Research on Government Subsidy Policy of Grain Supply Chain Considering the Efforts of Loss Reduction

Pan Liu, Mengjuan Li, Qian Liu

***Abstract*—Taking a grain supply chain (GASC) with a producer and a retailer as the research object, to encourage supply chain members' efforts on reducing grain quality and quantity losses, government will offer the subsidy. The paper constructed and analyzed four subsidy models. Findings: (1) Under the four modes, the wholesale price is negatively correlated with the producers' efforts of loss reduction (EOLR), positively correlated with the retailers' EOLR, and negatively correlated with the retail price and the producer' and retailer' EOLR. (2) The GASC members' EOLR can have a "spillover effect", meaning that their own EOLR can benefit the other party. (3) When the subsidy coefficient meets a certain value, the government subsidies for the EOLR of supply chain members can increase the profits of the producer and the retailer, and can stimulate the members to take the efforts to reduce losses, achieving the goal of "food loss and waste".**

***Index Terms*—efforts of loss reduction; grain supply chain; subsidy policy; game model**

I. Introduction

In 2021, the Food and Agriculture Organization of the United Nations proposed that approximately 14% of global grain losses occur between harvesting and retail processes. In 2021, the comprehensive post-harvest loss rate of major grain crops reached to7.9% in China [1], and at least 70 billion kilograms of grain were lost in stages of storage, transportation, and processing. The huge grain post-harvest losses, combined with the repeated fluctuations of the COVID-19 and the continuous turbulence of the international situation, pose a serious threat to national grain security. Although, in order to effectively reduce the losses in various stages of grain production, China has introduced various policies, such as the 'Action Plan for Grain Conservation' and the policy of scientific grain storage. However, the profit driven nature of the market has led to the enthusiasm lack among GASC members in adopting technology and facilities to reduce losses, namely, insufficient efforts to reduce losses. For example, the average adoption rate of scientific grain storage equipment in China is less than 40%, and the proportion of bulk grain transportation is only 25%, which is resulting in poor loss reduction effects in the current grain industry.

Therefore, for building a long-term mechanism about grain conservation and loss reduction, how to design the effective subsidy policies to motivate GASC members' efforts of loss reduction is of great practical significance. The strategy of building a strong country through quality proposed in the report of the 20th National Congress of the Communist Party of China and the 'Outline for Building a Strong Country through Quality' issued by the Central Committee of the Communist Party of China and the State Council in 2023 have put forward new requirements for grain quality. In order to meet the increasing demand of consumers for products quality, the grain quality losses cannot be ignored. Designing the effective subsidy policies requires balancing the grain quality and quantity losses, but a large number of existing studies only focus on the grain quantity losses.

Therefore, this paper regards the EOLR of the GASC members as an important factor in affecting the grain quality and quantity losses, and explores the impacts of government subsidy policy on the decisions of the EOLR of the GASC members. The results will provide reference for decision-making departments, such as the government, to formulate the postharvest loss reduction subsidy policies.

Manuscript received November 5, 2023; revised May 29, 2024.

This work is supported by the Top Talent Project of Henan Agricultural University (No. 30500681), Creator Talent Support Plan of Henan Agricultural University (No. 30200757), Humanities and Social Science Research Youth Project of the Education Ministry of China (No. 21YJC790076), Postdoctoral Science Foundation (2022M721039), Henan University Philosophy and Social Science Innovation Talent Support Program (No. 2023-CXRC-24).

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II. Literature review

A. Research on Postharvest Losses of the GASC

Grain postharvest loss refers to the measurable reduction of grain output at various stages of the postharvest system, including quantity, quality, and economic losses[2]. Grain postharvest loss involves the entire chain of grain circulation, and existing researches mainly focus on the causes and calculation of grain postharvest loss. For example, cause analyses about grain loss in harvest [3], storage [4], transportation [5], consumption [1] and other links, as well as analyses of the whole grain industry chain [6]. For the calculation of grain postharvest loss, the National Grain Administration releases grain loss reports from time to time, and researchers also use different calculation methods that are tailored to different regions or types of grain crops. Such as proportion method [7], literature research method [1], material flow measurement method [8]. It can be seen that most existing researches focus on the calculation and cause analysis of single link of grain postharvest loss, and few studies analyze grain postharvest loss from the perspective of the entire grain chain.

B. Research on efforts of loss reduction

Measures on reducing grain losses emerged with the emergence of grain postharvest loss, including the reconstruction of the GASC network and the application of equipment in various postharvest stages, etc. In terms of reducing harvest losses in grain production, the producers have begun to attach importance to issues such as grain harvesting machines, farmer operation training, and the technical level of harvester operators [1]. In terms of storage and transportation at the grain sale end, the retailers have begun to attach importance to the improvement of specialized containers for grain transportation and the scientific construction of storage facilities [5]. In terms of grain consumption, consumers have also begun to establish a correct outlook on grain consumption, reducing grain table waste, and so on [9], these all reflect the efforts of the GASC members in reducing grain losses, and we named it as the embryonic form of EOLR. Based on the EOLR, there is a lack of research on exploring policies for grain loss reduction subsidies. The relevant researches in the field of fresh supply chain provides strong support for this study. Such as, Zhang et al. [10] studied the optimal decision-making problem of the supplier's supply chain before and after government subsidizes the investments in freshness-keeping effort in an uncertain demand environment. In the field of low-carbon supply chain, Zhang et al. [11] explored the changes in social welfare and supply chain benefits after government subsidies for carbon reduction technologies. In the field of green supply chain, Chen et al. [12] considered the impacts of the government's reward and punishment mechanism on green supply chain investment and green efforts. Regarding the green supply chain led by retailers, Shang et al. [13] studied the impacts of different government subsidies on sales efforts. Wu et al. [14] studied the relationship between government punishment systems and manufacturers reducing carbon emissions.

In the field of GASC, relevant researches mainly focus on the application of measures about reducing postharvest loss. Such as, Wu [5] found that the grain loss reduction should be implemented at the technical level of harvesting and processing. Gao et al. [15]conducted the measures to reduce losses in the postharvest stages of the three main grains, such as harvesting and storage. Sun et al. [16] investigated the measures to reduce grain losses during the circulation process. Therefore, existing researches have considered the postharvest loss link to study supply chain loss reduction measures, and there are few studies exploring the impacts of supply chain members' EOLR on the loss reduction pattern. So, in response to the current poor effect of grain loss reduction, Gao et al. [17] proposed to promote the work of grain loss reduction throughout the entire chain. Considering both EOLR and postharvest losses, Li et al. [18] studied the impacts of EOLR of GASC members on their profits based on quantum games. The study of An et al. [19] showed that the EOLR of the GASC members subsidized by the government had a positive impact on reducing postharvest losses. Thus, existing researches have begun to focus on the impacts of EOLR on operational decisions in grain supply chain, but there is a lack of relevant research on the subsidy mechanism for the GASC loss reduction.

