Subsidizing Grain Post-harvest Loss Reduction Level or Loss Reduction Inputs? A Game Analysis in China

Pan Liu, Man Zhang, Muhammad Ahmad

***Abstract*—To reduce the post-harvest losses of the whole grain supply chain, the Chinese government often provides two kinds of subsidies to encourage the enthusiasm to use losses reduction equipment, namely, subsidizing loss reduction level or subsidizing loss reduction inputs. To explore which subsidy model is more beneficial to the loss reduction effect, four investment subsidy models were constructed and analyzed. The research indicated that: (1) When a certain condition is met, subsidizing loss reduction level can lead to higher returns for grain supply chain members than subsidizing loss reduction inputs. (2) Compared with the single subsidy model, the mixed subsidy model (subsidizing both post-harvest loss reduction level and loss reduction inputs) can make grain producers obtain higher profits. However, it failed to maximize the government benefit compared with only subsidizing the post-harvest loss reduction inputs. (3) The subsidy coefficient about the loss reduction level is related to quality and quantity loss reduction levels.**

***Index Terms*—case study, game theory, grain post-harvest losses, losses reduction level, subsidy policy**

I. INTRODUCTION

Grain security is crucial for human life. Under resource and environmental constraints, a country's grain output cannot continue to increase. At this time, reducing grain post-harvest losses is an important way to ensure grain supply. Grain post-harvest losses in China (hereafter, GPHL) were a serious problem. According to the China Agricultural Sector Development Report 2023, the annual losses of grain storage, transportation, and processing in China remain at more than 35 billion kilograms. Studies show that about 27 percent of China's grain is lost or wasted each year, 45 percent of which is related to post-harvest handling and storage [1]. In addition, the utilization rate of resources and technology in GPHL has stayed low. For example, the transportation proportion of bulk grain is only 25%, whereas 22.35% of rice is stored in metal containers [2].

To reduce the post-harvest losses of the whole grain supply chain, The Chinese government has developed various subsidy policies, as outlined in Table I.

Table I reveals that the Chinese government often provides two kinds of subsidies to encourage enthusiasm to use loss reduction equipment, namely, subsidizing loss reduction level or subsidizing loss reduction inputs. In this background, urgent questions arise regarding the optimal investment subsidy model and the subsidy threshold. Therefore, in this paper, we will explore the following questions:

(1) Which investment subsidy model is more effective?

(2) What are the subsidy thresholds under different investment subsidy models?

However, most of the existing research focuses on two aspects. Firstly, the measurement of GPHL [3]-[6], cause analysis [7]-[14], and reduction measures [15]-[18]. Secondly, subsidy strategies within the grain supply chain primarily rely on statistical and experimental methods [19]-[22]. Numerous scholars have also employed game theory to investigate government subsidy [19], [23]-[25].

Existing research has the following deficiencies:(1) GPHL can be divided into quality losses and quantity losses. The existing research on grain loss subsidy mechanisms lacks comprehensive consideration of grain quality and quantity losses. (2) Few studies have explored the impact of different government loss reduction subsidy models on loss reduction effect. Therefore, we focused on the government GPHL reduction subsidies (subsidizing GPHL reduction level or subsidizing GPHL reduction inputs) and explored the optimal investment subsidy model by using game theory. In addition, grain quality reduction level and quantity reduction level were considered comprehensively.

To solve the above questions, we introduced the concepts of grain quantity and quality loss reduction level, along with their functional expressions, and refined the demand function. Based on the impacts of existing subsidies, we constructed and analyzed four investment subsidy models. The results can enrich the theoretical framework of GPHL reduction subsidies in the grain supply chain. It also provides support for government policy formulation and supply chain investment decisions.

Our contributions are as follows: (1) We proposed novel concepts and functional expressions for grain quality and quantity loss reduction levels. Considering the convenience of data obtaining, we use quality and quantity loss reduction costs to reflect loss reduction inputs. (2) We modified the market demand function considering the influence of grain

Manuscript received Apr 5, 2024; revised Dec 30, 2024.

This work was supported in part by the Top Talent Project of Henan Agricultural University (No. 30500681), Henan Agricultural University Social Sciences Prosperity Project Key Project (No. FRZS2024A02), the Humanities and Social Sciences Planning Fund Project of the Ministry of Education of China (24YJA790034), China Postdoctoral Science Foundation General Project (2022M721039), Henan University Philosophy and Social Science Innovation Talent Support Program (No. 2023-CXRC-24), Henan Province High-level Talent International Training Project (GCC2025016), and Henan Province Philosophy and Social Sciences Planning Annual Project (2024CJJ065).

Pan Liu is a professor of College of Information and Management Science, Henan Agricultural University, Zhengzhou 450046, China. (corresponding author to provide phone: 16603850622; e-mail: hnycliupan@163.com).

Man Zhang is a postgraduate student of College of Information and Management Science, Henan Agricultural University, Zhengzhou 450046, China. (e-mail: 936781892@qq.com).

Ahmad Muhammad is a postgraduate student of College of Information and Management Science, Henan Agricultural University, Zhengzhou 450046, China. (e-mail: ahmadsarfraz0996@gmail.com).

quality loss reduction level on consumer acceptance. (3) We constructed four investment subsidy models and worked out the subsidy threshold.

TABLE I
SUMMARY OF RELEVANT GRAIN SUBSIDY POLICIES FROM CHINA

Date	Policy Name	Policy contents
2002	Subsidy for high-quality seed	The subsidy is provided according to the planting area, which encourages grain producers to use good seeds and then improve grains' yield and quality.
2004	Purchase subsidy for agricultural machinery	Grain producers who buy agricultural machinery can receive a certain percentage of the subsidy.
2004	Direct subsidy for grain	The subsidy is provided according to the planting area, which encourages grain producers to grow more grains.
2006	Integrated subsidy	This subsidy is mainly to compensate for the rising cost of production means.
2015	Agricultural support and protection subsidy	This subsidy includes subsidy for high-quality seed, direct subsidy for grain, and integrated subsidy.
2016	Four subsidies	This subsidy includes subsidy for high-quality, the purchase subsidy for Grain, and the integrated subsidy.
2016	Subsidy for the protection of cultivated land capacity	This subsidy includes the subsidy for high-quality Seed and the integrated subsidy.
2020	Subsidy for agricultural product loss reduction	This policy proposes that by 2025, the loss rate of agricultural product processing should be reduced to less than 5%.
2021	Food Conservation Action program	Strengthen grain production links, transportation links, processing links, and other links to reduce grain losses.
2024	Opinions on the implementation of subsidies for the purchase and application of agricultural machinery from 2024 to 2026	Subsidies shall be provided in proportion, and the estimated proportion of the subsidy amount shall not exceed 35% in principle.

Data Source: http://www.moa.gov.cn/

II. LITERATURE REVIEW

Our research involved the following two aspects. Firstly, we focused on the post-harvest losses within the grain supply chain. Secondly, subsidy strategies of the grain supply chain.

A. Post-harvest losses of grain supply chain

Research on post-harvest losses within the grain supply chain predominantly focuses on three areas: (1) Measurement of GPHL. In developing countries, post-harvest losses can reach up to 70% [3]. Accurately measuring the losses is crucial for understanding the severity of the problem and developing effective intervention strategies. Therefore, many studies focused on the measurement methods of GPHL [4]-[6]. (2) Cause analysis. People often attribute it to outdated harvest techniques and inadequate post-harvest infrastructure [7]. Some scholars also carried out specific analyses of each supply chain link [8]-[12]. Research has shown that traditional harvesting and threshing methods lead to substantial grain spillage and damage. Insufficient drying facilities and poor storage conditions make the grain susceptible to pests, mildew, spoilage and so on [13], [14]. The presence of foreign objects in rice collections is known to pose significant concerns for both food safety and product quality. [15] (3) Reduction measures, such as variety improvement, farmer education, enhanced storage techniques, and integrated pest management, are implemented. [16]-[19].

B. subsidy strategies of grain supply chain

Studies on subsidy strategies within the grain supply chain primarily rely on statistical and experimental methods. For instance, Yi et al. [20] examined the impact of grain subsidies on farming households, while Ricker-Gilbert and Jones [21] studied the effects of corn warehousing subsidies on farmer adoption behavior. Other works assessed the introduction of new storage technologies [22] or analyzed the impacts of agricultural machinery subsidies [23]. Numerous scholars have also employed game theory to investigate government subsidy [20], [24]-[28], although few have applied it specifically to GPHL reduction subsidy strategies [29], [30].

Current research reveals two significant gaps: (1) Few studies incorporate game theory, taking into account both the reduction of quantity and quality losses when examining government subsidy policies. (2) There's a dearth of comparisons between subsidizing GPHL reduction level and GPHL reduction inputs, along with an exploration of subsidy thresholds under different models. This research comprehensively discussed government subsidy strategies that take into account the reduction of grain quality and quantity losses.

III. PROBLEM PRESENTATION

In our study, we chose grain producers and the government as our research subjects. If the grain producer invests in GPHL reduction equipment, the Chinese government will provide a series of subsidies. We divided these subsidy models into the following three types: subsidizing GPHL reduction inputs independently, subsidizing GPHL reduction level independently, and subsidizing both GPHL reduction inputs and GPHL reduction level. Therefore, four investment subsidy models were constructed, namely, NCL, CNL, LNC, and CLB (this is shown in Fig.1). We refer to the CNL and LNC models as a single subsidy strategy, while we describe the CLB model as a hybrid subsidy strategy.

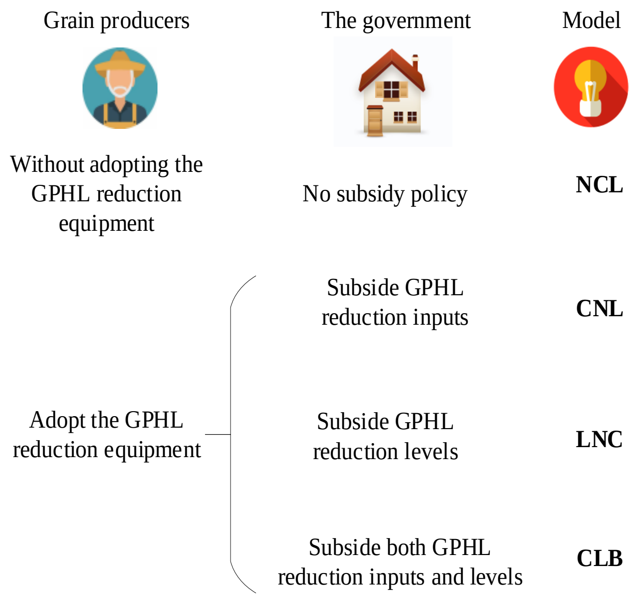

Fig. 1 Four investment subsidy models

A. Parameter Specification

Table II displays the parameters used in our research.

