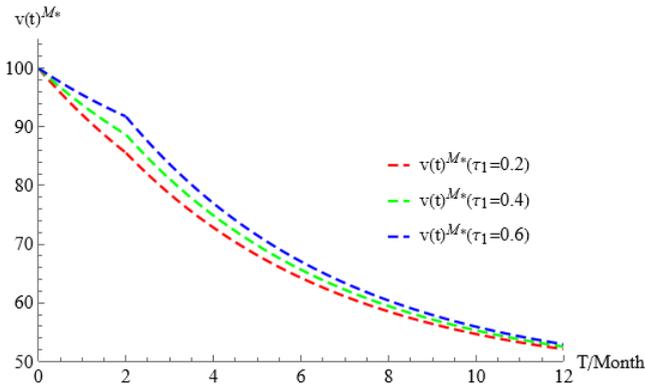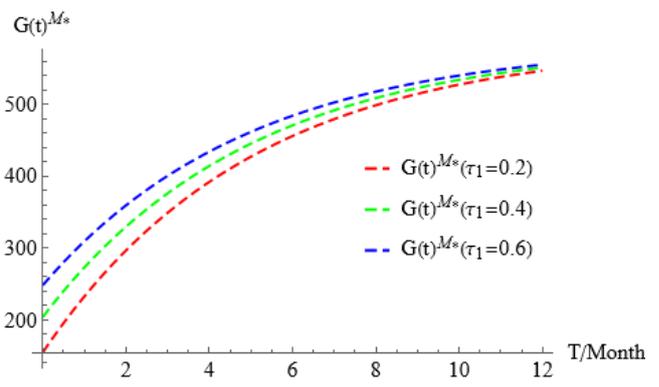
Figure 7(a). Impact on grain quality.
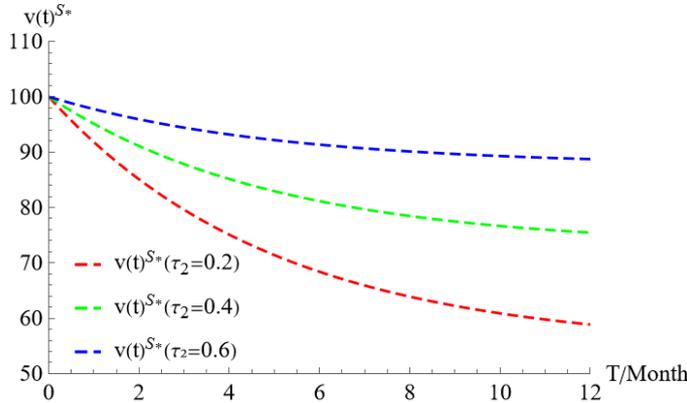
Figure 7(b). Impact on marketing efforts.

Figure 7(c). Impact of storage tool subsidy rate on grain quality.

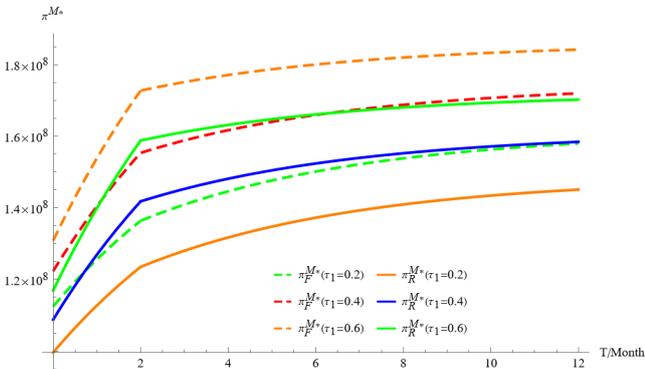**Figure 7.** The impact of the grain price subsidy rate.