C. Research on the loss reduction Subsidies of GASC

In order to encourage the GASC members to actively invest in loss reduction, many countries have begun to encourage and support the loss reduction behavior of the GASC members from a policy perspective. At present, the domestic and foreign policies on grain postharvest loss reduction involve links such as harvesting, storage, transportation, and processing. For example, the subsidies for purchasing agricultural machinery, scientific grain storage facilities, and the application of bulk grain containers in transportation. It can be seen that relevant policies mostly drive social capital to increase investment in the field of grain saving and loss reduction by setting up special funds by the government, and improve equipment and technology for grain saving and loss reduction. For grain loss reduction subsidies, existing researches are mostly based on statistical analysis and experimental methods, such as, Zhao et al. [20]found that agricultural machinery subsidies can increase grain production. Chatterjee [21] studied the impacts of subsidy storage facilities on grain yield. There are few studies based on game theory, such as, Yu et al. [22] constructed a tripartite game between agricultural enterprises, sellers, and the government based on agricultural insurance subsidy policies, and found that government subsidies can improve supply chain returns. Peng's et al. [23] research showed that government subsidies could affect farmers' efforts and the profits of distributors and suppliers. As a result, the existing researches on subsidies related to the GASC loss reduction focus more on single postharvest links such as production and retail.

In summary, there have been a lot of studies on the measurement of grain postharvest losses, loss factors and loss reduction measures. But there is a lack of studies that takes the whole grain chain as the research object and considers the effects of government subsidies on the efforts of loss reduction behavior of grain management entities. Therefore, our research focus on a GASC composed of a producer and a retailer as the research object, considering the EOLR of relevant decision-makers, constructing a new game model under government subsidy policies, and exploring relevant loss reduction subsidy mechanisms by integrating various stages of the postharvest grain supply chain.

III. Problem Description and Main Assumptions

A. Parameter Description

According to the needs of the paper, we set some parameters as follows:

TABLE I
MODEL PARAMETERS AND THEIR DEFINITIONS

Parameter	Definitions
a	Potential market demand
e	Price-sensitive coefficient
b	Quality-sensitivity coefficient
w^i	Wholesale price of grain in mode
p^i	Retail price of grain in i mode
i	Losses reduction and subsidy models, . $i=\{N,PT,RT,JT\}$.
q^i	Grain quality level in i mode
z_1	Producer efforts cost sensitivity coefficient
$\frac{z_1 h_p^2}{2}$	Cost of the EOLR by producer (Jiang et al. 2015, Swami et al. 2013)
h_p	The producer's EOLR
h_r	The retailer's EOLR
θ_p^i	Producer's grain loss rate in i mode
θ_r^i	Retailer's grain loss rate in. i mode
c_1	Unit production cost of the producer
γ	Government subsidy coefficient for the producer's cost of EOLR
λ	Government subsidy coefficient for the retailer's cost of EOLR
z_2	Retailer efforts cost sensitivity coefficient
$\frac{z_2 h_r^2}{2}$	Cost of the EOLR by retailer (Jiang et al. [24], Swami et al. [25]
h_p	The producer's EOLR
h_r	The retailer's EOLR
θ_p^i	Producer's grain loss rate in i mode
θ_r^i	Retailer's grain loss rate in i mode

B. Description of Grain Losses

Grain quantity losses refer to a decrease in the weight or calorie content of grain [26]. The existing researches on the measurement of grain quantity losses mostly use the concept of grain quantity loss rate to describe it. Therefore, this paper uses the concept of quantity loss rate (θ_p^i and θ_r^i) to describe the grain quantity losses various supply chain stages.

As the consumers' demands for grain quality gradually increase [27], the market demand for products is positively correlated with product quality [28]. The decline in grain quality will ultimately lead to the grain waste and losses by affecting consumers' consumption experience. And the negative consumption experience brought to consumers will in turn affect the market demand. Therefore, exploring the relationship between the decline in grain quality and demand can better reflect the special background needs of this study (research on grain subsidy policy considering the EOLR).

Storage conditions and time are the key characteristics that affect grain quality, and are also the main factors affecting consumer purchasing decisions. According to Taguchi's [29] research, the relationship between the grain quality losses and time is $f(t)=qt^2$ [30]. Assuming the shelf life of the grain is T_m , then there is $0\le t\le T_m$. We set $A_0=f(T_m)$, and A_0 represents the maximum grain losses. Assuming the quality level of grain at time t is $q(t)$, previous studies have shown that $q(t)=\frac{2A_0}{T_m^2}(T_m-t)$.

C. The Demand Function Model Considering Quality Losses and Mitigation Efforts

In order to reduce the grain quality losses and extend the shelf life, the measures to reduce the losses of grain storage, harvest, and other links have been widely studied and discussed [31]. This represents the efforts made by supply chain members to reduce grain losses in the process of grain circulation, this paper refers to the EOLR. The adoption of different storages, harvesting and other equipment can lead to different grain loss rates, which reflects the degree of the EOLR. The higher the degree of the EOLR, the smaller the losses of grain. Usually, the quality level of grain throughout the entire circulation process from producers to retailers is related to the EOLR of each member of the GASC.

Assuming that consumer demand is price and quality sensitive, based on Chen et al.'s research [30], the demand for grain market is shown in formula (1).

$$D=a-ep+bq(t) \tag{1}$$

From $q(t)=\frac{2A_0}{T_m^2}(T_m-t)$, we know $D=a-ep+b\frac{2A_0}{T_m^2}(T_m-t)$. Due to the impact of supply chain members' EOLR on the shelf life of grain, under the different EOLR, T_m is different.

This paper selects a GASC composed of a producer and a retailer as the research object. There are four types of supply chain members' EOLR and government subsidies. ①N mode: neither the producer nor the retailer engages in EOLR, and the government does not provide the subsidy. ②PT mode: the producer independently adopts the EOLR, and the government subsidizes the producer's loss reduction actions. ③RT mode: the retailer independently adopts the EOLR, and the government subsidizes the retailer's loss reduction actions. ④JT mode: both the producer and the retailer adopt the EOLR, and the government subsidizes their two loss reduction actions. The complete operational process of the government subsidy mechanism for the GASC considering EOLR is shown in Fig. 1.

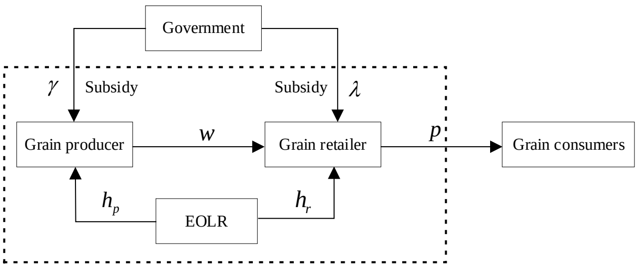


Fig. 1 GASC operation mechanism considering EOLR under government subsidy mechanism

Under the different modes, the shelf life of grains varies, therefore, the demand function is shown in formula (2).

$$D^i=a-ep^i+b\frac{2A_0^i}{(T_m^i)^2}(T_m^i-t) \tag{2}$$

For the convenience of calculation, let $q^i=\frac{2A_0^i}{(T_m^i)^2}(T_m^i-t)$, based on the implementation of EOLR, it is assumed that $q^N<q^{PT}=q^{RT}<q^{JT}$. Now, $D^i=a-ep^i+bq^i$.