TABLE II
THE DESCRIPTION OF THE RELATED VARIATE

Parameter	Explanation
λ_1	The unit quantity loss coefficient of grain producers before adopting GPHL reduction equipment.
c	The plant cost of grain producers.
C	The GPHL reduction inputs of grain producers.
a	Basic demand for grain.
m	The unit yield of grain.
q_0	The initial quality of grain during the harvest stage is important.
α_1	The quality loss coefficient of grain producers before adopting GPHL reduction equipment, $1 \ge \alpha_1 \ge 0$.
k_1	The cost coefficient of the quantity loss reduction from grain producers.
k_2	The cost coefficient of the quality loss reduction from grain producers.
i	$i = \{NCL, CNL, LNC, CLB\}$.
p_i	The retail price of grain in the i model.
$p_{\max}$	The price is when the market demand equals zero.
s	The subsidy coefficient of loss reduction inputs.
F_1	The subsidy coefficient of loss reduction level.
δ_1	The loss coefficient per unit quantity of grain producers when the government subsidizes loss reduction inputs, $0 \le \delta_1 \le 1$.
β_1	The quality loss coefficient of grain producers when the government subsidizes loss reduction inputs, $\beta_1 > 1$.
$\delta_1^{'}$	The loss coefficient per unit quantity of grain producers when the government subsidizes loss reduction level, $0 \le \delta_1^{'} \le 1$.
$\beta_1^{'}$	The quality loss coefficient of grain producers when the government subsidizes loss reduction level, $\beta_1^{'} > 1$.
δ	The reduction level of quantity losses when the government subsidizes loss reduction inputs, $\delta = 1 - \delta_1$.
β	The reduction level of quality losses when the government subsidizes loss reduction inputs, $\beta = \beta_1 - 1$.
$\delta^{'}$	The reduction level of quantity losses when the government subsidizes loss reduction level, $\delta^{'} = 1 - \delta_1^{'}$.
$\beta^{'}$	The reduction level of quality losses when the government subsidizes loss reduction level, $\beta^{'} = \beta_1^{'} - 1$.

B. Assumptions

(1) We assume that the unit yield of grain is m. Before grain producers adopt the GPHL reduction equipment, the unit quantity losses of grain producers can be expressed as $\lambda_1 m$. When the government subsidizes GPHL reduction inputs, the unit quantity losses of grain producers are $\delta_1 \lambda_1 m$. Thus, the GPHL reduction level $\delta = \frac{(\lambda_1 m - \delta_1 \lambda_1 m)}{\lambda_1 m} = 1 - \delta_1$. When the government subsidizes the GPHL reduction level, the unit quantity losses of grain producers are $\delta_1^{'} \lambda_1 m$. Thus, the GPHL reduction level $\delta^{'} = \frac{(\lambda_1 m - \delta_1 \lambda_1 m)}{\lambda_1 m} = 1 - \delta_1^{'}$. Similar to Liu and Ls et al. [31], [32], the quantity losses reduction cost $k_1 \delta^2 / 2$ (or $k_1 (\delta^{'})^2 / 2$).

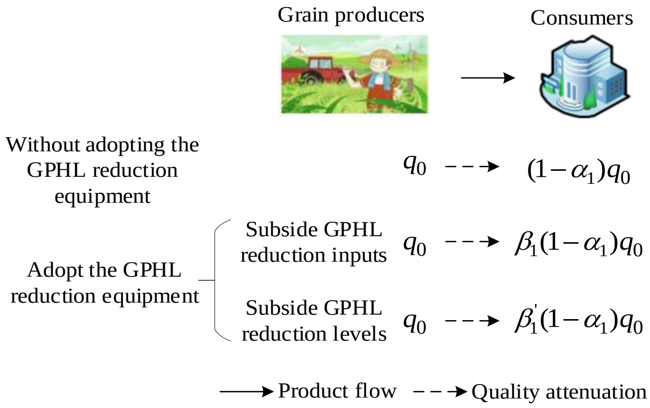

Fig. 2. Deterioration situation of grain quality in different loss reduction backgrounds

(2) We assume that the initial quality of the grain at the harvest stage is q_0 (see Fig. 2). Before grain producers adopt the GPHL reduction equipment, the quality of the grain decreases to $(1-\alpha_1) q_0$. When the government subsidizes GPHL reduction inputs, the quality of grain decreases to $\beta_1 (1-\alpha_1) q_0$ (due to $\beta = \beta_1 - 1$, $\beta_1 (1-\alpha_1) q_0 = (\beta + 1) \cdot (1-\alpha_1) q_0$). When the government subsidizes GPHL reduction level, the quality of grain decreases to $\beta_1^{'} (1-\alpha_1) q_0$ (due to $\beta' = \beta_1^{'} - 1$, $\beta_1^{'} (1-\alpha_1) q_0 = (\beta' + 1)(1-\alpha_1) q_0$). Here, $1 \ge \beta_1 (1-\alpha_1) \ge (1-\alpha_1) \ge 0$ and $1 \ge \beta_1^{'} (1-\alpha_1) \ge (1-\alpha_1) \ge 0$.

(3) When the government subsidizes GPHL reduction inputs, the quality losses Δq are $(\beta_1 - 1)(1-\alpha_1) q_0$, and the reduction level of quality losses are $\Delta q / (1-\alpha_1) q_0 = (\beta_1 - 1) = \beta$. When the government subsidizes the GPHL reduction level, the quality losses Δq are $(\beta_1^{'} - 1)(1-\alpha_1) q_0$, and the reduction level of quality losses is $\Delta q / (1-\alpha_1) q_0 = (\beta_1^{'} - 1) = \beta^{'}$. Like Chen & Chen [33] and Mla et al. [34], we assume that grain producers' inputs of quality loss reduction are $k_2 (\beta_1 - 1)^2 / 2 = k_2 \beta^2 / 2$ (or $k_2 (\beta_1^{'} - 1)^2 / 2 = k_2 (\beta^{'})^2 / 2$).

(4) Considering the convenience of data acquisition about GPHL reduction cost, we proposed to use quality loss reduction cost and quantity loss reduction cost to reflect the GPHL reduction inputs. Namely, the GPHL reduction inputs of grain producers equal $C = k_1 \delta^2 / 2 + k_2 \beta^2 / 2$ (or $C = k_1 (\delta^{'})^2 / 2 + k_2 (\beta^{'})^2 / 2$).

(5) Similar to Nie et al. [35] and Zhang et al. [36], we assume that the demand formula can be as $D^i = a - p_i + (\beta + 1)^{z_1} (1-\alpha_1)^{z_2} q_0$. When $i = \{NCL\}$, $z_2 = 1$ and $z_1 = 0$, otherwise, $z_2 = 1$ and $z_1 = 1$.

(6) To stimulate grain producers to reduce GPHL, the government will offer a subsidy with a variable coefficient. We assume that coefficient s or F_1.

(7) Consumer surplus is an important index to measure consumer welfare. It reflects the difference between the actual market price and the maximum price that consumers are willing to pay for a certain quantity of goods. The function

expression of consumer surplus in this paper is as follows: $CS = \int_{p_i}^{p_{mas}} D_i dp = \frac{D_i^2}{2}$.

(8) We assume that the grain demand is in tight equilibrium, that is, the output is saleable.

IV. RESULTS

A. NCL Model

In the NCL model, grain producers will not adopt the GPHL reduction equipment. The profit functions of grain producers and the government are as follows:

$$\pi_p^{NCL} = (p^{NCL} - c)D^{NCL}(1-\lambda_1) \tag{1}$$

$$\pi_g^{NCL} = \pi_p^{NCL} + CS^{NCL} \tag{2}$$

From equations (1) and (2), we can get proposition 1 (the analysis process sees Appendix A-1).

Proposition 1. In the NCL model, we constructed the optimal decision about equilibrium price, and benefits of grain producers and the government (see Eq. (3) and Eq. (4)).

$$\begin{cases} p^{NCL*} = \dfrac{a+c+q_0(1-\alpha_1)}{2} \\ D^{NCL*} = \dfrac{a-c+q_0(1-\alpha_1)}{2} \end{cases} \tag{3}$$

$$\begin{cases} \pi_p^{NCL*} = \dfrac{(1-\lambda_1)A^2}{4} \\ \pi_g^{NCL*} = \dfrac{A^2(3-2\lambda_1)}{8} \end{cases} \tag{4}$$

Here, $A = a-c+q_0(1-\alpha_1)$.

B. CNL Model

In the CNL model, grain producers will adopt the GPHL reduction equipment, and the government will subsidize the GPHL reduction inputs. The profit functions of grain producers and the government are as follows:

$$\pi_p^{CNL} = (p^{CNL} - c)D^{CNL}[1-(\delta+1)\lambda_1] - \frac{(1-s)[k_1\delta^2 + \mathrm{k}_2\beta^2]}{2} \tag{5}$$

$$\pi_g^{CNL} = \pi_p^{CNL} + CS^{CNL} - \frac{s[k_1\delta^2 + \mathrm{k}_2\beta^2]}{2} \tag{6}$$

From equations (5) and (6), we can get Proposition 2 (the analysis process is similar to it in Proposition 1).

Proposition 2. In the CNL model, we constructed the optimal decision about equilibrium price, and benefits of grain producers and the government (see Eq. (7) and Eq. (8)).

$$\begin{cases} p^{CNL*} = \dfrac{a+c+(\beta+1)q_0(1-\alpha_1)}{2} \\ D^{CNL*} = \dfrac{a-c+(\beta+1)q_0(1-\alpha_1)}{2} \end{cases} \tag{7}$$

$$\begin{cases} \pi_p^{CNL*} = \dfrac{[1-(\delta+1)\lambda_1]E^2}{4} - \dfrac{(1-s)[k_1\delta^2 + \mathrm{k}_2\beta^2]}{2} \\ \pi_g^{CNL*} = \dfrac{E^2[3-2\lambda_1(\delta+1)]}{8} - \dfrac{k_1\delta^2 + \mathrm{k}_2\beta^2}{2} \end{cases} \tag{8}$$

Here, $E = a-c+(\beta+1)q_0(1-\alpha_1)$.

According to proposition 2, we can get inference 1 (the analysis process sees Appendix B-1).

Inference 1.

① $\frac{\partial p^{CNL*}}{\partial s} = 0$, $\frac{\partial \pi_p^{CNL*}}{\partial s} > 0$, $\frac{\partial \pi_g^{CNL*}}{\partial s} = 0$

From ① in inference 1, we can get that in the CNL model, the subsidy coefficient of GPHL reduction inputs (s) does not influence the equilibrium price and the government income (p^{CNL*} and π_g^{CNL*}), but positively correlates with the grain producers income (π_p^{CNL*}).

The phenomenon can be attributed to the following factors. Grain producers typically face high marginal production costs. The government subsidy for GPHL reduction inputs can effectively address economic limitations of scale. In this way, the marginal costs for grain producers are reduced, which increases the supply of grain. Because of the tight balance of grain demand in the grain market, the income of grain producers will be increased. However, the subsidy predominantly impacts the supply side. Due to the assumption that output is saleable, the equilibrium price is not influenced by the subsidy coefficient. In other words, the government subsidy does not directly lead to a decrease in the equilibrium price but rather alleviates supply constraints. Furthermore, government subsidies, as a form of market intervention, primarily serve to assist grain producers in ensuring the continuity of production and the stability of supply. It doesn't aim to regulate the equilibrium price or increase the government's income.

② $\frac{\partial p^{CNL*}}{\partial \delta} = 0$, $\frac{\partial \pi_p^{CNL*}}{\partial \delta} < 0$, $\frac{\partial \pi_g^{CNL*}}{\partial \delta} < 0$

From ② in inference 1, we can see that quantity loss reduction level (δ) does not influence equilibrium price (p^{CNL*}), but negatively correlates with both producer and government income (π_p^{CNL*} and π_g^{CNL*}).

This phenomenon can be attributed to the following factors. The demand for necessities such as grain is relatively stable and has a low-price elasticity. Therefore, the equilibrium price is not affected by the reduction level of quantity losses. In addition, any reduction in quantity losses enables grain producers to sell more grain, which in turn leads to an increase in storage and transportation costs. Since the equilibrium price of grain remains unchanged, the additional revenue generated by selling more grain is not enough to offset these increased costs. Government revenue is composed of the profits of supply chain members, consumer surplus, and related subsidy expenditures. The decline in grain producers' profits leads to a decrease in government revenue.