Figure 8(a). Grain price subsidy.
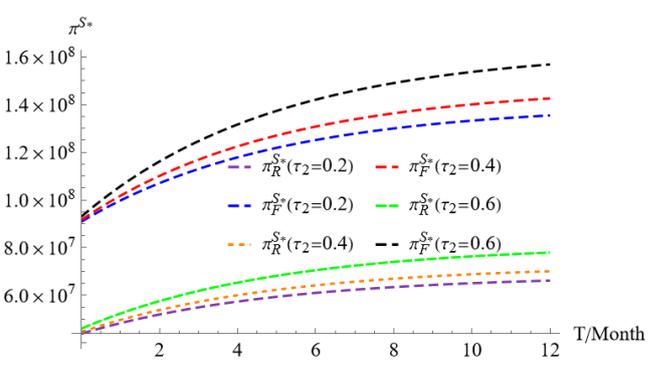
Figure 8(b). Storage tool subsidy.

Figure 8. Impact of the rate on farmer and grain enterprise income.

As shown in Figure 7, both grain quality and marketing investments by grain enterprises exhibit an upward trend as subsidy intensity increases. This phenomenon primarily arises from the dual regulatory role of subsidies in terms of costs and returns. On the one hand, subsidies effectively reduce the actual input costs for farmers and enterprises, thereby motivating farmers to increase storage efforts and improve grain quality. On the other hand, the improvement in grain quality enhances market competitiveness and sales potential, which in turn drives enterprises to increase marketing investment in

order to achieve market expansion and strengthen brand value, thereby forming a virtuous cycle. As can be seen from Figure 8, the increase in subsidy intensity has significantly promoted the growth of the incomes of farmers and grain enterprises. Combined with the results in Figure 7, it can be inferred that with the increase in subsidy intensity, grain quality and the marketing efforts of grain enterprises have also improved simultaneously, and these are precisely the key factors driving the rise in incomes. Specifically, on the one hand, the enhancement of subsidy intensity has encouraged farmers to increase storage investment, thereby improving the overall quality of grain during the circulation process; on the other hand, it has provided grain enterprises with more disposable resources, enabling them to increase investment in brand promotion, channel expansion, and other aspects. The improvement of grain quality helps to enhance market competitiveness, while the increase in marketing investment is conducive to expanding sales scope and improving product awareness. These two aspects work synergistically to jointly push up the economic returns of farmers and enterprises.

6.2. A comparative study of the mixed subsidy model and the single subsidy model

As shown in Table 2 and Figure 9(a), under the condition of the same subsidy intensity, the optimal grain storage quality achieved by the mixed subsidy model is significantly better than that of the single storage tool subsidy model. This result indicates that the synergistic effect of price incentives and technical support can more effectively stimulate farmers' willingness to invest in storage, thereby improving the quality of stored grain. At the same time, with the extension of storage time, the gap in grain quality under different subsidy models gradually narrows, which shows that subsidy policies have a more significant impact on farmers' behaviors in the early stage, while their long-term effects are restricted by the natural deterioration of grain quality.
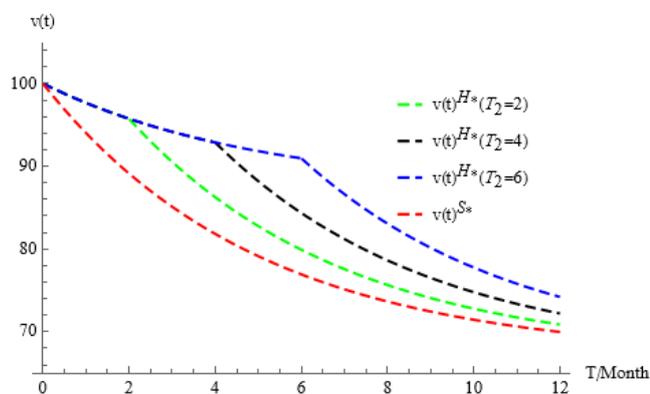