The loss rate θ_x^i is affected by the GASC members'

EOLR $h_i(0<h_i<1)(i=p,r)$, denoted as $\theta_x^i(h_i)$. Reference Cai et al. [32], let $\theta_x^i(h_i)=\rho_0(1-h_i)$. Among them, $\rho_0(0<\rho_0<1)$ is the initial loss rate of each link of grain, and let $\rho_0=1$, so $\theta_x^i(h_i)=1-h_i$. Without considering other losses in circulation, it is assumed that the supply and demand of grain in the market are in a tight balance or supply is less than demand. Assuming that the actual grain produced by the producer is D_o, due to the losses of quantity in production processes such as harvesting and storage, the actual amount of grain flowing into the retailer is $(1-\theta_p^i)D_o$. Moreover, due to the losses of quantity in the retailer's storage and other processes, the actual grain delivered to consumers is $(1-\theta_p^i)(1-\theta_r^i)D_o$. Consumer surplus is C_s^N, $C_s^N=\frac{1}{2}(\overline{p}^N-p^{N*})(1-\theta_r^N)D^N$, wherein, $\overline{p}^N$ is the critical retail price of grain when no consumers purchase grain in the N mode.

IV. Research on Government Subsidy Policy under Different Models

The game rules of members in the GASC comply with the master-slave game. Government revenue consists of the producer revenue, retailer revenue, government fiscal expenditure, and consumer surplus.

A. N mode

Under the N-mode, the revenue functions of producer, retailer, and government are shown in formulas (3)~(5):

$$\pi_p^N=(w^N-c_1)D^N-c_1\frac{\theta_p^N D^N}{(1-\theta_p^N)} \tag{3}$$

$$\pi_r^N=(p^N-w^N)(1-\theta_r^N)D^N-w^N\theta_r^N D^N \tag{4}$$

$$\pi_g^N=\pi_r^N+\pi_p^N+C_s^N \tag{5}$$

We will use the reverse induction method to solve the optimal solution under this model. By incorporating the demand function $D^N=a-ep^N+bq^N$ into the retailer's revenue function, when $\frac{\partial\pi_r^N}{\partial p^N}=0$, we can obtain the retail price p^N. Bring p^N into the producer revenue function to get the optimal wholesale price w^{N*}. Then, the optimal decisions of the GASC members are as follows:

$$w^{N*}=\frac{(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)+c_1e}{2e(1-\theta_p{}^N)} \tag{6}$$

$$p^{N*}=\frac{(a+bq^N)\left[(1-\theta_p{}^N)(1-\theta_r{}^N)+2\right]+c_1e}{4e(1-\theta_p{}^N)(1-\theta_r{}^N)} \tag{7}$$

$$D^{N*}=\frac{(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)-c_1e}{4(1-\theta_p{}^N)(1-\theta_r{}^N)} \tag{8}$$

$$\pi_p^{N*}=\frac{\left[(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)-c_1e\right]^2}{8e(1-\theta_r{}^N)(1-\theta_p{}^N)^2} \tag{9}$$

$$\pi_r^{N*}=\frac{\left[(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)-c_1e\right]^2}{16e(1-\theta_r{}^N)(1-\theta_p{}^N)^2} \tag{10}$$

$$\pi_g^{N*}=\frac{7\left[(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)-c_1e\right]^2}{32e(1-\theta_r{}^N)(1-\theta_p{}^N)^2} \tag{11}$$

Without loss of generality, $D^{N*}>0$, we get $\Delta_1=(a+bq^N)(1-\theta_p{}^N)(1-\theta_r{}^N)-c_1e>0$.

B. PT mode

Under the PT mode, the revenue functions of producer, retailer, and government are shown in formulas (12)~(14):

$$\pi_p^{PT}=(w^{PT}-c_1)D^{PT}-c_1\frac{\theta_p^{PT}D^{PT}}{1-\theta_p^{PT}}-(1-\gamma)\frac{z_1h_p^2}{2} \tag{12}$$

$$\pi_r^{PT}=(p^{PT}-w^{PT})(1-\theta_r^{PT})D^{PT}-w^{PT}\theta_r^{PT}D^{PT} \tag{13}$$

$$\pi_g^{PT}=\pi_r^{PT}+\pi_p^{PT}+C_s^{PT}-\gamma\frac{z_1h_p^2}{2} \tag{14}$$

Under the PT mode and N mode, the retailer has not taken any loss reduction measures, so it is assumed that $\theta_r^{PT}=\theta_r^N$. The optimal decisions of the GASC members are obtained using the reverse induction method as follows (the solving process is the same as the N model, omitted here):

$$w^{PT*}=\frac{h_p(a+bq^{PT})(1-\theta_r^{PT})+c_1e}{2eh_p} \tag{15}$$

$$p^{PT*}=\frac{3h_p(a+bq^{PT})(1-\theta_r^{PT})+c_1e}{4eh_p(1-\theta_r^{PT})} \tag{16}$$

$$D^{PT*}=\frac{h_p(a+bq^{PT})(1-\theta_r^{PT})-c_1e}{4h_p(1-\theta_r^{PT})} \tag{17}$$

$$\pi_p^{PT*}=\frac{\left[h_p(1-\theta_r^{PT})(a+bq^{PT})-c_1e\right]^2-4ez_1h_p{}^4(1-\gamma)(1-\theta_r^{PT})}{8eh_p{}^2(1-\theta_r^{PT})} \tag{18}$$

$$\pi_r^{PT*}=\frac{\left[h_p(a+bq)(1-\theta_r^{PT})+c_1e\right]^2}{16eh_p^2(1-\theta_r^{PT})} \tag{19}$$

$$\pi_g^{PT*}=\frac{7\left[h_p(a+bq^{PT})(1-\theta_r^{PT})-c_1e\right]^2-16ez_1h_p{}^4(1-\theta_r^{PT})}{32eh_p{}^2(1-\theta_r^{PT})} \tag{20}$$

Without loss of generality, $D^{PT*}>0$, we get $\Delta_2=h_p(a+bq^{PT})(1-\theta_r^{PT})-c_1e>0$.

Proposition 1: Under the PT model, the wholesale and retail prices are negatively correlated with the producer's EOLR, the retailer revenue is positively correlated with the producer's EOLR. When $\gamma>1-\frac{c_1\Delta_2}{4h_p{}^4z_1(1-\theta_r^{PT})}$, the revenue of producer is positively correlated with its EOLR, and vice versa, when $h_p{}^4<\frac{7c_1\Delta_2}{16z_1(1-\theta_r^{PT})}$, there is a positive correlation between government revenue and producer's EOLR, while the opposite is negative.

Proof: Taking the partial derivative of w^{PT*}, p^{PT*}, π_p^{PT*}, π_r^{PT*}, and π_g^{PT*} over h_p, we get $\frac{\partial w^{PT*}}{\partial h_p}=-\frac{c_1}{2h_p{}^2}<0$, $\frac{\partial p^{PT*}}{\partial h_p}=\frac{c_1}{4h_p{}^2(\theta_r^{PT}-1)}<0$, $\frac{\partial\pi_p^{PT*}}{\partial h_p}=\frac{4h_p{}^4z_1(1-\theta_r^{PT})(1-\gamma)+c_1{}^2e-(1-\theta_r^{PT})(a+bq^{PT})c_1h_p}{4h_p{}^3(\theta_r^{PT}-1)}$.