③ $$\begin{cases} \dfrac{\partial p^{CNL*}}{\partial \beta} > 0 \\ \dfrac{\partial \pi_p^{CNL*}}{\partial \beta} = 0, \quad \beta = \dfrac{q_0(1-\alpha_1)[\lambda_1(\delta+1)-1]E}{2k_1(s-1)} \\ \dfrac{\partial \pi_g^{CNL*}}{\partial \beta} = 0, \quad \beta = \dfrac{Aq_0(\alpha_1-1)[2\lambda_1(\delta+1)-3]}{4k_2 - {q_0}^2(\alpha_1-1)^2[3-2\lambda_1(\delta+1)]} \end{cases}$$

From ③ in Inference 1, we can see that quality loss reduction level (β) positively correlates with equilibrium price (p^{CNL*}). When the reduction level of quality losses (β) is below a certain threshold, it positively correlates with both producer and government income (π_p^{CNL*} and π_g^{CNL*}). Conversely, it negatively correlates above this threshold.

This phenomenon can be attributed to the following factors. As the reduction level of quality losses increases, the quality of grain supplied in the market improves. In this case, consumers are willing to pay a higher price. This willingness increases the equilibrium price. For grain producers, when the reduction level of quality losses is below a certain threshold (Here, we got $\beta = \frac{q_0(1-\alpha_1)[\lambda_1(\delta+1)-1]E}{2k_1(s-1)}$), the rise in equilibrium price enables grain producers to sell grain at a higher price, thereby increasing profits. However, as the reduction level of quality losses continues to rise, the marginal benefits decrease. When the reduction level of quality losses is higher than this threshold, the cost of further increasing the reduction level of quality losses will be higher than the profit brought by the improvement in grain quality. Due to the increase in grain producer income, government revenue will also increase under certain circumstances. When the reduction level of quality losses is lower than a certain threshold, the government income increases (Here, we got $\beta = \frac{Aq_0(\alpha_1-1)[2\lambda_1(\delta+1)-3]}{4k_2 - {q_0}^2(\alpha_1-1)^2[3-2\lambda_1(\delta+1)]}$). However, when the reduction level of quality losses exceeds this threshold, the government income decreases. This could be because the revenue from improved grain quality is insufficient to cover the associated subsidy expenditures.

C. LNC Model

In the LNC model, grain producers will implement the GPHL reduction equipment, and the government will subsidize the GPHL reduction level. The profit functions of the grain producers and the government are as follows:

$$\pi_p^{LNC} = (p^{LNC}-c)D^{LNC}[1-(\delta^{'}+1)\lambda_1] - \frac{k_1(\delta^{'})^2 + k_2(\beta^{'})^2}{2} + F_1(\delta^{'}+\beta^{'}) \tag{9}$$

$$\pi_g^{LNC} = \pi_p^{LNC} + CS^{LNC} - F_1(\delta^{'}+\beta^{'}) \tag{10}$$

From equations (9) and (10), we can get Proposition 3 (the analysis process is similar to it in Proposition 1).

Proposition 3. In the LNC model, we constructed the optimal decision about equilibrium price and benefits of grain producers and the government (see Eq. (11) and Eq. (12)).

$$\begin{cases} p^{LNC*} = \dfrac{a+c+(\beta^{'}+1)q_0(1-\alpha_1)}{2} \\ D^{LNC*} = \dfrac{a-c+(\beta^{'}+1)q_0(1-\alpha_1)}{2} \end{cases} \tag{11}$$

$$\begin{cases} \pi_p^{LNC*} = \dfrac{(E^{'})^2[1-(\delta^{'}+1)\lambda_1]}{4} - \dfrac{k_1(\delta^{'})^2+k_2(\beta^{'})^2}{2} + F_1(\beta^{'}+\delta^{'}) \\ \pi_g^{LNC*} = \dfrac{(E^{'})^2[3-2\lambda_1(\delta^{'}+1)]}{8} - \dfrac{k_1(\delta^{'})^2+k_2(\beta^{'})^2}{2} \end{cases} \tag{12}$$

Here, $E^{'} = a - c + (\beta^{'}+1)q_0(1-\alpha_1)$.

According to Proposition 3, we can get inference 2 (the analysis process sees Appendix B-2).

Inference 2.

① $\frac{\partial p^{LNC*}}{\partial F_1} = 0$, $\frac{\partial \pi_p^{LNC*}}{\partial F_1} > 0$, $\frac{\partial \pi_g^{LNC*}}{\partial F_1} = 0$

From ① in inference 2, in the LNC model, the subsidy coefficient (F_1) of the loss reduction level does not influence the equilibrium price and the government income (p^{LNC*} and π_g^{LNC*}), but positively correlates with the grain producers income (π_p^{LNC*}).

The main reasons for this phenomenon are as follows. Restricted by many factors such as land resources and technological input, grain producers often face higher marginal costs. Government subsidies increase the marginal benefits of grain producers by covering part of the costs. Therefore, the subsidy coefficient is positively correlated with the income of grain producers. In a tight equilibrium market, the equilibrium price is greatly affected by the demand side, while government subsidies mainly affect the supply side. They do not directly lead to a drop in the equilibrium price, but rather ease supply constraints. As a form of market intervention, the main function of government subsidies is to support grain farmers and ensure the continuity of production.

② $\begin{cases} \dfrac{\partial p^{LNC*}}{\partial \delta^{'}} = 0 \\ \dfrac{\partial \pi_p^{LNC*}}{\partial \delta^{'}} = 0, \quad \delta^{'} = \dfrac{4F_1 - \lambda_1 E^2}{k_1} \\ \dfrac{\partial \pi_g^{LNC*}}{\partial \delta^{'}} < 0 \end{cases}$

From ② in inference 2, we can see that the reduction level of quantity losses ($\delta^{'}$) does not influence the equilibrium price (p^{LNC*}), but negatively correlates with the government income (π_g^{LNC*}). When the reduction level of quantity losses ($\delta^{'}$) is below a certain threshold, it positively correlates with the income of grain producers (π_p^{LNC*}). Conversely, it negatively correlates above this threshold.

This phenomenon can be attributed to the following factors. In a tight market, grain demand is relatively stable and price elasticity is low. Therefore, the reduction level of grain quantity losses will not affect the equilibrium price. For grain producers, profits will increase as the reduction level of quantity losses increases when the level is below a certain threshold (here, we got $\delta^{'} = \frac{4F_1 - \lambda_1 E^2}{k_1}$). This is because the cost of loss reduction measures is relatively low in the initial stage, but the effect is significant. The increase in grain production makes up for the costs borne by grain producers. Therefore, the profits of grain producers in the initial stage are positively related to the reduction level of quantity losses. However, as grain producers continue to increase the reduction level of quantity losses, their marginal benefits continue to decrease. Once the threshold is exceeded, the costs of further reducing losses become large. The additional benefits brought by increased grain production are not enough to offset these costs, thus showing a negative correlation. Furthermore, the additional income of grain producers and consumer surplus are not enough to offset the cost of subsidies, so government revenue is negatively correlated with the reduction level of quantity losses.

③ $$\begin{cases} \dfrac{\partial p^{LNC*}}{\partial \beta'} > 0 \\ \dfrac{\partial \pi_p^{LNC*}}{\partial \beta'} = 0,\ \beta' = \dfrac{F_1 - Aq_0(1-\alpha_1)[\lambda_1(\delta'+1)-1]}{2k_2 + q_0{}^2(\alpha_1-1)^2[\lambda_1(\delta'+1)-1]} \\ \dfrac{\partial \pi_g^{LNC*}}{\partial \beta'} = 0,\ \beta' = \dfrac{Aq_0(\alpha_1-1)[2\lambda_1(\delta'+1)-3]}{4k_2 - q_0{}^2(\alpha_1-1)^2[3-2\lambda_1(\delta'+1)]} \end{cases}$$

From ③ in inference 2, we can see that the reduction level of quality losses (β') positively correlates with equilibrium price (p^{LNC*}). When the reduction level of quality losses (β') is below a certain threshold, it positively correlates with both producer and government income (π_p^{LNC*} and π_g^{LNC*}). Conversely, it negatively correlates above this threshold.

The emergence of this phenomenon can be attributed to the following factors. As the reduction level of quality losses increases, the quality of market grain supply improves, and consumers are willing to pay higher prices, causing the equilibrium price to rise. For grain producers, the cost of loss reduction measures is relatively low in the initial stage, and the effect is significant. The increase in equilibrium prices allows grain producers to obtain higher profits, making up for the costs of reducing grain losses. Therefore, the reduction level of quality losses is positively related to the income of grain producers in the early stages. However, as grain producers continue to increase the reduction level of quality losses, their marginal revenue decreases, and the additional revenue is not enough to offset the cost of inputs. The income of grain producers will be negatively related to the reduction level of quality losses (here, we got the threshold $\beta' = \dfrac{F_1 - Aq_0(1-\alpha_1)[\lambda_1(\delta'+1)-1]}{2k_2 + q_0{}^2(\alpha_1-1)^2[\lambda_1(\delta'+1)-1]}$). From the aspect of the government, the profits are positively correlated with the reduction level of quality losses when certain conditions are met (here, we got $\beta' = \dfrac{Aq_0(\alpha_1-1)[2\lambda_1(\delta'+1)-3]}{4k_2 - q_0{}^2(\alpha_1-1)^2[3-2\lambda_1(\delta'+1)]}$). However, the marginal returns diminish as the reduction level of quality losses continues to rise. Once the threshold is exceeded, the additional profits of grain producers no longer cover the costs, thereby affecting the government's income.

D. CLB Model

In the CLB model, grain producers will adopt the GPHL reduction equipment, and the government will subsidize both GPHL reduction inputs and GPHL reduction level. The profit functions of both the grain producer and the government are outlined below:

$$\pi_p^{CLB} = (p^{CLB} - c)D^{CLB}[1-(\delta'+1)\lambda_1] - (1-s) \cdot \frac{[k_1(\delta')^2 + k_2(\beta')^2]}{2} + F_1(\delta' + \beta') \tag{13}$$

$$\pi_g^{CLB} = \pi_p^{CLB} + CS^{CLB} - F_1(\delta'+\beta') - \frac{s[k_1(\delta')^2 + k_2(\beta')^2]}{2} \tag{14}$$

From equations (13) and (14), we can get Proposition 4 (the analysis process is similar to it in Proposition 1).

Proposition 4. In the CLB model, we constructed the optimal decision about equilibrium price, and benefits of grain producers and the government (see Eq. (15) and Eq. (16)).

$$\begin{cases} p^{CLB*} = \dfrac{a + c + (\beta'+1)q_0(1-\alpha_1)}{2} \\ D^{CLB*} = \dfrac{a - c + (\beta'+1)q_0(1-\alpha_1)}{2} \end{cases} \tag{15}$$

$$\begin{cases} \pi_p^{CLB*} = \dfrac{[1-(\delta'+1)\lambda_1](E')^2}{4} + F_1(\delta'+\beta') - \dfrac{(1-s)[k_2(\beta')^2 + k_1(\delta')^2]}{2} \\ \pi_g^{CLB*} = \dfrac{(E')^2[3-2\lambda_1(1+\delta')]}{8} - \dfrac{k_1(\delta')^2 + k_2(\beta')^2}{2} \end{cases} \tag{16}$$

According to Proposition 4, we can get inference 3 (the analysis process sees Appendix B-3).