Figure 9(a). Comparison of grain quality.
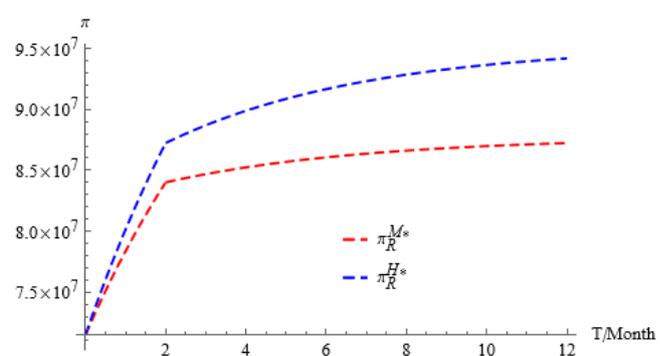
Figure 9(b). Comparison of farmer income.

Figure 9. Comparison of the hybrid subsidy and storage tool subsidy.

Furthermore, when combining the data from Table 3 and Figure 9(b), it can be observed that under the same duration of grain price subsidies, the hybrid subsidy model demonstrates significant advantages over the single price subsidy model in increasing farmers' income. Moreover, this income gap continues to widen as the subsidy period extends. This phenomenon indicates that the hybrid subsidy not only enhances farmers' sales motivation in the short term through price signals but also slows down grain quality deterioration by improving storage conditions, thereby amplifying the cumulative effect of income growth over the long term. In contrast, while the single price subsidy can quickly boost farmers'

immediate income, it lacks sustained support for grain quality improvement, making it difficult to achieve continuous income growth.

Table 2. Comparison of grain quality under the hybrid subsidy and new storage tool subsidy models.

T_2	v^{S*}	T_3	T_4	v^{H*}
0.2	58.90	0.2	0.2	62.87
			0.4	63.40
			0.6	63.92
0.4	75.70	0.4	0.2	80.81
			0.4	81.50
			0.6	82.20
0.6	88.70	0.6	0.2	89.51
			0.4	90.29
			0.6	91.07

Table 3. Comparison of farmer income under the hybrid subsidy and grain price subsidy models.

τ_1	π_F^{M*}	τ_3	τ_4	π_F^{H*}
0.2	8.069×10^7	0.2	0.2	8.437×10^7
			0.4	8.541×10^7
			0.6	8.610×10^7
0.4	8.134×10^7	0.4	0.2	9.145×10^7
			0.4	9.220×10^7
			0.6	9.295×10^7
0.6	8.199×10^7	0.6	0.2	1.049×10^8
			0.4	1.076×10^8
			0.6	1.085×10^8

7. Conclusions and implications

7.1. Conclusions

As the starting point of the grain supply chain, farmers play a crucial role in influencing grain quality and quantity during the post-harvest stage. However, in China, a high proportion of grain is stored by farmers themselves, and due to outdated traditional storage tools, significant losses occur during storage [4]. To safeguard grain quality from the source and reduce storage losses, this study proposes three policy interventions: grain price subsidies, subsidies for new storage tools, and a hybrid subsidy model. These policies aim to protect farmers' profits while minimizing losses in the grain storage process. Through rigorous analysis, the following conclusions are drawn:

1) On the premise that the subsidy intensity and duration remain unchanged, the hybrid subsidy model, by incentivizing farmers to increase storage efforts and grain enterprises to enhance marketing input simultaneously, demonstrates significantly greater advantages than the single subsidy model in improving grain quality and ensuring farmers' income. By acting on two key links—storage and sales—at the same time, this model creates a synergistic effect, thereby achieving better policy performance.

2) Both grain price subsidies and new storage tool subsidies help improve grain quality and increase the income of farmers and grain enterprises. However, due to their different focus areas, the new storage tool subsidies are significantly more effective than price subsidies in improving grain quality, while grain price subsidies have a more notable effect in increasing farmers' income.

3) Grain price subsidies and hybrid subsidies can effectively boost the marketing input of grain enterprises, but the new storage tool subsidies have little impact on enterprises' marketing efforts. Meanwhile, grain price subsidies and hybrid subsidies can raise the grain purchase price; and as the subsidy period extends, grain quality, the marketing input of grain enterprises, and the income of both farmers and enterprises all show an upward trend.