When $\gamma>1-\frac{c_1\Delta_2}{4h_p{}^4z_1(1-\theta_r^{PT})}$, $\frac{\partial\pi_p^{PT*}}{\partial h_p}>0$, conversely $\frac{\partial\pi_p^{PT*}}{\partial h_p}<0$, $\frac{\partial\pi_r^{PT*}}{\partial h_p}=\frac{c_1\left[(a+bq^{PT})(1-\theta_r^{PT})h_p-c_1e\right]}{8h_p{}^3(1-\theta_r^{PT})}>0$,

$\frac{\partial \pi_g^{PT*}}{\partial h_p^{PT}} = \frac{7\left[c_1 h_p\left(a+bq^{PT}\right)\left(1-\theta_r^{PT}\right)-c_1^2 e\right]-16h_p^4 z_1\left(1-\theta_r^{PT}\right)}{16h_p^3\left(1-\theta_r^{PT}\right)}$,

when $h_p^4 < \frac{7c_1\Delta_2}{16z_1\left(1-\theta_r^{PT}\right)}$, $\frac{\partial \pi_g^{PT*}}{\partial h_p^{PT}} > 0$, conversely, $\frac{\partial \pi_g^{PT*}}{\partial h_p^{PT}} < 0$. Proposition 1 is valid.

Proposition 2: Under the PT model, the wholesale price, retail price, retailer revenue, and government revenue are not related to the government's subsidy coefficient for producer. The revenue of producer is positively correlated with the government's subsidy coefficient to producer.

Proof: Taking the partial derivative of w^{PT*}, p^{PT*}, π_p^{PT*}, π_r^{PT*} and π_g^{PT*} over γ, we get $\frac{\partial w^{PT*}}{\partial \gamma}=0$, $\frac{\partial p^{PT*}}{\partial \gamma}=0$, $\frac{\partial \pi_r^{PT*}}{\partial \gamma}=0$, $\frac{\partial \pi_g^{PT*}}{\partial \gamma}=0$ and $\frac{\partial \pi_p^{PT*}}{\partial \gamma}=\frac{z_1 h_p^2}{2}>0$. Proposition 2 is valid.

C. RT mode

Under the RT mode, the revenue functions of producer, retailer, and government are shown in formulas (21)~(23):

$$\pi_p^{RT} = (w^{RT}-c_1)D^{RT} - c_1\frac{\theta_p^{RT}D^{RT}}{1-\theta_p^{RT}} \tag{21}$$

$$\pi_r^{RT} = \left(p^{RT}-w^{RT}\right)(1-\theta_r^{RT})D^{RT} - w^{RT}\theta_r^{RT}D^{RT} - (1-\lambda)\frac{z_2 h_r^2}{2} \tag{22}$$

$$\pi_g^{RT} = \pi_r^{RT} + \pi_p^{RT} + C_s^{RT} - \lambda\frac{z_2 h_r^2}{2} \tag{23}$$

Under the RT mode and N mode, the producer has not taken any loss reduction measures, so it is assumed that $\theta_p^{RT}=\theta_p^N$. The optimal decisions of the GASC members are obtained using the reverse induction method as follows (the solving process is the same as the N model, omitted here):

$$w^{RT*} = \frac{h_r\left(a+bq^{RT}\right)\left(1-\theta_p^{RT}\right)+c_1 e}{2e\left(1-\theta_p^{RT}\right)} \tag{24}$$

$$p^{RT*} = \frac{3h_r\left(a+bq^{RT}\right)\left(1-\theta_p^{RT}\right)+c_1 e}{4eh_r\left(1-\theta_p^{RT}\right)} \tag{25}$$

$$D^{RT*} = \frac{h_r\left(a+bq^{RT}\right)\left(\theta_p^{RT}-1\right)+c_1 e}{4h_r\left(\theta_p^{RT}-1\right)} \tag{26}$$

$$\pi_p^{RT*} = \frac{\left[h_r\left(a+bq^{RT}\right)\left(1-\theta_p^{RT}\right)-c_1 e\right]^2}{8eh_r\left(1-\theta_p^{RT}\right)^2} \tag{27}$$

$$\pi_r^{RT*} = \frac{\left[h_r\left(1-\theta_p^{RT}\right)\left(a+bq^{RT}\right)-c_1 e\right]^2 - 8ez_2h_r^3(1-\lambda)\left(1-\theta_p^{RT}\right)^2}{16eh_r\left(1-\theta_p^{RT}\right)^2} \tag{28}$$

$$\pi_g^{RT*} = \frac{7\left[h_r\left(1-\theta_p^{RT}\right)\left(a+bq^{RT}\right)-c_1 e\right]^2 - 16ez_2h_r^3\left(1-\theta_p^{RT}\right)^2}{32eh_r\left(1-\theta_p^{RT}\right)^2} \tag{29}$$

Without loss of generality, $D^{RT*}>0$, we get $\Delta_3 = h_r\left(a+bq^{RT}\right)\left(1-\theta_p^{RT}\right)-c_1 e>0$.

Proposition 2: Under the RT mode, the wholesale price and the producer revenue are positively correlated with the retailer's EOLR. The retail price is negatively correlated with the retailer's EOLR. When $\lambda\left(2\theta_p^{RT}-1\right) < \frac{\Delta_3\left(\Delta_3+2c_1 e\right)}{16ez_2h_r^3} - \left(\theta_p^{RT}-1\right)^2$, the retailer revenue is positively correlated with its EOLR, and vice versa, when $h_r^3 < \frac{7\Delta_3\left(\Delta_3+2c_1 e\right)}{32ez_2\left(1-\theta_p^{RT}\right)^2}$, the government revenue is positively correlated with the retailer's EOLR, while vice versa. (The proof process is the same as proposition 1, omitted here)

Proposition 4: The wholesale price, retail price, producer revenue, and government revenue are not related to the government subsidy coefficient for retailer. The retailer's revenues are positively correlated with the government's subsidy coefficient to retailer. (The proof process is the same as proposition 2, omitted here)

D. JT mode

Under the JT mode, the revenue functions of producer, retailer, and government are shown in formulas (30)~(32):

$$\pi_p^{JT} = (w^{JT}-c_1)D^{JT} - c_1\frac{\theta_p^{JT}D^{JT}}{1-\theta_p^{JT}} - (1-\gamma)\frac{z_1 h_p^2}{2} \tag{30}$$

$$\pi_r^{JT} = \left(p^{JT}-w^{JT}\right)(1-\theta_r^{JT})D^{JT} - w^{JT}\theta_r^{JT}D^{JT} - (1-\lambda)\frac{z_2 h_r^2}{2} \tag{31}$$

$$\pi_g^{JT} = \pi_r^{JT} + \pi_p^{JT} + C_s^{JT} - \gamma\frac{z_1 h_p^2}{2} - \lambda\frac{z_2 h_r^2}{2} \tag{32}$$