Inference 3.

① $\dfrac{\partial p^{CLB*}}{\partial F_1} = 0$, $\dfrac{\partial \pi_p^{CLB*}}{\partial F_1} > 0$, $\dfrac{\partial \pi_g^{CLB*}}{\partial F_1} = 0$

From ① in inference 3, we can see that the subsidy coefficient (F_1) of the loss reduction level does not influence the equilibrium price and the government income (p^{CLB*} and π_g^{CLB*}), but positively correlates with the income of grain producers (π_p^{CLB*}).

There are several main reasons for this phenomenon. Due to the constraints of many factors such as land resources and technological input, the marginal production costs faced by grain producers are generally high. Government subsidies can partially offset the producers' cost expenditures and increase their marginal benefits. Therefore, the subsidy coefficient is positively correlated with the income of grain producers. The equilibrium price is greatly affected by the demand side, so the subsidy coefficient does not affect the equilibrium price in a tight balance market. Government subsidies are a form of market intervention. Their main function is to support grain producers and ensure the continuity of production and the stability of supply. Therefore, the subsidy coefficient has nothing to do with government revenue.

② $$\begin{cases} \dfrac{\partial p^{CLB*}}{\partial \delta'} = 0 \\ \dfrac{\partial \pi_p^{CLB*}}{\partial \delta'} = 0,\ \delta' = \dfrac{4F_1 + \lambda_1(E')^2}{4k_1(1-s)} \\ \dfrac{\partial \pi_g^{CLB*}}{\partial \delta'} < 0 \end{cases}$$

From ② in inference 3, we can see that the reduction level of quantity losses ($\delta^{'}$) does not influence the equilibrium price (p^{CLB*}), but negatively correlates with the government income (π_g^{CLB*}). When the reduction level of quantity losses ($\delta^{'}$) is below a certain threshold, it positively correlates with the producer's income (π_p^{CLB*}). Conversely, it negatively correlates above this threshold.

This phenomenon can be attributed to the following factors. Under the condition of tight balance between grain supply and demand, grain demand is relatively stable and price elasticity is small, so the equilibrium price is not affected by the reduction level of quantity losses. For grain producers, when the reduction level of quantity losses is below a certain threshold, the profit is positively correlated with the level of loss reduction (here, we got $\delta^{'} = \frac{4F_1 + \lambda_1 (E^{'})^2}{4k_1(1-s)}$). This is because the initial cost of reduction measures is relatively low and can yield significant effects. The revenue from increased quantity compensates for the costs. However, the producers' marginal returns will diminish as they continue to increase the reduction level of quantity losses. Once the threshold is exceeded, further increasing the reduction level of quantity losses necessitates substantial costs. The extraneous earnings fail to cover the additional costs, leading to a negative correlation. Furthermore, the government subsidy provides economic incentives for grain loss reduction. It greatly motivates grain producers to invest in loss reduction technology. The government income consists of the grain producers' income, consumer surplus, and related subsidy expenditures. As the reduction level of quantity losses increases, the government subsidy expenditures rise. The increase in producers' income and consumer surplus cannot offset the government subsidy expenditures. Thus, there is a negative correlation between the government income and the reduction level of quantity losses.

③ $$\begin{cases} \frac{\partial p^{CLB*}}{\partial \beta^{'}} > 0 \\ \frac{\partial \pi_p^{CLB*}}{\partial \beta^{'}} = 0, \beta^{'} = \frac{2F_1 - E^{'} q_0 (1-\alpha_1)[\lambda_1(\delta^{'}+1)-1]}{2k_2(1-s)} \\ \frac{\partial \pi_g^{CLB*}}{\partial \beta^{'}} = 0, \beta^{'} = \frac{A q_0 (\alpha_1 - 1)[2\lambda_1(\delta^{'}+1)-3]}{4k_2 - {q_0}^2(\alpha_1-1)^2[3-2\lambda_1(\delta^{'}+1)]} \end{cases}$$

From ③ in inference 3, we can see that quality loss reduction level ($\beta^{'}$) positively correlates with equilibrium price ($p^{\mathrm{CLB}*}$). When the reduction level of quality losses ($\beta^{'}$) is below a certain threshold, it positively correlates with both producer and government income(π_p^{CLB*} and π_g^{CLB*}). Conversely, it negatively correlates above this threshold.

The phenomenon can be attributed to the following factors. The reduction of quality losses leads to improvement in the quality of grain supply. In this case, consumers are willing to pay higher prices, which leads to an increase in equilibrium price. For grain producers, the initial costs of reduction measures are relatively low and yield significant effects. The rise in the equilibrium price allows the grain producer to achieve higher revenues, compensating for the costs invested in quality loss reduction. Therefore, there is a positive correlation between the reduction level of quality losses and the grain producers' income initially. However, the marginal returns will diminish as the reduction level continues to increase. Once it exceeds a certain threshold (here, we got $\beta^{'} = \frac{F_1}{k_2(1-s)} - \frac{E^{'} q_0 (1-\alpha_1)[\lambda_1(\delta^{'}+1)-1]}{2k_2(1-s)}$), there will be a negative correlation. This may be because further improving the reduction level of quality losses needs substantial costs. In this scenario, the additional revenue generated from high-quality grain falls short of covering the associated costs. The government income consists of the grain producers' income, consumer surplus, and related subsidy expenditures. Therefore, when the reduction level of quality losses is below a certain threshold (here, we got $\beta^{'} = A q_0 (\alpha_1 - 1) \cdot \frac{2\lambda_1(\delta^{'}+1)-3}{4k_2 - {q_0}^2(\alpha_1-1)^2[3-2\lambda_1(\delta^{'}+1)]}$), it has a positive correlation with the government income. However, the marginal returns will diminish as the reduction level of quality losses continues to increase. When it exceeds the threshold, the revenue gained by the grain producers fails to cover the subsidy expenditures. Hence, the reduction level of quality losses shows a negative correlation with the government income.

④ $\frac{\partial p^{CLB*}}{\partial s} = 0$, $\frac{\partial \pi_p^{CLB*}}{\partial s} > 0$, $\frac{\partial \pi_g^{CLB*}}{\partial s} = 0$

From ④ in Inference 3, in the CLB model, the subsidy coefficient of GPHL reduction inputs (s) does not influence the equilibrium price and the government income ($p^{\mathrm{CLB}*}$ and π_g^{CLB*}) but positively correlates with the producers' income (π_p^{CLB*}).

The phenomenon can be attributed to the following factors. Due to the constraints of land resources, technical input, and many other factors, grain producers typically face high marginal production costs. The government subsidy for GPHL reduction inputs can effectively reduce the marginal costs. Both the grain supply and the grain producer's income will increase in this way. However, the government subsidy primarily affects the supply side. In a tightly balanced market, grain prices may be strongly influenced by the demand side. Therefore, the government subsidy does not directly lead to a decrease in equilibrium price but can alleviate supply constraints. Moreover, as a form of market intervention, the main role of government subsidy is to assist the grain producer. It ensures the continuity of production rather than directly regulating market prices or increasing the government income.

E. Analysis of Subsidy Strategy

Inference 4. When $1 \ge s > \psi_1$ or $C(\gamma) < \psi_2$ can be met, the CNL model is feasible. (The analysis process is Appendix C-1).

According to inference 4, the government subsidy for GPHL reduction inputs can increase both the grain producers' income and the government income when certain conditions are met. Therefore, the grain producers adopt GPHL reduction technology and the government subsidizes GPHL reduction inputs is feasible.

Inference 5. When $F_1 > \upsilon$, the LNC model can make the grain producers gain higher profits than the CNL model. (See Appendix C-2 for the analysis process).

According to inference 5, when the subsidy coefficient for loss reduction level exceeds a certain threshold, subsidizing loss reduction level yields higher returns for the grain producer compared to subsidizing GPHL reduction inputs. Conversely, when the subsidy coefficient is below this threshold, subsidizing GPHL reduction inputs yields higher returns for the grain producer. The critical value of the subsidy coefficient for loss reduction level has been calculated to be $F_1 = \frac{(s-1)(k_1\delta^2 + k_2\beta^2) + k_1(\delta^{'})^2 + k_2(\beta^{'})^2}{2(\delta^{'} + \beta^{'})} + \frac{[\lambda_1(\delta^{'}+1)-1]A^2(\beta^{'}+1)^2}{4(\delta^{'}+\beta^{'})} - \frac{[\lambda_1(\delta+1)-1]A^2(\beta+1)^2}{4(\delta^{'}+\beta^{'})}$. In addition, we found the threshold of F_1 is positively correlated with $\delta^{'}$ and negatively correlated with δ. In a certain range, the threshold is positively correlated with β ($\beta^{'}$). Otherwise, it is negatively correlated.

Inference 6. When $F_1 > \omega$, $\pi_p^{CLB*} \geq \pi_p^{NCL*}$, $\pi_p^{CLB*} \geq \pi_p^{CNL*}$, $\pi_p^{CLB*} \geq \pi_p^{LNC*}$, the CLB model can make the grain producers gain higher profits than the others. (See Appendix C-3 for the analysis process).

According to inference 6, when the subsidy coefficient for loss reduction exceeds a certain threshold, the producer's income under a mixed subsidy strategy is higher than that under other subsidy strategies. Therefore, to encourage grain producers to adopt GPHL reduction technology and enhance the post-harvest loss reduction level, the government can implement a mixed subsidy strategy.

V.CASE STUDY

A. Case description

Based on the research of Zhang et al. [27], we assume the following assumptions combined with the actual situation: According to the investigation of grain losses in Shangqiu City, Henan Province, grain losses are different for different farmers or grain producers in Shangqiu City. For grain producers using backward technology, the quantity losses and quality losses of grain averaged 8%-18% and 6%-20%. For grain producers using advanced technology, the quantity loss rate and quality loss rate of grain were less than 3% and 2% respectively. Therefore, we further assume the relevant influence values as $\alpha_1 = 0.01$, $\lambda_1 = 0.1$, $\delta = 0.4$, $\delta_1 = 0.5$, $\beta = 0.3$, $\beta_1 = 0.4$. In addition, set $a = 3$, $c = 0.5$, $q_0 = 2$, $k_1 = 10$, $k_2 = 10$. Based on the above values, propositions, and inferences, the following results are obtained.

Figure 3 shows the variation trends of equilibrium price and benefits with s, δ, and β in the CNL model. It can be seen from Figure 2 that the subsidy coefficient of GPHL reduction inputs (s) will not influence the equilibrium price and the government income but is positively correlated with the grain producers' income. The quantity losses level (δ) will not influence the equilibrium prices. With the increase of the reduction level of quantity losses, profits for grain producers and the government will increase in a certain range and decrease beyond this range. The reduction level of quality losses (β) is positively correlated with the equilibrium price. With the increase of the reduction level of quality losses, the incomes of grain producers and the government will increase in a certain range and decrease beyond this range.

Figure 4 shows the variation trends of equilibrium price and benefits with F_1, $\delta^{'}$, and $\beta^{'}$ in the LNC model. The subsidy coefficient of the GPHL reduction level (F_1) will not influence the equilibrium price and the government income but is positively correlated with the income of grain producers. The reduction level of quantity losses ($\delta^{'}$) will not influence the equilibrium price. With the increase in the reduction level of quantity losses, the profits of grain producers and the government will increase in a certain range and decrease beyond this range. The reduction level of quality losses ($\beta^{'}$) is positively correlated with the equilibrium price. With the increase of the reduction level of quality losses, the incomes of grain producers and the government will increase in a certain range and will decrease beyond this range.

