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Post-disaster grain supply chain resilience with government aid

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ABSTRACT

Assessing the disruption and resilience of the agricultural grain supply chain is critical to ensure grain supply and stabilize grain price in the final market. This research proposes a quantitative model to analyze how a grain processor regains robustness when supply is disrupted by a natural disaster upstream, and how this disruption affects grain retailers downstream. Two supply chain recovery methods, contingent sourcing and government aid, are considered for grain processor recovery. The results show that (1) a processor prefers timely full recovery, and (2) government aid as an intervention means is indispensable but cannot fully replace the backup supplier.

1. Introduction

Risk and uncertainty are ubiquitous in agriculture supply chain (SC). Particularly, when extreme weather events like hail storms, thunderstorms, tornados, hurricanes, and snowstorms impact agriculture, yield of agricultural products is markedly reduced. For example, corn production declined by up to 30% in some growing regions in Jilin Province, northeast China, due to extreme winds and insect infestations earlier in 2012. A drought in Russia in 2010 reduced grain output by about one third, and the per unit area yield of maize in America fell by 12.7% due to a few months of drought in 2012. The Dongting Lake area, located in northern Hunan Province, China, is prone to natural disasters. Floods, droughts, and pest infestations have occurred frequently, adversely affecting grain production (Jaffee et al., 2010; Zhong et al., 2010; Sun, 2013).

Post-disaster agricultural SC disruptions have become a crucial global issue. A most recent natural disaster, Typhoon Haiyan (Yolanda), made companies with agricultural SC located in the disaster region in Philippines face serious risks of disruption. According to Maplecroft estimates, some 120,000 metric tons (MT) of sugar and 131,600 MT of rice were damaged, affecting supply in the "medium term" (Alegado, 2013; Huh and Lall, 2013). Disruption may occur in any links of the SC from upstream to downstream. Six SC disruption modes are identified, including disruptions in supply, disruptions in transportation, disruptions in production facilities (internal), disruptions in communication (or information) flow, disruptions in human resource capacity, and freight breaches. Therein, supply disruption can cut off cash flows and halt the operation of an entire SC (Sheffi et al., 2003; Hou et al., 2010). Since natural disasters are very common upstream in the agricultural SC, this study mainly focuses on supply disruption caused by reduced grain production due to natural disasters.

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Supply disruption because of reduced grain yield inevitably disrupts the grain supply chain (GSC) when no countermeasures are adopted, and eventually increases the market grain price. According to the food price index of the Food and Agriculture Organization of the United Nations, food prices started rising again in June 2010 after the food price crisis of 2007–08, with international prices of maize and wheat roughly doubling by May 2011. Extreme weather events helped raise food prices in 2007–08 and 2010–11, as mentioned by 2011 Global Food Policy Report. Intense and frequent natural disasters such as droughts and floods, resulting from climate change can decrease yield significantly, such that prices and market volatility increase (Torero, 2011). Moreover, since grain is a strategic commodity with special status, increases in grain prices due to disruption of the GSC can induce panic buying and social unrest. Panic buying by government can be seen easily in the world grain market in January, 2011, especially for developing nations and grain importers, like Algeria, Saudi Arabia, and Bangladesh (Evans, 2011). For instance, Bangladesh, one of the world's largest rice importers, raised its import target for the grain to 1,200,000 tonnes, up from an initial estimate of 600,000 tonnes. And Saudi Arabia planned to double the size of its wheat stocks to cover the demand of a year.

To stabilize grain prices on the domestic market, the GSC must recover quickly after supply disruption by natural disasters. As a major member of a GSC, the grain processor connects the grain producer upstream and the grain retailer downstream. Hence, the rapid recovery of the grain processor after natural disasters is extremely important. Mitigation or contingency strategies that enhance general SC resilience, such as multiple sourcing, inventory management, product substitution, and backup suppliers, have been proposed and systematically investigated by several researchers, which can be applied to the GSC resilience (Tang and Tomlin, 2008; Lu et al., 2011; Qi, 2013).

Furthermore, government aid is often used as an effective method for the GSC resilience. In fact, stabilization of grain prices is an important element of food policy in many countries, including those in the developing and developed worlds. Panic buying of governments in the world grain market is mainly to secure the domestic demand if they feel social unrest is looming because of rising domestic food prices. Metrobank in Philippines provided adequate supply of rice and sugar coupled with price caps after Typhoon Haiyan to cushion the pressures of steep increase in the prices of these commodities (Evans, 2011; Alegado, 2013). In China, stabilizing grain prices is an important goal for the Chinese government, and the government really comes into play in the grain market when grain prices are rising (Li and Zhang, 2012). For instance, although international grain prices fluctuated dramatically in 2008, grain prices in China remained stable, almost unaffected by the world food price volatility.