4) As the grain decay rate increases, grain quality decreases significantly, and the effectiveness of subsidies in improving grain quality also diminishes. Furthermore, a higher forgetting rate weakens the incentivizing effect of grain price subsidies on enterprises' marketing efforts. This indicates that in high-decay or high-forgetting environments, the marginal effects of policy interventions are significantly constrained, necessitating the optimization of subsidy strategies based on practical conditions.

5) As the grain decay rate increases, grain quality decreases significantly, and the effectiveness of subsidies in improving grain quality also diminishes. Furthermore, a higher forgetting rate weakens the incentivizing effect of grain price subsidies on enterprises' marketing efforts. This indicates that in high-decay or high-forgetting environments, the marginal effects of policy interventions are significantly constrained, necessitating the optimization of subsidy strategies based on practical conditions.

7.2. Policy recommendations

To effectively safeguard farmers' incomes and reduce post-harvest losses, based on the above research conclusions, we put forward the following policy recommendations:

1) To ensure grain quality at the source and increase farmers' incomes, the government should give priority to implementing the mixed subsidy policy. The conclusions of this study indicate that the mixed subsidy model is significantly superior to the single subsidy model in improving grain quality and increasing farmers' incomes. From the perspective of policy implementation, the mixed subsidy has greater flexibility and adaptability—it can not only effectively share market risks but also better mobilize the enthusiasm of both farmers and grain enterprises. For instance, although a single price subsidy can stimulate enterprises' sales in the short term, it may induce enterprises to pursue short-term profits and neglect long-term investment in agricultural product quality; while a single storage subsidy can improve grain quality, it may lead to inventory backlogs and poor sales due to the lack of market driving force. In contrast, the mixed subsidy exerts "two-way efforts" on the supply side and the demand side, realizing the coordinated optimization of quality improvement and market efficiency. While stabilizing the grain market, it also takes into account the fairness and sustainability of the policy. Therefore, the mixed subsidy model has greater practical promotion value and deserves priority consideration and in-depth exploration in policy design.

2) To reduce post-harvest grain losses, the government should appropriately increase the intensity of subsidies and extend their duration. This is because subsidies not only serve the basic function of "cost compensation" but also, to a certain extent, guide positive behavioral changes: driven by subsidies, farmers attach greater importance to grain storage management, while enterprises focus more on brand building and market expansion. Therefore, from the perspective of policy design, reasonably enhancing the intensity and duration of subsidies—especially implementing more targeted and precise subsidies in the links of grain storage and circulation—will not only help improve the income levels of all parties in the industrial chain but also is expected to achieve the coordinated improvement of grain quality and market-oriented capabilities.

7.3. Limitations and future research directions

Although this study systematically analyzes the impact of subsidy policies on grain quality and farmer income from perspectives of subsidy intensity, duration, and models, limitations remain regarding policy implementation heterogeneity and refined design. The simulation analysis primarily operates under unified assumptions, without fully accounting for potential variations in responses across regions, crop types, and farm operation scales. In practice, factors such as regional climate conditions, infrastructure levels, crop storage characteristics, and farmers' resource endowments may significantly influence the marginal effects of subsidies. For instance, economically underdeveloped regions may rely more heavily on subsidies to promote improved storage practices, while large-scale farmers with abundant resources may exhibit lower sensitivity to subsidies. A one-size-fits-all subsidy mechanism could lead to inefficient allocation of policy resources or even mismatched subsidies. Future research should therefore focus on developing differentiated subsidy models that systematically incorporate key variables like regional characteristics, crop varieties, and farm sizes. Such efforts would help advance tailored policy designs based on local conditions and actual needs, ultimately enhancing the adaptability and effectiveness of subsidy policies.

Author contributions

Jianhua Wang was responsible for conceptualization and supervision, while Xing Huang handled manuscript writing and methodology.

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Conflict of interest

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

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