Figure 5 shows the variation trends of equilibrium price and benefits with F_1, $\delta^{'}$, $\beta^{'}$, and s. The subsidy coefficient of the GPHL reduction level (F_1) will not influence the equilibrium price and the government income but is positively correlated with the income of grain producers. The reduction level of quantity losses ($\delta^{'}$) will not influence the equilibrium price. With the increase of the reduction level of quantity losses, the incomes of grain producers and the government will increase in a certain range and decrease beyond this range. The reduction level of quality losses ($\beta^{'}$) is positively correlated with the equilibrium price. With the increase of the reduction level of quality losses, the benefits to grain producers and the government will increase within a certain range and will decrease beyond this range. Besides, it is positively correlated with the equilibrium price. The subsidy coefficient of GPHL reduction inputs (s) does not correlate with the equilibrium prices and the government income but is positively correlated with the grain producers' income.

Figure 6 compares the income variation trends of grain producers and the government with s and C under the models of NCL and CNL. As we can see, when the subsidy coefficient of GPHL reduction inputs (s) is less than a certain value, subsidizing GPHL reduction inputs can help grain producers and the government obtain more benefits compared with adopting none subsidy policy. When the GPHL reduction inputs (C) are less than a certain value, grain producers and the government can obtain more benefits by subsidizing GPHL reduction inputs than adopting no subsidy policy. Grain producers invest in the GPHL reduction technology, and the government subsidizes the GPHL reduction inputs is feasible when certain conditions are met.

Figure 7 shows the change trends of the producers' income with F_1 in models of CNL and LNC. Here we set $s = 0.2$.

As we can see, when the subsidy coefficient of GPHL reduction level (F_1) is greater than a certain value, subsidizing GPHL reduction level can make grain producers gain more income than subsidizing GPHL reduction inputs. Conversely, subsidizing GPHL reduction inputs is more conducive to the income of grain producers. As we can see from Figure 8, the threshold of F_1 is positively correlated with δ' and negatively correlated with δ . It is positively correlated with β (β') in a certain range.

Figure 9 shows the variation trends of the producers' income with F_1 among the models of NCL, CNL, LNC, and CLB. As we can see, when certain conditions are met, the grain producer's income in the mixed subsidy mode is higher than in the other three models. When certain conditions are met, subsidizing GPHL reduction inputs can help the government gain more benefits than in the other models. In other words, when certain conditions are met, the mixed subsidy can improve the grain producers' income. However, the government cannot gain more benefits compared with solely subsidizing GPHL reduction inputs.

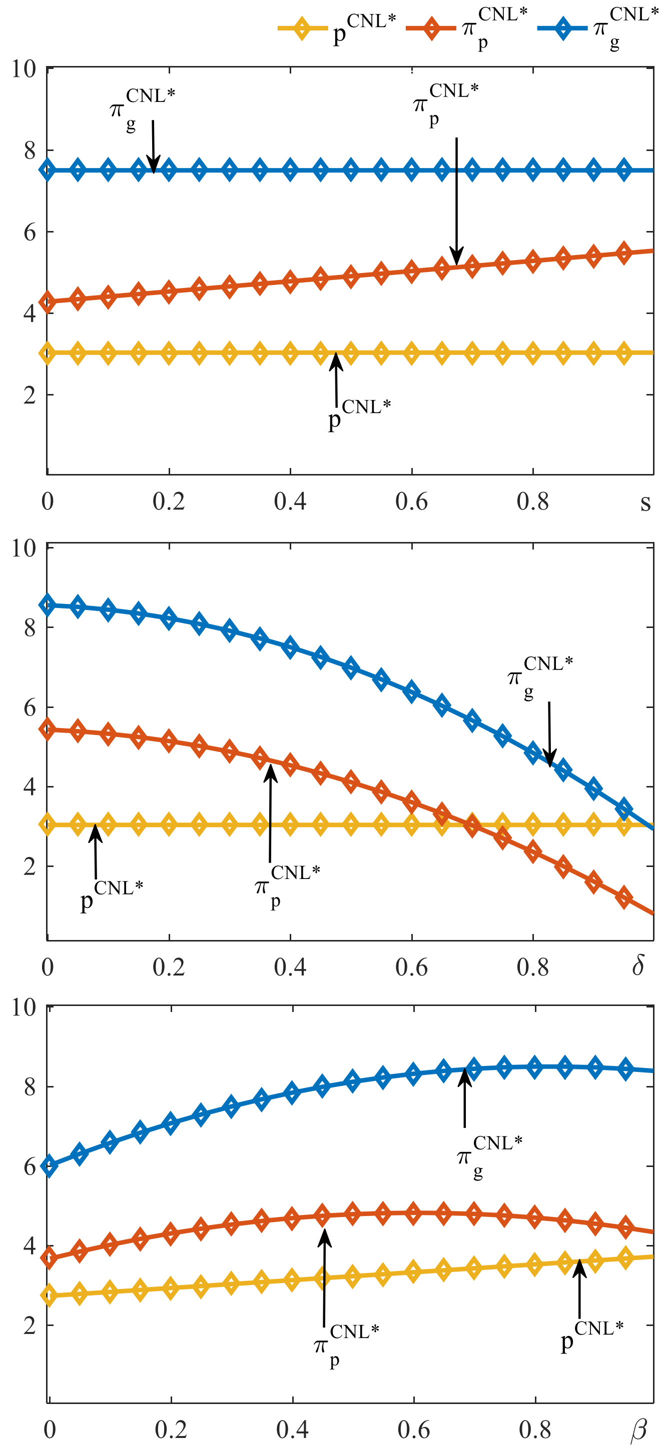

Fig. 3. The variation trend of equilibrium price and benefits with s , δ , and β in the CNL model.

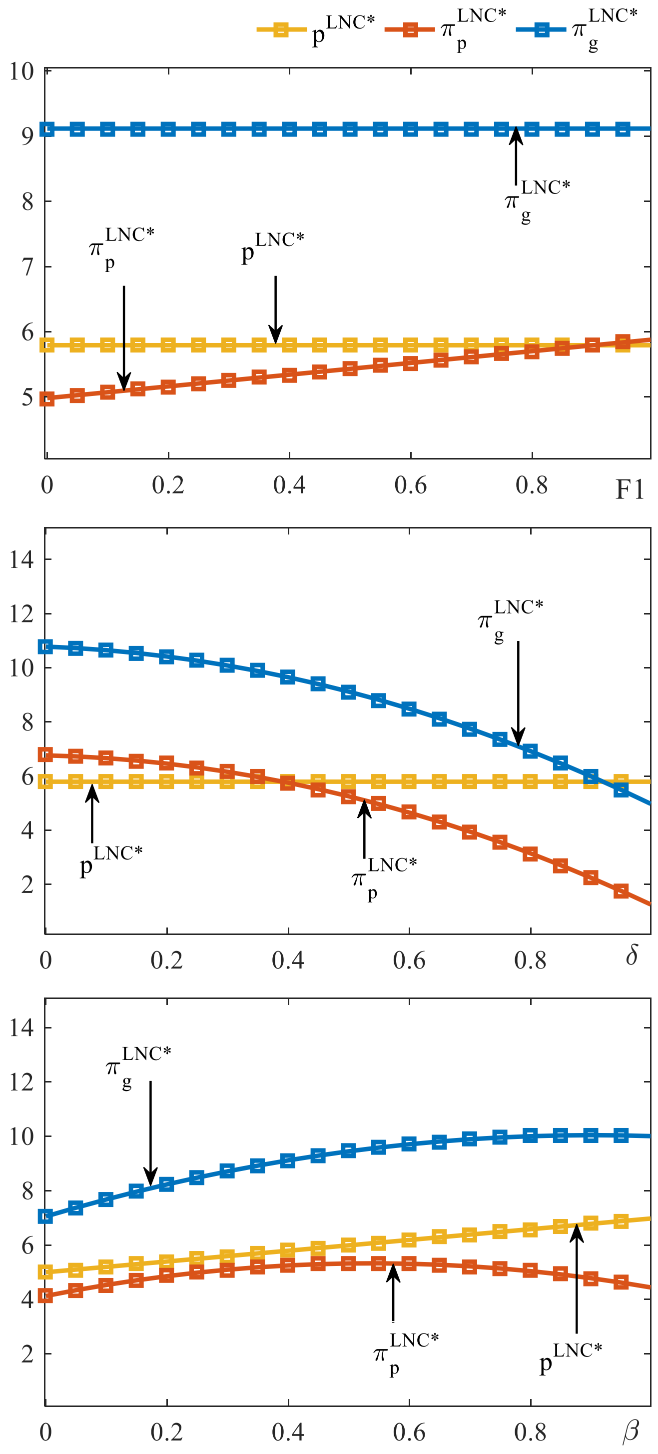

Fig. 4. The variation trend of equilibrium price and benefits with F_1 , δ' , and β' in the LNC model.

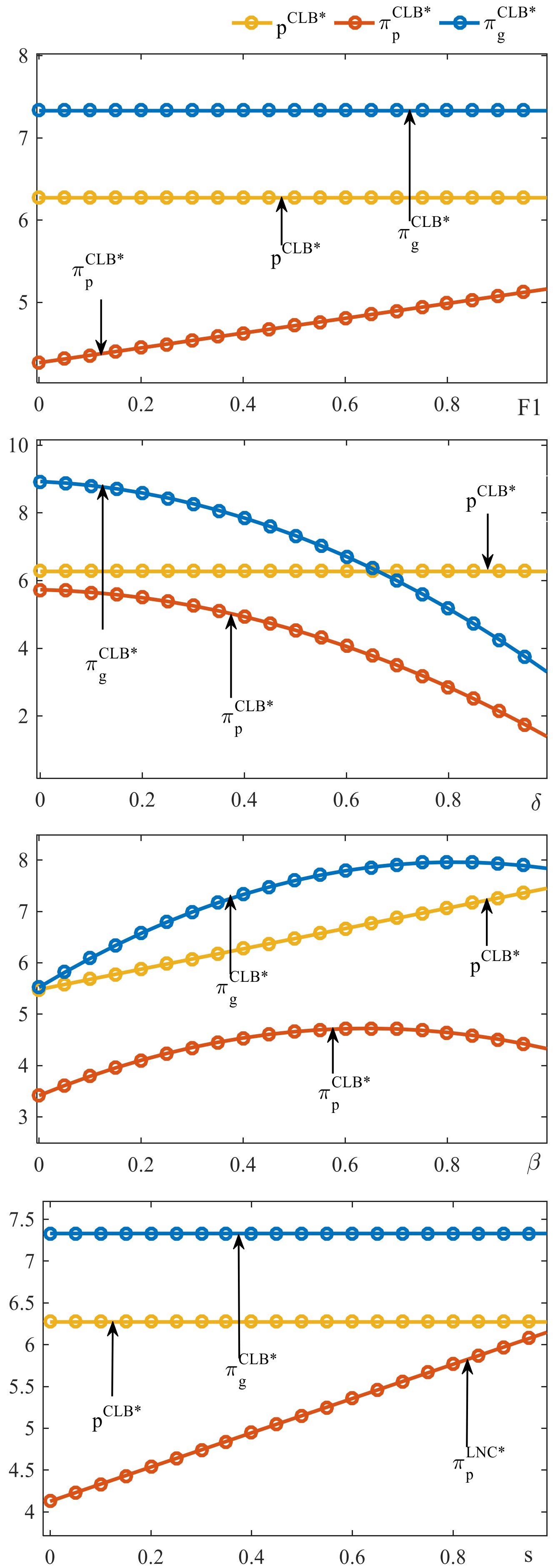

Fig. 5. The variation trend of equilibrium price and benefits with F_1, $\delta^{'}$, $\beta^{'}$, and s in the CLB model.