Under the JT mode, the producer and retailer simultaneously take loss reduction measures, so it is assumed that $\theta_p^{JT}=\theta_p^{PT}$, $\theta_r^{JT}=\theta_r^{RT}$. The optimal decisions of the GASC members are obtained using the reverse induction method as follows (the solving process is the same as the N model, omitted here):

$$w^{JT*} = \frac{h_p h_r\left(a+bq^{JT}\right)+c_1 e}{2eh_p} \tag{33}$$

$$p^{JT*} = \frac{3h_p h_r\left(a+bq^{JT}\right)+c_1 e}{4eh_p h_r} \tag{34}$$

$$D^{JT*} = \frac{h_p h_r\left(a+bq^{JT}\right)-c_1 e}{4h_p h_r} \tag{35}$$

$$\pi_p^{JT*} = \frac{\left[h_p h_r\left(a+bq^{JT}\right)-c_1 e\right]^2 - 4ez_1h_rh_p^4(1-\gamma)}{8eh_p^2 h_r} \tag{36}$$

$$\pi_r^{JT*} = \frac{\left[h_p h_r\left(a+bq^{JT}\right)-c_1 e\right]^2 - 8ez_2h_p^2h_r^3(1-\lambda)}{16eh_p^2 h_r} \tag{37}$$

$$\pi_g^{JT*} = \frac{7\left[h_p h_r\left(a+bq^{JT}\right)-c_1 e\right]^2 - 16eh_rh_p^2\left(z_1h_p^2+z_2h_r^2\right)}{32eh_p^2 h_r} \tag{38}$$

Without loss of generality, $D^{JT*}>0$, we get $\Delta_4 = \left(a+bq^{JT}\right)h_p h_r - c_1 e>0$.

Proposition 5: Under the JT model, the wholesale price and the retail price are negatively correlated with the producer's EOLR. The retailer revenues are positively correlated with the producer's EOLR. When $\gamma > 1-\frac{c_1\Delta_4}{4h_p^4 h_r z_1}$, the producer revenue is positively correlated with its EOLR, and vice versa, when $h_p^4 h_r < \frac{7c_1\Delta_4}{16z_1}$, there is a positive correlation between government revenue and the producer's EOLR, while the opposite is negative. (The proof process is the same as proposition 1, omitted here)

Proposition 6: Under the JT model, the wholesale price and the producer's profits are positively correlated with the retailer's EOLR. The retail price is negatively correlated with its EOLR. When $\lambda > 1-\frac{\Delta_4\left(\Delta_4+2c_1e\right)}{16h_p{}^2h_r{}^3ez_2}$, the retailer's revenues are positively correlated with its EOLR, and vice versa, when $h_p{}^2h_r{}^3 < \frac{7\Delta_4\left(\Delta_4+2c_1e\right)}{32ez_2}$, government revenues are positively correlated with the retailer's EOLR, while vice versa. (The proof process is the same as proposition 1, omitted here)

Proposition 7: Under the JT model, the wholesale price, the retail price, the retailer's revenues, and the government revenues are not related to the government's subsidy coefficient for producer. The producer's revenues are positively correlated with the government's subsidy coefficient to producer. (The proof process is the same as proposition 2, omitted here)

Proposition 8: Under the JT model, the wholesale price, the retail price, the producer's revenues, and the government revenues are not related to the government subsidy coefficient for retailer. The retailer's revenues are positively correlated with the government's subsidy coefficient to retailer. (The proof process is the same as proposition 2, omitted here)

E. Analysis of subsidy effect under different EOLR

By comparing the prices and benefits of the optimal decisions made by the GASC members under four modes, this study analyzes the impact of the loss reduction efforts and government subsidy coefficient of the GASC members on the optimal wholesale price, optimal retail price, and government benefits.

Conclusion 1: When only one producer or retailer adopts the EOLR, the wholesale price is negatively correlated with the producer's loss reduction efforts and positively correlated with the retailer's loss reduction efforts. When EOLR is adopted by both producer and retailer, the change in wholesale price depends on both the producer's and the retailer's EOLR. Therefore, the change in the final wholesale price depends on the level of impairment loss reduction efforts of both producer and retailer.

This conclusion indicates that the reduction in their grain loss rate is equivalent to an increase in grain production after the producer takes reduction measures. In order to sell all of their products, the producer will lower the wholesale price. Correspondingly, the grain loss rate at the retailer's location decreases after the retailer takes loss reduction measures, leading to an increase in grain storage and a decrease in grain purchases from the producer. At this point, the producer will increase the wholesale price to ensure that its own profits do not decrease.

Conclusion 2: Under the three modes, the retail price is negatively correlated with the GASC members' loss reduction efforts. Moreover, when one GASC member takes the loss reduction efforts, the impact on the retail price is larger than when both members take it.

The conclusion shows that the reduction in grain loss rate at the producer and retailer is equivalent to an increase in grain supply and storage at the production and retail ends after the producer and retailer take the EOLR. The producer has more grain wholesale to the retailer, and the retailer has more grain to sell to the consumers. At this point, a market with low profits but high sales will form, resulting in a decrease in the retail price of grain. When one GASC member takes the loss reduction efforts, the impact on the retail price is larger than when both members take it. This indicates that the joint EOLR taken by the producer and retailer has a smaller impact on market retail price. At this point, the more impact lies in the game between the producer and the retailer, such as the game between the wholesale price, and there is less competition with consumers.

Conclusion 3: The grain producer's EOLR will increase retailer's profits, while the retailer's EOLR will increase the producer's profits.

This conclusion indicates that the loss reduction efforts of the GASC members will have a "spillover effect", and due to the existence of this effect, the GASC members will engage in "free riding" speculative behavior. Therefore, the government should try its best to introduce some subsidy policies to stimulate the GASC members to adopt the EOLR and improve the overall efficiency of the supply chain.

Conclusion 4: When $\gamma > 1+\psi_1$, $\pi_p^{PT*} > \pi_p^{N*}$. When $h_p < \frac{\psi_2}{2c_1e\left(Q^{JT}-Q^{PT}\right)}$, $\pi_p^{JT*} > \pi_p^{PT*}$. Among them,

$$\psi_1 = \frac{c_1}{2h_p^2z_1}\left[\frac{Q^{PT}}{h_p}-\frac{Q^N}{\left(1-\theta_p^N\right)}\right]-\frac{c_1^2e}{4z_1h_p^2\left(1-\theta_r^N\right)}\left[\frac{1}{h_p^2}-\frac{1}{\left(1-\theta_p^N\right)^2}\right]-\frac{\left(1-\theta_r^N\right)}{4ez_1h_p^2}\left[\left(Q^{PT}\right)^2-\left(Q^N\right)^2\right],$$

$$\psi_2 = h_p^2\left[\left(Q^{JT}\right)^2h_r-\left(Q^{PT}\right)^2\left(1-\theta_r^{PT}\right)\right]+c_1^2e^2\left[\frac{1}{h_r}-\frac{1}{\left(1-\theta_r^{PT}\right)}\right].$$

That is to say, when $\gamma > 1+\psi_1$, the producer is willing to take the EOLR, and the government should also adjust subsidy rate to stimulate the producer to actively reduce grain losses and achieve the goal of grain saving and loss reduction subsidies. When $h_p < \frac{\psi_2}{2c_1e\left(Q^{JT}-Q^{PT}\right)}$, both the producer and the retailer take the EOLR. At this point, the producer's revenues are higher than that of the individual loss reduction efforts. To stimulate the enthusiasm of producer to adopt the EOLR, the government can adjust the subsidy level on producer and retailer to influence their EOLR, so as to achieve $h_p < \frac{\psi_2}{2c_1e\left(Q^{JT}-Q^{PT}\right)}$ as possible.