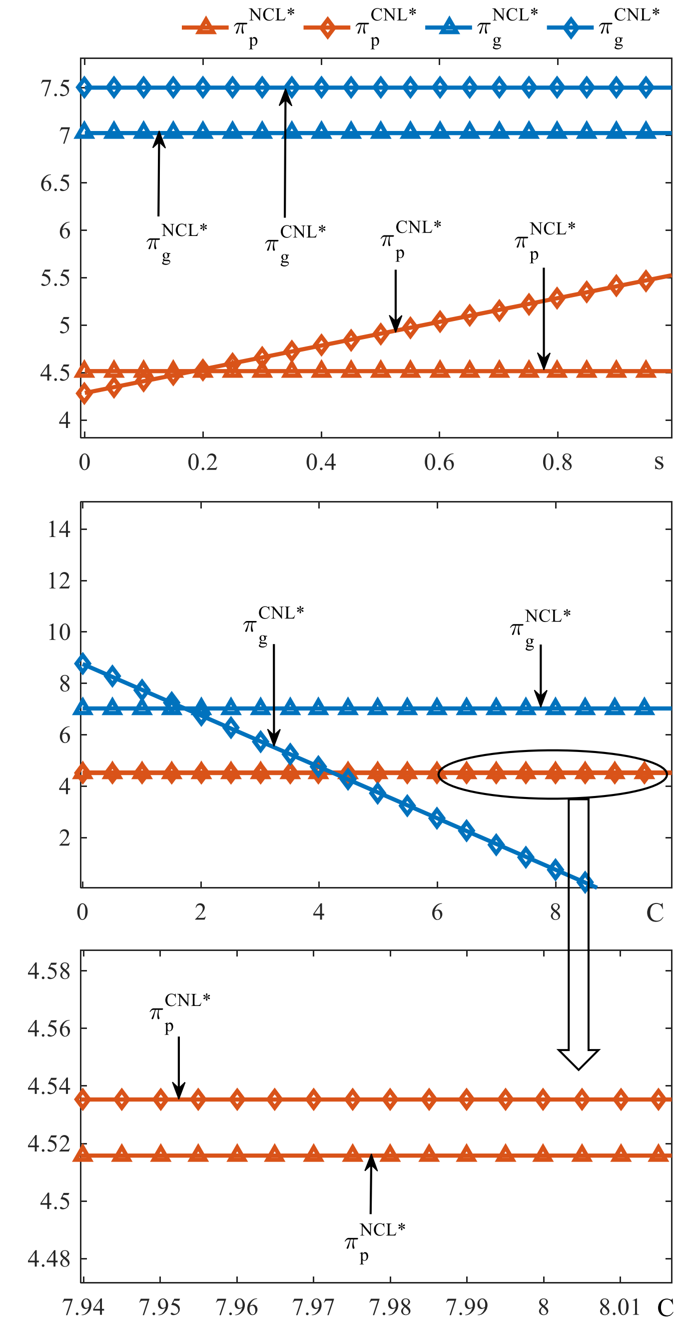

Fig. 6. The income variation trends of grain producers and the government with s and C.

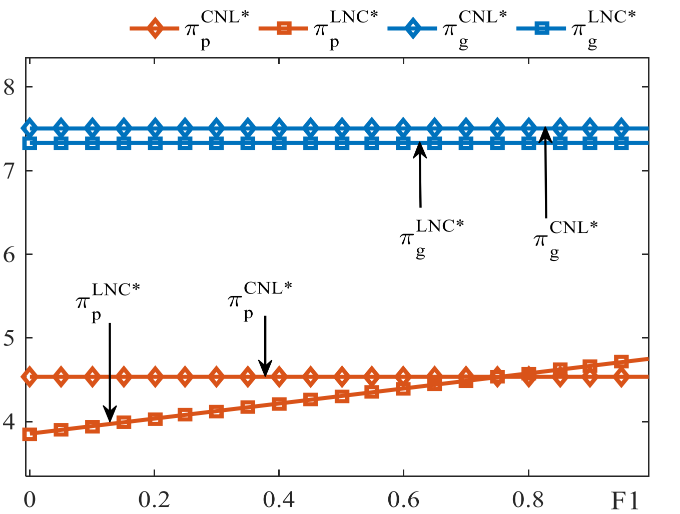

Fig. 7. The variation trend of incomes with F_1 between the CNL model and the LNC model.

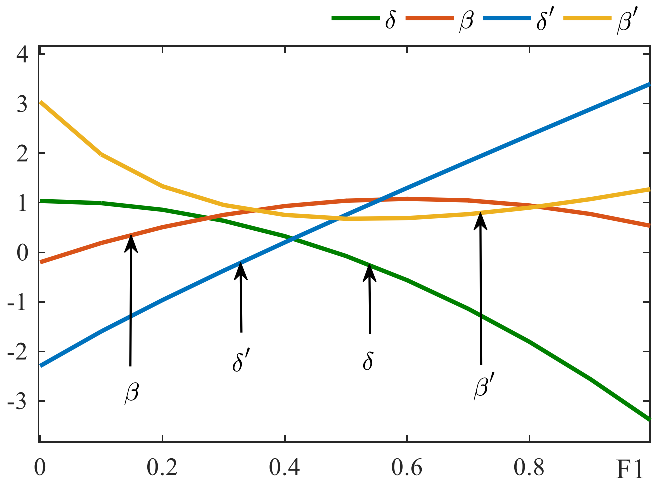

Fig. 8. The variation trend of F_1 with δ , δ' , β and β' .

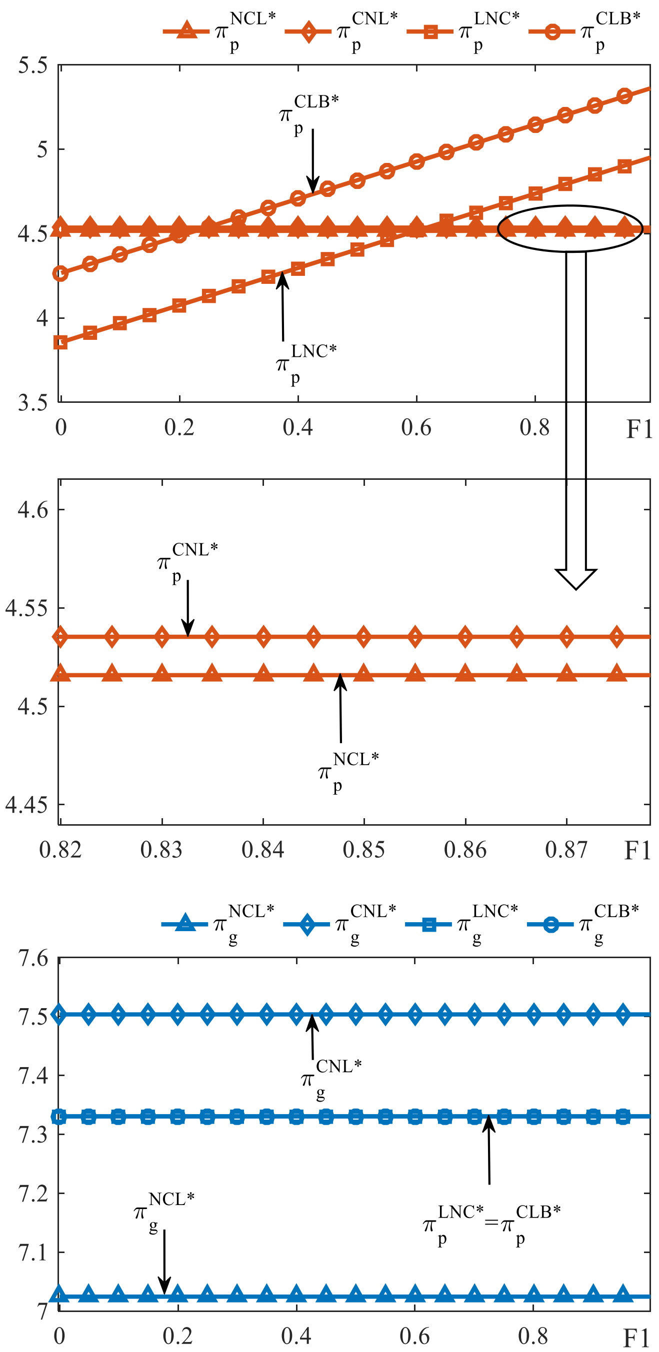

Fig. 9. The variation trend of government and grain producers' income with F_1 among NCL, CNL, LNC, and CLB models.

B. Robustness analyses

The robustness of the proposed views will be discussed in this section. In the proposed models of NCL, CNL, LNC, and CLB, we only discussed the case of the government providing variable subsidies. Besides providing variable subsidies, the government can also provide fixed subsidies and mixed subsidies. Based on the three existing investment subsidy models in the case of variable subsidies, three models in the case of fixed subsidies can be expanded, namely DCNL, DLNC, and DCLB. We use S_1 and S_2 respectively represent the government fixed subsidies for the GPHL reduction inputs and GPHL reduction level (see Appendix D for a detailed analysis process). The results demonstrated that when the government solely provided fixed subsidies, they did not affect the equilibrium price or government income in the extended models (DCNL, DLNC, and DCLB models). However, it had a significant effect on the income of grain producers. The result is similar to that in the variable subsidy models. If the government provided both fixed subsidies and variable subsidies, the effect of the subsidy coefficient on the equilibrium price and the income remains unchanged under the three expanded models (DCNL, DLNC, and DCLB models). All these indicate that the models constructed in this paper have good robustness.

C. Discussion

GPHL reduction is an important measure to increase grain supply and ensure national food security. For this reason, numerous countries have introduced corresponding subsidy policies. Some scholars have made significant progress in reducing post-harvest losses through investment subsidy policies in the grain supply chain. [37], [38]. However, some differences exist in this study.

In terms of research perspectives, most of the existing studies focus on the impacts of government subsidies on agricultural pollution and output. Few studies concentrate on GPHL reduction subsidy policies for grain. For example, Chen et al. studied agricultural subsidy policies from the perspective of environmental impact. They found the impacts of two agricultural subsidy programs (quantity subsidy and emission reduction innovation subsidy) on agricultural pollution [37]. Peng and Pang analyzed the impacts of the government subsidy on the production decisions of risk-averse farmers. Their research showed that with the increase of subsidies, the overall target output of farmers would also increase. This indicated the government subsidy had a positive impact on farmers with a high degree of risk aversion [38].

Chinese grain supply and demand have been in a tight balance for a long time. We proposed the idea that production equals demand and compared existing studies [36], [37]. The assumptions in this paper are more realistic. Furthermore, we categorized post-harvest grain losses into two distinct types: quantitative losses and qualitative losses. We then introduced the concept of loss level for both quantity and quality, which served as the basis for refining the demand function. loss Given the ease of data acquisition for GPHL reduction inputs, we utilized grain quality and quantity loss reduction costs to accurately represent the GPHL reduction inputs of grain producers. In this paper, we focused on two kinds of government subsidy policies: subsidizing GPHL reduction inputs and GPHL reduction level. Subsidy strategies of grain supply chain were proposed considering both grain quality and quantity loss reduction levels.