Conclusion 5: When $\lambda > 1+\psi_3$, $\pi_r^{RT*} > \pi_r^{N*}$. When $\frac{\psi_4}{2c_1e} > h_r\left(\frac{Q^{JT}}{h_p}-\frac{Q^{RT}}{\left(1-\theta_p^{RT}\right)}\right)$, $\pi_r^{JT*} > \pi_r^{RT*}$. Among them,

$$\psi_3 = \frac{c_1\left(Q^{RT}-Q^N\right)}{4h_r^2z_2\left(1-\theta_p^N\right)}-\frac{c_1^2e\left[\frac{1}{h_r}-\frac{1}{\left(1-\theta_r^N\right)}\right]}{8z_2h_r^2\left(1-\theta_p^N\right)^2}-\frac{\left[\left(Q^{RT}\right)^2h_r-\left(Q^N\right)\left(1-\theta_r^N\right)\right]}{8ez_2h_r^2},$$

$$\psi_4 = h_r^2\left[\left(Q^{JT}\right)^2-\left(Q^{RT}\right)^2\right]+c_1^2e^2\left[\frac{1}{h_p^2}-\frac{1}{\left(1-\theta_p^{RT}\right)^2}\right].$$

That is to say, when $\lambda > 1+\psi_3$, the retailer is willing to take the EOLR, and the government should also adjust subsidy rate to stimulate the retailer to actively reduce grain losses and achieve the goal of grain saving and loss reduction subsidies. When $h_r\left(\frac{Q^{JT}}{h_p}-\frac{Q^{RT}}{\left(1-\theta_p^{RT}\right)}\right) < \frac{\psi_4}{2c_1e}$, both the producer and the retailer take the EOLR. At this point, the retailer's revenues are higher than that of the individual loss reduction efforts. To stimulate the enthusiasm of retailer to adopt the EOLR, the government can adjust the subsidy level on producer and retailer to influence their EOLR, so as to achieve $h_r\left(\frac{Q^{JT}}{h_p}-\frac{Q^{RT}}{\left(1-\theta_p^{RT}\right)}\right)<\frac{\psi_4}{2c_1e}$ as possible.

Conclusion 6: When $h_p^2<\psi_5$, $\pi_g^{PT*}>\pi_g^{N*}$. When $h_r^2<\psi_6$, $\pi_g^{RT*}>\pi_g^{N*}$. Among them,

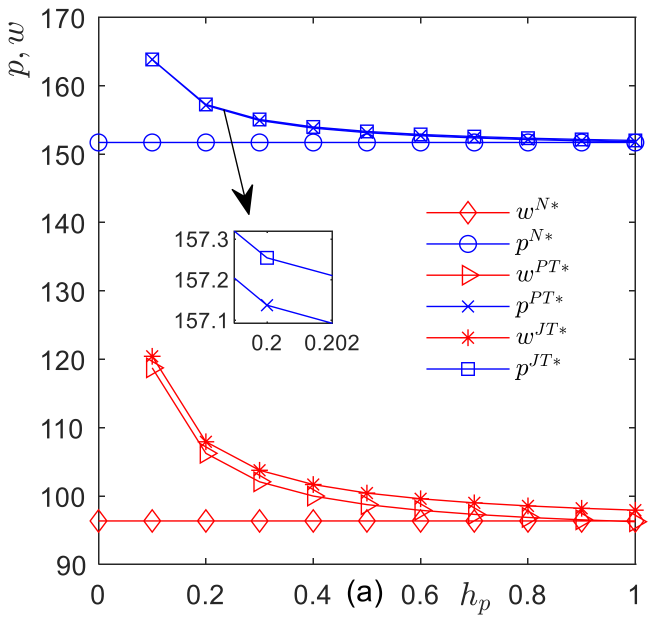
$$\psi_5=\frac{7\left(1-\theta_r^N\right)\left[\left(Q^{PT}\right)^2-\left(Q^N\right)^2\right]}{16ez_1}+\frac{7c_1^2e\left[\frac{1}{h_p^2}-\frac{1}{\left(1-\theta_p^N\right)^2}\right]}{16z_1\left(1-\theta_r^N\right)}-\frac{7c_1}{8z_1}\left[\frac{Q^{PT}}{h_p}-\frac{Q^N}{\left(1-\theta_p^N\right)}\right],$$

$$\psi_6=-\frac{7c_1\left(Q^{RT}-Q^N\right)}{8z_2}+\frac{7\left[h_r\left(Q^{RT}\right)^2-\left(1-\theta_r^N\right)\left(Q^N\right)^2\right]}{16ez_2}+\frac{7c_1^2e\left[\frac{1}{h_r}-\frac{1}{\left(1-\theta_r^N\right)}\right]}{16z_2\left(1-\theta_p^N\right)^2}.$$

That is to say, when $h_p^2<\psi_5$, the government is willing to provide subsidy to the producer. When $h_r^2<\psi_6$, the government is willing to provide subsidy to the retailer. The government subsidy for the producer's and retailer's EOLR are conditional, and it is only feasible for the government to provide subsidy when their reduction efforts are within a certain range. Therefore, the GASC members want to receive subsidies, they must control their EOLR in order to improve the overall social welfare after government subsidy.

V. Numerical Simulation

Taking Zhao Xia et al.'s [8] field research results on major grains in China as an example, this section uses numerical simulation to further explain the rationality of the conclusions obtained, and analyzes the impact of some important parameters on the GASC members' loss reduction efforts, government subsidy willingness, etc. We set $a=100$, $b=0.5$, $q^N=0.3$, $q^{PT}=q^{RT}=0.6$, $q^{JT}=0.9$, $\theta_p^N=\theta_p^{RT}=0.0915$, $\theta_r^N=\theta_r^{PT}=0.0654$, $\theta_p^{PT}=\theta_p^{JT}=0.05$, $\theta_r^{RT}=\theta_r^{JT}=0.05$, $z_1=z_2=0.5$, $c_1=0.5$, $e=0.5$. Based on the proof process of conclusions 1 and 2, we obtain Fig. 2.



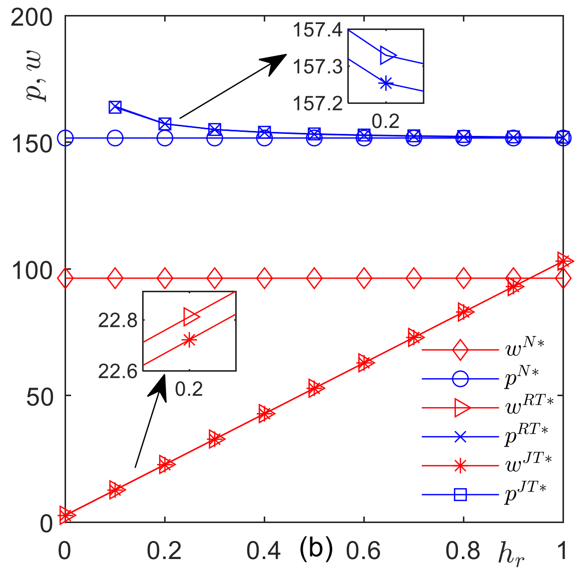
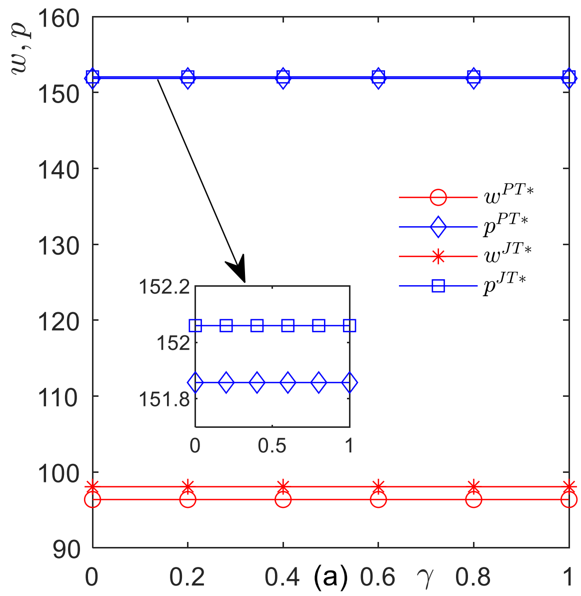


Fig. 2 The relationship between price and the EOLR

From the Fig. 2, the optimal wholesale price decreases with the increase of producer's EOLR and increases with the increase of retailer's EOLR. The optimal retail price decreases as the producer and retailer increase their EOLR. Indicating that producer's EOLR will reduce the grain loss rate in the production process. To prevent grain backlog, the producer will lower the wholesale price. The retailer's EOLR will reduce the grain loss rate in the retail process, leading to an increase in grain storage at the retailer and a decrease in grain purchases. At this point, the producer will increase the wholesale price to ensure that their own profits do not decrease. When the producer and the retailer simultaneously take measures to reduce losses, the loss rate of grain in circulation decreases. At this time, the market tends to have low profits but high sales, resulting in a decrease in the retail price. Therefore, conclusions 1 and 2 are confirmed.



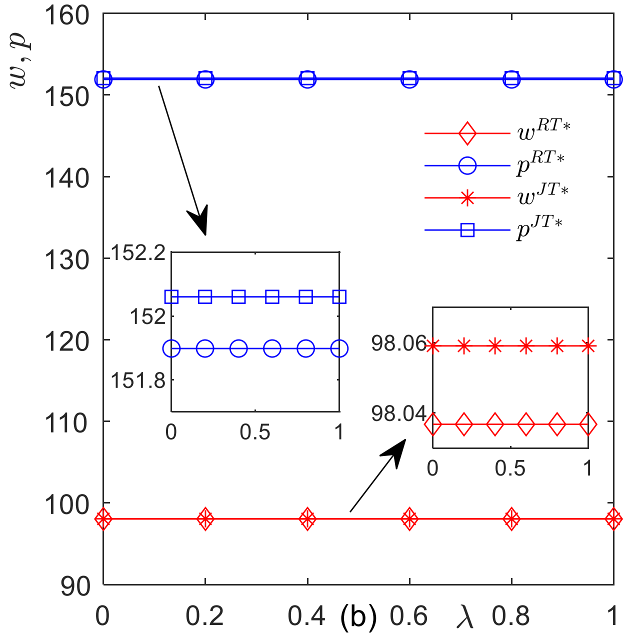
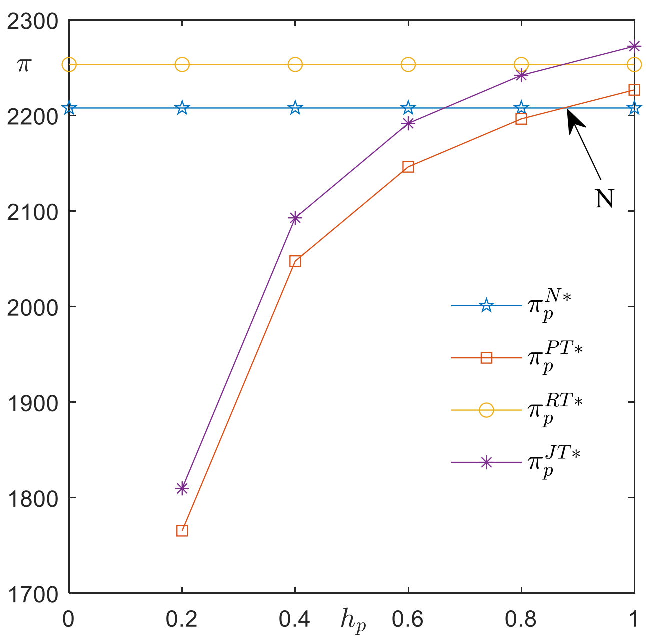


Fig. 3 The relationship between price and government subsidy coefficient

From the Fig. 3, the optimal retail price and the optimal wholesale price are independent of the government subsidy coefficient. It indicates that the government subsidy to the GASC members' EOLR does not directly affect the retail price and the wholesale price. Based on the conclusions 1 and 2, the government can adjust the supply chain members' EOLR through the subsidy rate, thereby affecting the optimal wholesale and retail prices.



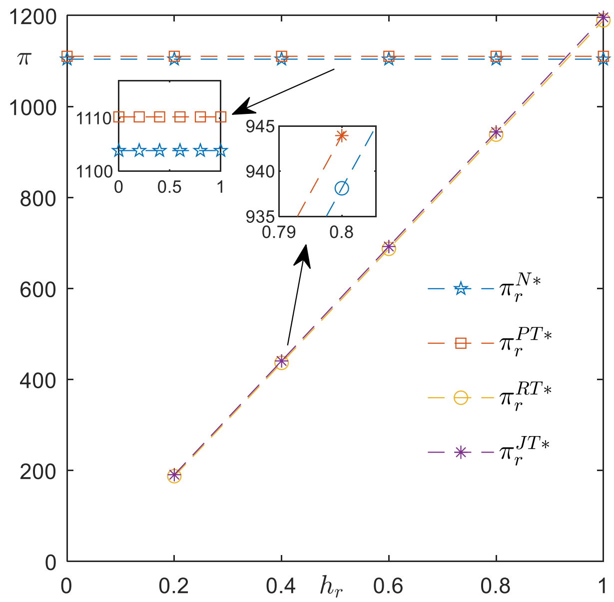
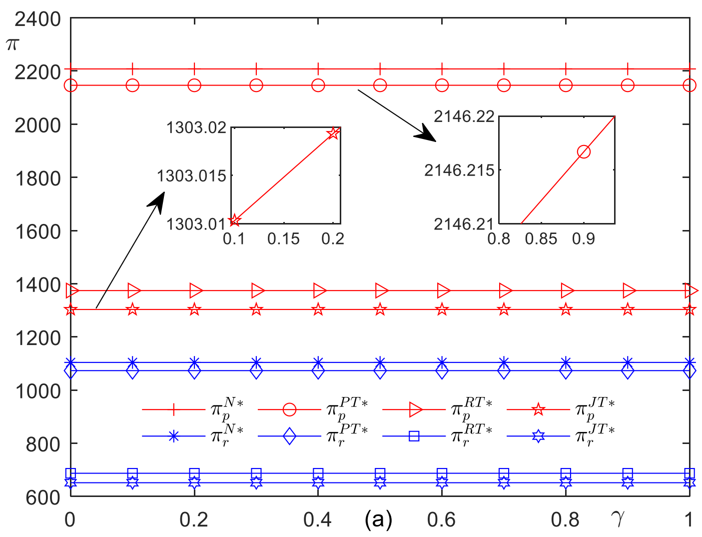