In this study, we analyzed the impact of different parameters on equilibrium price, grain producers, and government returns based on the four proposed models. However, other studies have not yet proposed and analyzed the influences of these parameters on decision variables in the grain supply chain [29], [36], [37], [39]-[41].

VI. Conclusions and significance

A. Conclusions

We aimed to investigate the ideal model and the threshold for subsidies under various investment subsidy schemes. We proposed the concept and function expression of grain quantity and quality loss reduction level. Then, four investment subsidy models for GPHL were constructed and analyzed. We found some intriguing things in the process.

(1) In order to promote the adoption of GPHL reduction facilities and technology, Chinese government can provide a subsidy for the GPHL reduction inputs. In this way, the income of grain producers will be improved when the GPHL reduction inputs are below a threshold.

(2) The government subsidy does not guarantee an increase in the incomes of grain producers. When the quantity or quality loss reduction level is too high, the government subsidy cannot improve the income of grain producers. Therefore, the Chinese government should pay attention to these two parameters to avoid blind incentives that lead to resource wastage.

(3) Subsidizing the GPHL reduction inputs can enable the Chinese government to achieve greater benefits with lower investment. The grain producers and the government can obtain higher revenue than subsidizing the GPHL reduction level in certain range.

(4) Subsidizing the GPHL reduction level is feasible when a suitable subsidy coefficient is determined. We have calculated the subsidy threshold is related to grain quality and quantity loss reduction level. The government can determine the subsidy coefficient based on these factors.

(5) Compared with the single subsidy model, the mixed subsidy model can make the grain producers obtain higher profits. However, it failed to maximize the government income compared with only subsidizing the GPHL reduction inputs.

B. Significance

Our research has some scientific value. (1) Academically, we put forward the concept and function expression of the quantity and quality loss reduction level of grain producers and amended the demand function. Based on the influence of GPHL reduction level on the incomes of grain producers and the government, four investment and subsidy models of grain loss reduction were constructed and analyzed. These models could compensate for the lack of research on GPHL reduction subsidies and enhance the theory of grain supply chain management. (2) In practice, the investment subsidy rules in different modes in this paper can help grain producers make appropriate investment decisions in loss reduction technology adoption. For the government, these subsidies rules can help it develop appropriate subsidy strategies to ensure grain security.

The results hold significant implications for the Chinese government as they formulate policies to reduce GPHL.

(1) Establish reasonable subsidy thresholds: The government should scientifically determine subsidy thresholds based on the reduction levels of quality losses and quantity losses. When the level is too high, the subsidy policy should be adjusted appropriately to avoid ineffective investment.

(2) Encourage technological innovation: The government can support enterprises in researching and developing efficient and low-cost grain loss reduction equipment, thereby reducing the cost of GPHL reduction through technological innovation and increasing producers' enthusiasm for adopting grain loss reduction equipment.

(3) Optimize the subsidy approach: The government might consider subsidizing the GPHL reduction inputs rather than solely subsidizing the GPHL reduction level. When the subsidy coefficient for the reduction level below a certain value, this approach can not effectively increase the grain producers' profits and social benefits.

(4) Adopt a mixed subsidy model: The government can implement a mixed subsidy model that combines GPHL reduction input subsidy with GPHL reduction level subsidy to encourage grain producers to adopt GPHL reduction technologies. At the same time, it is important to balance producers' profits with social benefits to ensure the effectiveness of the subsidy policy.

C. Future research

There are some limitations. Although GPHL reduction subsidies for grain producers were considered in this paper, the coupling relationships between the GPHL reduction subsidy and other subsidies were not discussed. In addition, we only discussed the case of variable subsidies provided by the Chinese government. The government can also provide a mixed subsidy strategy, such as combining variable subsidies with fixed subsidies. In the next study, we will focus on these issues and explore them further in the future.

Appendix

Appendix A.

Appendix A-1.

Proof. Based on Assumptions (5), we know that in the NCL model $D^{NCL} = a - p_{NCL} + (1-\alpha_1)q_0$, and put it into formula (1). We solved the first partial derivative of π_p^{NCL} concerning p^{NCL} and let it equal to zero. So we can got p^{NCL*}. Then put p^{NCL*} into the demand formula D^{NCL} and got D^{NCL*}. Based on p^{NCL*} and D^{NCL*}, we further got π_p^{CNL*} and π_g^{CNL*}.

Appendix B.

Appendix B-1.

According to Proposition 2, we can get $\frac{\partial p^{CNL*}}{\partial s}=0$, $\frac{\partial \pi_p^{CNL*}}{\partial s}=\frac{k_1\delta^2+k_2\beta^2}{2}>0$, $\frac{\partial \pi_g^{CNL*}}{\partial s}=0$. $\frac{\partial p^{CNL*}}{\partial \delta}=0$, $\frac{\partial \pi_p^{CNL*}}{\partial \delta}=-k_1\delta(1-s)-\frac{\lambda_1 E^2}{4}<0$, $\frac{\partial \pi_g^{CNL*}}{\partial \delta}=-k_1\delta-\frac{\lambda_1 E^2}{4}<0$. $\frac{\partial p^{CNL*}}{\partial \beta}=\frac{q_0(1-\alpha_1)}{2}>0$, $\frac{\partial \pi_p^{CNL*}}{\partial \beta}=k_2\beta(1-\mathrm{s})-\frac{Eq_0(1-\alpha_1)[\lambda_1(\delta+1)-1]}{2}$, $\frac{\partial \pi_g^{CNL*}}{\partial \beta}=-k_2\beta<0$. Thus, we can get inference 1.

Appendix B-2.

According to Proposition 2, we can get $\frac{\partial p^{LNC*}}{\partial F_1}=0$, $\frac{\partial \pi_p^{LNC*}}{\partial F_1}=\beta^{'}+\delta^{'}>0$, $\frac{\partial \pi_g^{LNC*}}{\partial F_1}=0$. $\frac{\partial p^{LNC*}}{\partial \delta^{'}}=0$, $\frac{\partial \pi_p^{LNC*}}{\partial \delta^{'}}=F_1-\frac{\lambda_1 E^2}{4}-k_1\delta^{'}$, $\frac{\partial \pi_g^{LNC*}}{\partial \delta^{'}}=-\frac{\lambda_1 E^2}{4}-k_1\delta^{'}<0$. $\frac{\partial p^{LNC*}}{\partial \beta^{'}}=\frac{q_0(1-\alpha_1)}{2}>0$, $\frac{\partial \pi_g^{LNC*}}{\partial \beta^{'}}=-k_2\beta^{'}<0$, $\frac{\partial \pi_p^{LNC*}}{\partial \beta^{'}}=-k_2\beta^{'}-\frac{Eq_0(1-\alpha_1)[\lambda_1(\delta^{'}+1)-1]}{2}$. Thus, we can get inference 2.

Appendix B-3.

According to Proposition 2, we can get $\frac{\partial p^{CLB*}}{\partial F_1}=0$, $\frac{\partial \pi_p^{CLB*}}{\partial F_1}=\beta^{'}+\delta^{'}>0$, $\frac{\partial \pi_g^{CLB*}}{\partial F_1}=0$. $\frac{\partial p^{CLB*}}{\partial \delta^{'}}=0$, $\frac{\partial \pi_g^{CLB*}}{\partial \delta^{'}}=-\frac{\lambda_1 E^2}{4}-k_1\delta^{'}<0$. $\frac{\partial p^{CLB*}}{\partial \beta^{'}}=\frac{q_0(1-\alpha_1)}{2}>0$, $\frac{\partial \pi_p^{CLB*}}{\partial \beta^{'}}=F_1+k_2\beta^{'}(s-1)-\frac{Eq_0(1-\alpha_1)[\lambda_1(\delta^{'}+1)-1]}{2}$, $\frac{\partial \pi_g^{CLB*}}{\partial \beta^{'}}=-k_2\beta^{'}<0$. $\frac{\partial p^{CLB*}}{\partial s}=0$, $\frac{\partial \pi_g^{CNL*}}{\partial s}=0$, $\frac{\partial \pi_p^{CLB*}}{\partial s}=\frac{k_1(\delta^{'})^2+k_2(\beta^{'})^2}{2}>0$. Thus, we can get inference 3.

Appendix C

Appendix C-1.

If $\pi_p^{CNL*}>\pi_p^{NCL*}$, grain producers will adopt the loss reduction technology, thus, we got $1\geqslant s>(\lambda_1-1)\cdot\frac{[c-a+q_0(\alpha_1-1)]}{2(k_1\delta^2+k_2\beta^2)}+\frac{[\lambda_1(\delta+1)-1]E^2}{4}+\frac{k_1\delta^2+k_2\beta^2}{2}$, we call it $1\geqslant s>\psi_1$. If $\pi_{\mathrm{g}}^{CNL*}>\pi_{\mathrm{g}}^{NCL*}$, the government subsidizes the loss reduction inputs will get more social benefits, therefore, we can get $\frac{k_1\delta^2+k_2\beta^2}{2}<\frac{(2\lambda_1-3)A^2}{8}-\frac{[2\lambda_1(\delta+1)-3]E^2}{8}$, we call it $C<\psi_2$. Namely, when $1\geqslant s>\psi_1$ and $C<\psi_2$ can be met, investment behavior of grain producers in the GPHL reduction technology, and subsidy behavior of the government on this investment is feasible.

Appendix C-2.

If $\pi_p^{LNC*}>\pi_p^{CNL*}$, subsidizing the loss reduction level will help the government gain more benefits, we can get $F_1>\frac{2(k_1\delta^2+k_2\beta^2)(s-1)+2k_1(\delta^{'})^2+2k_2(\beta^{'})^2-[\lambda_1(\delta+1)-1]E^2}{4(\delta^{'}+\beta^{'})}+\frac{[\lambda_1(\delta^{'}+1)-1](E^{'})^2}{4(\delta^{'}+\beta^{'})}$. We call it $F_1>\nu$. Take the partial derivative of F_1 concerning δ, β, $\delta^{'}$, and $\beta^{'}$, we can get $\frac{\partial F_1}{\partial \delta}<0$, $\frac{\partial F_1}{\partial \delta^{'}}>0$. When β (or $\beta^{'}$) is in a certain range, $\frac{\partial F_1}{\partial \beta}>0$ (or $\frac{\partial F_1}{\partial \beta^{'}}>0$), if above this range, $\frac{\partial F_1}{\partial \beta}<0$ (or $\frac{\partial F_1}{\partial \beta^{'}}<0$)

Appendix C-3.

If $\pi_p^{CLB*}>\pi_p^{NCL*}$, we can get $F_1>\frac{2(k_1(\delta^{'})^2+k_2(\beta^{'})^2)}{4(\delta^{'}+\beta^{'})}+\frac{[\lambda_1(\delta^{'}+1)-1](E^{'})^2-(\lambda_1-1)(A-1)^2}{4(\delta^{'}+\beta^{'})}$. If $\pi_p^{CLB*}>\pi_p^{CNL*}$, we can get $F_1>\frac{2(k_1\delta^2+k_2\beta^2)(s-1)+2(k_1(\delta^{'})^2+k_2(\beta^{'})^2)}{4(\delta^{'}+\beta^{'})}+\frac{[\lambda_1(\delta^{'}+1)-1](E^{'})^2-[\lambda_1(\delta+1)-1]E^2}{4(\delta^{'}+\beta^{'})}$, and we know that $\pi_p^{CLB*}>\pi_p^{LNC*}$

Appendix D

In the DCNL model, the income functions of grain producers and governments are as follows: $\pi_p^{CNL}=(p^{CNL}-c)D^{CNL}[1-(\delta+1)\lambda_1]-\frac{(1-s)[k_1\delta^2+\mathrm{k}_2\beta^2]}{2}+S_1$, $\pi_g^{CNL}=\pi_p^{CNL}+CS^{CNL}-\frac{s[k_1\delta^2+\mathrm{k}_2\beta^2]}{2}-S_1$. Based on this, we present optimal decisions about equilibrium prices, grain producers, and government yields.

$$\begin{cases} p^{CNL*}=\dfrac{a+c+(\beta+1)q_0(1-\alpha_1)}{2} \\ D^{CNL*}=\dfrac{a-c+(\beta+1)q_0(1-\alpha_1)}{2} \end{cases}$$

$$\begin{cases} \pi_p^{CNL*}=\dfrac{[1-(\delta+1)\lambda_1]E^2}{4}-\dfrac{(1-s)[k_1\delta^2+\mathrm{k}_2\beta^2]}{2}+S_1 \\ \pi_g^{CNL*}=\dfrac{E^2[3-2\lambda_1(\delta+1)]}{8}-\dfrac{k_1\delta^2+\mathrm{k}_2\beta^2}{2}-S_1 \end{cases}$$

Here, $E=a-c+(\beta+1)q_0(1-\alpha_1)$. Based on this and Section V, the following table data is obtained.

S_1	s	p^{DCNL*}	π_p^{DCNL*}	π_g^{DCNL*}
	0.1	3.037	4.5103	7.4035
	0.3	3.037	4.7603	7.4035
0.1	0.5	3.037	5.0103	7.4035
	0.7	3.037	5.2603	7.4035
	0.9	3.037	5.5103	7.4035
	0.1	3.037	4.7103	7.2035
	0.3	3.037	4.9603	7.2035
0.3	0.5	3.037	5.2103	7.2035
	0.7	3.037	5.4603	7.2035
	0.9	3.037	5.7103	7.2035
	0.1	3.037	4.9103	7.0035
	0.3	3.037	5.1603	7.0035
0.5	0.5	3.037	5.4103	7.0035
	0.7	3.037	5.6603	7.0035
	0.9	3.037	5.9103	7.0035
	0.1	3.037	5.1103	6.8035
	0.3	3.037	5.3603	6.8035
0.7	0.5	3.037	5.6103	6.8035
	0.7	3.037	5.8603	6.8035
	0.9	3.037	6.1103	6.8035
	0.1	3.037	5.3103	6.6035
	0.3	3.037	5.5603	6.6035
0.9	0.5	3.037	5.8103	6.6035
	0.7	3.037	6.0603	6.6035
	0.9	3.037	6.3103	6.6035

The calculation process of DLNC mode and DCLB mode is like that of DCNL mode and will not be described here.

REFERENCES

[1] X. Li, X. Liu, S. Lu, et al. "China's food loss and waste embodies increasing environmental impacts," Nature Food, vol. 2, no.7, pp519-528, 2021.

[2] Y. Luo, D. Huang, and L. Wu, "On-farm post-harvest loss and loss reduction methods: evidence from China," International Journal of Agricultural Sustainability, vol. 20, no.7, pp1322-1332, 2022.

[3] B. Prakash, "Research and Technological Advances in Food Science," 2021.

[4] Issah Sugri, Mutari Abubakari, Robert Kwasi Owusu, and John Kamburi Bidzakin, "Postharvest losses and mitigating technologies: evidence from Upper East Region of Ghana," Sustainable Futures, vol. 3, pp3100048, 2021.

[5] Martin-Julius Chegere, "Post-harvest losses reduction by small-scale maize farmers: The role of handling practices," Food Policy, vol. 77, pp103-115, 2018.

[6] Apurba Shee, Parmar Aditya, Raut Sharvari, et al. "Assessing the measurement methods of post-harvest food loss and waste: opportunities and challenges," Enterprise Development & Microfinance, vol. 33, no.4, 2022.

[7] W.E. Bendinelli, C.T. Su, and T.G. Péra, and J.V. Caixeta, "What are the main factors that determine post-harvest losses of grains?" Sustainable Production and Consumption, vol. 21, pp228-238, 2020.

[8] X. Li, D. Huang, and L. Wu, "Research on the loss of grain harvest link of different scale farmers: Based on the empirical analysis of 3251 farmers in 28 provinces of China," China Soft Science, no.8, pp184-192, 2019.

[9] C.J. Dao, S. Karunarathna, A. Ekanayaka, et al. Isolation and Identifi cation of Postharvest Fungal Pathogens of Some Selected Fruits in Yunnan, China[J]. Chiang Mai Journal of Science, vol. 50, no.3, pp1-16, 2023.

[10] T. Tefera, F. Kanampiu, H. De Groote, et al. "The metal silo: An effective grain storage technology for reducing post-harvest insect and pathogen losses in maize while improving smallholder farmers' food security in developing countries," Crop Protection, vol. 30, no.3, pp240-245, 2011.

[11] M. Tadesse, "Post-harvest loss of stored grain, its causes and reduction strategies," Food Science and Quality Management, vol. 96, pp26-35, 2020.

[12] T. Pera and C.F. José, "Post-harvest losses during the transportation of grains from farms to aggregation points," International Journal of Logistics Economics and Globalisation, vol. 7, no.3, pp1, 2018.

[13] Deepak Kumar and Kalita Prasanta, "Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries," Foods, vol. 6, no.1, pp8, 2017.

[14] Martin-Julius Chegere, "Post-harvest losses reduction by small-scale maize farmers: The role of handling practices," Food Policy, vol. 77, pp103-115, 2018.

[15] Aji Setiawan, Kusworo Adi, and Catur Edi Widodo, "Comparative Analysis of Deep Convolutional Neural Network for Accurate Identification of Foreign Objects in Rice Grains," Engineering Letters, vol. 32, no.2, pp315-324, 2024.

[16] Deepak Kumar and Prasanta Kalita, "Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries," Foods, vol. 6, no.1, pp8, 2017.

[17] S. Odjo, N. Palacios-Rojas, J. Burgueño, et al. "Hermetic storage technologies preserve maize seed quality and minimize grain quality loss in smallholder farming systems in Mexico," Journal of Stored Products Research, vol. 96, pp101954, 2022.

[18] Y. Luo, X. Li, Dong Huang, and L. Wu, "The progress and prospects of research on food loss and waste," Journal of Natural Resources, vol. 35, no.5, pp1030-1042, 2020.

[19] Muhammad Yasin, Wakil Waqas, Ali Kazam, et al. "Postharvest Technologies for Major Agronomic Crops," Agronomic Crops, vol. 1, pp679-710, 2019.

[20] F. Yi, D. Sun, and Y. Zhou, "Grain subsidy, liquidity constraints and food security—Impact of the grain subsidy program on the grain-sown areas in China," Food Policy, vol. 50, pp114-124, 2015.

[21] J. Ricker-Gilbert and M. Jones, "Does storage technology affect adoption of improved maize varieties in Africa? Insights from Malawi's input subsidy program," Food Policy, vol. 50, pp92-105, 2015.

[22] O.J. Omotilewa, J. Ricker-Gilbert, J.H. Ainembabazi, et al. "Does improved storage technology promote modern input use and food security? Evidence from a randomized trial in Uganda," Journal of Development Economics, vol. 135, pp176-198, 2018.

[23] Jin Liu, Jiefei Jia, and Qing Xu, "How agricultural machinery purchase subsidies affect small farmers' access to agricultural machinery socialization services: An analysis based on the data of fixed observation points in rural China," Chinese Rural Economy, no.2, pp85-108, 2023.

[24] H. Zhang, and Y. Zhang, "Do agricultural subsidies improve the technical efficiency of grain production? An empirical study based on data of 552 grain-producing family farms in Jiangsu Province," Journal of Huazhong Agricultural University (Social Sciences Edition), no.6, pp58-67, 2022.

[25] L. Shen, Q. Yang, Y. Hou, et al. "Research on information sharing incentive mechanism of China's port cold chain logistics enterprises based on blockchain," Ocean & Coastal Management, vol. 225, pp106229, 2022.

[26] P. Fan, A.K. Mishra, S. Feng, et al. "The effect of agricultural subsidies on chemical fertilizer use: Evidence from a new policy in China," Journal of Environmental Management, vol, 344, pp118423, 2023.

[27] T. Li, S. Wang, and Z. He, "Research on Logistics Service Supply Chain Joint Carbon-emission Reduction Considering Consumers' Low-carbon Preference," Engineering Letters, vol. 31, no.2, pp467-473, 2023.

[28] S. Sang, "Optimal Policies in a Green Supply Chain with Socially Responsible Manufacturer," Engineering Letters, vol. 27, no.4, pp696-707, 2019.

[29] K. An and Y. Ouyang, "Robust grain supply chain design considering post-harvest loss and harvest timing equilibrium," Transportation Research Part E: Logistics and Transportation Review, vol. 88, pp110-128, 2016.

[30] Y. Yu, Y. He, M. Salling, "Pricing and Safety Investment Decisions in Food Supply Chains with Government Subsidy," Journal of Food Quality, vol. 2021, pp11-18, 2021.

[31] P. Liu, "Pricing policies and coordination of low-carbon supply chain considering targeted advertisement and carbon emission reduction costs in the big data environment," Journal of Cleaner Production, vol. 210, pp343-357, 2019.

[32] L. Sun and X. Cao, Alharthi Majed, et al. "Carbon emission transfer strategies in supply chain with lag time of emission reduction technologies and low-carbon preference of consumers," Journal of Cleaner Production, vol. 264, pp121664, 2020.

[33] S.P. Chen and C.Y. Chen, "Dynamic markdown decisions based on a quality loss function in on-site direct-sale supply chains for perishable food," Journal of the Operational Research Society, vol. 72, no.4, pp822-836, 2020.

[34] M. Liu, B. Dan, S. Zhang, et al. "Information sharing in an E-tailing supply chain for fresh produce with freshness-keeping effort and value-added service," European Journal of Operational Research, vol. 290, no.2, pp572-584, 2021.

[35] P. Nie, "A monopoly with pollution emissions," Journal of Environmental Planning and Management - J ENVIRON PLAN MANAG, vol. 55, pp705-711, 2012.

[36] R. Zhang, W. Ma, and J. Liu, "Impact of government subsidy on agricultural production and pollution: A game-theoretic approach," Journal of Cleaner Production, vol. 285, pp124806, 2020.

[37] Y. Chen, X. Wen, B. Wang, and P. Nie, "Agricultural pollution and regulation: How to subsidize agriculture?" Journal of Cleaner Production, vol. 164, pp258-264, 2017.

[38] H. Peng and T. Pang, "Optimal strategies for a three-level contract-farming supply chain with subsidy," International Journal of Production Economics, vol. 216, pp274-286, 2019.

[39] D. Cardoen, P. Joshi, L. Diels, et al. "Agriculture biomass in India: Part 2. Post-harvest losses, cost and environmental impacts," Resources Conservation and Recycling, vol. 101, pp143-153, 2015.

[40] B.V. Gogh, H. Boerrigter, M. Noordam, et al. "Post-harvest loss reduction: a value chain perspective on the role of post-harvest management in attaining economically and environmentally sustainable food chains," Wageningen Food & Biobased Research, no.1751, 2017.

[41] M. Chandrasekaran and R. Ranganathan, Modelling and optimisation of Indian traditional agriculture supply chain to reduce post-harvest loss and CO 2 emission[J]. Industrial Management & Data Systems, vol. 117, no.9, pp1817-1841, 2017.