Fig. 4 The relationship between revenue and the EOLR

From the Fig. 4, the benefits of the GASC members increase with their own EOLR. It indicates that under a certain condition (after N point), chain members can improve their own profits by implementing EOLR. In addition, the grain producer' EOLR will increase the retailer's profits, and the retailer's EOLR will also increase the producer's profits. This indicates that the individual investment behavior of the GASC members will generate a "spillover effect", based on which chain members will engage in "free riding" speculative behavior. Therefore, the government should introduce some subsidy policies to stimulate the GASC members to actively take EOLR and improve the overall efficiency of the supply chain. Therefore, conclusion 3 is confirmed.



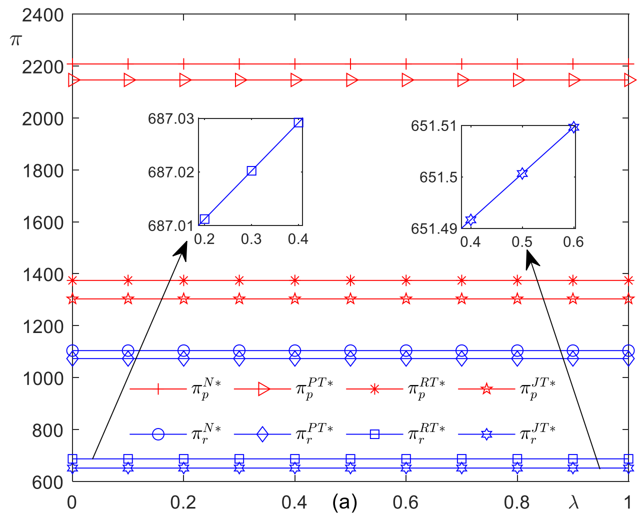


Fig. 5 The relationship between revenue and the government subsidy coefficient

From the Fig. 5, the revenues of the grain producer increase with the government subsidy coefficient to the producer, while the revenues of the retailer and government are independent of it. The revenues of the grain retailer increase with the government subsidy coefficient to the retailer, while the revenues of producer and government are independent of it. Based on the conclusion 3, it can be concluded that under the government subsidy, the benefits of the subsidized entities will increase, while the benefits of the GASC members will not be directly affected by the subsidy coefficient. Their benefits are influenced by changes in market demand caused by the EOLR implemented by the subsidized entities.

VI. Conclusion and Prospect

A. Conclusions

This paper studies the impacts of government subsidy on the GASC members' EOLR decisions considering quality and quantity losses. By optimizing the market demand function, this paper constructs and analyzes the optimal pricing and government subsidy policy of the producer and retailer under the four modes, and draws the following conclusions, and based on the relevant conclusions, we give some opinions and suggestions.

(1) When the GASC members adopt the EOLR, the optimal wholesale price decreases with the increase of the producer's EOLR and increases with the increase of retailer's EOLR. The optimal retail price decreases as the EOLR of the producer and the retailer increase. This indicates that in a fully information environment, the producer's EOLR will reduce the grain loss rate in the production process and increase the "intangible fertile land" of the grain supply. At this time, the retailer will set a lower wholesale price to ensure their own profits. The retailer's EOLR will make the grain losses reduce at the retailer's location, and the producer will increase the wholesale price to ensure their own benefits. The EOLR of the producer and the retailer will reduce the grain loss rate in their respective stages, achieving full grain chain loss reduction, which will lead to a decrease in grain retail price. In other words, when the GASC members adopt the EOLR, the grain losses can be effectively reduced.

(2) There is a "spillover effect" on the value of the GASC members' EOLR. The EOLR taken by the GASC producer will increase the retailer's profits, and at the same time, the EOLR taken by the retailer will also increase the producer's profits. Based on this effect, the GASC members may engage in speculative behavior of free riding. Therefore, the government should introduce some subsidy policies to stimulate the GASC members to actively take loss reduction measures and improve the overall efficiency of the grain supply chain. This can maximize the investment behavior of the GASC members and improve the efficiency of the grain supply chain.

(3) The government subsidy behavior can motivate the grain producer and the retailer to actively take the EOLR, stimulate the grain demand, enhance the GASC members, promote the effectiveness of grain loss reduction, and thus enhance the profits of the entire GASC.

Therefore, we propose the following suggestions. Firstly, based on the implementation of efforts of loss reduction by the first batch of enterprises, a certain subsidy will be given to encourage their loss reduction behaviors. Secondly, explore the "free riding" behavior of upstream and downstream members of the GASC, and impose penalties or cost subsidies on enterprises that do not adopt EOLR to encourage them to adopt the EOLR, encouraging upstream and downstream members to actively and jointly take EOLR. Finally, the government can play a leading role in promoting products and increasing sales to those GASC members that undertake the EOLR. This is also an effective way to encourage enterprises to implement the EOLR. Therefore, from the perspective of the government, the goal of "saving grain and reducing losses" can be achieved, and from the perspective of the producer and retailer, their profits can be increased. So, the government subsidy for the GASC members' EOLR is effective.

The research conclusions of this paper have certain theoretical and practical significance. This paper integrates the theory of efforts behavior into the demand function, expanding the theory of supply chain operation management, and providing reference for other studies in similar backgrounds. The research results have the theoretical guiding significance for the stakeholders in the GASC when considering investment decisions on whether to adopt the EOLR, and provide policy recommendations for the government to provide loss reduction subsidy to the grain supply chain members.

B. Research prospect

This study only considers a grain supply chain consisting of one grain producer and one grain retailer as the research object. However, in actual production and life, the grain supply chain system is extremely complex, consisting of a two-level supply chain system of one to many, many to one, and many to many, as well as a multi-level supply chain system, including grain management entities such as purchasers and third-party logistics. Future research can consider exploring the coordination and optimization problem of multi-level grain supply chain systems in this context. The four models proposed in this article are all based on the perspective of maximizing the interests of members in the grain supply chain, and we have not verified whether they have achieved supply chain coordination. Therefore, in the next step of work, we should explore the coordination issue of the grain supply chain. At the same time, we should focus on other links that affect the post-natal loss of grain.

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