Government may intervene in the GSC and demand market in a public mode mainly by purchasing grains from the market or selling grains to the market. Protective purchase prices and limited sale prices of the main grain varieties are formulated by the government to avoid excessive volatility. When market prices for grains fall to near or below the protective price, the government will purchase grains from the market and stockpile them to restore reasonable market prices. When market prices for grains rise to near or above the limit price, the government will sell its reserves on the market to keep prices acceptable. In China, the government has developed the minimum purchase prices policy for grain, including wheat and rice, since 2004 (Yang et al., 2008).

Raw grains possessed by the government can be sold on the market by public auction, based on the policy for minimum purchase prices for staple grains. The auction base price has a certain markup (mainly including storage cost and minimum profit) on minimum purchase prices. According to China's Department of Agriculture, 34 auctions were held for wheat reserves between November 3, 2006 and July 26, 2007 (Yang et al., 2008). This auction behavior can be interpreted as a support for the resilience of GSC members from disruptions by the government.

This study attempts to investigate the optimal solution for the contingency tactics of GSC when grain processors face shortages in their SC due to natural disasters. It offers simplified models to illustrate the two scenarios of GSC resilience under supply disruption: with or without government aid, and aims to answer the following research questions: (1) What is the optimal recovery strategy for a processor without government aid? (2) With government aid, how does a processor allocate total loss between the two recovery methods? (3) Should a government intervene to help GSC members when they face supply disruption? (4) Can government aid help SC members restore their robustness quickly and thereby their profit? This is one of the first attempts to tackle agricultural SC disruptions and resilience in SC disaster management and related areas.

The remainder of this paper is organized as follows. Section 2 briefly reviews literature. A detailed description of the problem and model assumptions are given in Section 3. In Section 4, models are constructed to analyze the different scenarios in the recovery process. Numerical examples and sensitivity analysis are conducted and the associated results as well as managerial implications are given in Section 5. Concluding remarks and suggestions for future research are given in Section 6. All the proofs for analytical results are in the Appendix A.

2. Literature review

A large body of literature shows risk management for SC disruption in the industrial field. Interested readers may refer to Kleindorfer and Saad (2005) for a thorough reading. This study mainly reviews articles from the following aspects: SC risks and disruptions in agricultural fields; mitigation or contingency strategies for SC resilience; and government aid in the GSC and grain market.

According to Jaffee et al. (2010), the main activities for SC entities in an agricultural SC include supply, farm production, processing, and domestic or international logistics. Farmers and firms in an agricultural SC face risks from multiple sources, summarized as eight types: weather-related risks; natural disasters (including extreme weather events); biological and environmental risks; market-related risks; logistical and infrastructural risks; managerial and operational risks; public policy and institutional risks; and political risks. In literature, natural disasters comprise a major risk to agricultural SC stability. In practice, the effect of climate change and natural disasters on agricultural products may vary in areas. Holst et al. (2013) analyze the impacts of regional climate change on grain production in China, and found that changes in climate have a different impact on the grain production in North and South China. Zhong et al. (2010) assessed the natural disaster risk of grain production in Dongting Lake area to show the different area hazard ratio of grain production in different county.

Multiple or dual sourcing is typically used to effectively mitigate supply disruptions. Dual sourcing means that a firm can source from two suppliers: an inexpensive and unreliable supplier with capacity constraints; and a reliable and more expensive supplier with volume flexibility. The firm's optimal disruption management strategy is determined by supplier characteristics such as uptime percentage, disruption length, capacity flexibility, and firm characteristics such as risk tolerance and product cost. While if most of the supply risk growth comes from an increase in disruption probability, a firm should order more from a reliable source and less from a cheaper but less reliable source (Tomlin, 2006; Chopra et al., 2007; Giri, 2011; Xanthopoulos et al., 2012). Contingent sourcing differs from dual sourcing. The main difference is a retailer's ordering behavior, *i.e.*, ordering from suppliers sequentially or simultaneously. In the latter case, the entire order quantity is split between two suppliers and placed at the same time; while in the former case, the contingent source serves as a backup supplier, which receives orders only when the primary supplier cannot fulfill the order (Qi et al., 2009; Yu et al., 2009; Wang et al., 2010; Yang et al., 2012; Qi, 2013). Interested readers can read the study by Qi et al. (2009) for a comprehensive literature review on the difference between primary suppliers and backup suppliers. This study uses contingent sourcing, *i.e.*, the backup supplier, as a recovery resource to deal with SC disruption.

Compared with a great number of studies that investigated in supply disruption and countermeasures in industrial fields, few studies have examined government aid for agricultural SC resilience. Government aid in the agricultural SC is mainly manifested in price support policies. Government has a role to play in price stabilization, and policy-makers are typically more concerned about the stability of domestic prices than their level relative to world prices, especially in Asia, where rice-based economies dominate. In India, the government intervenes to increase food accessibility rather than reduce grain prices. In Japan, the government alters the environment of agriculture producers by indirectly regulating prices for agricultural goods. In China, government relief policy to cope with price fluctuations in staple grains including corn, wheat, rice and soybeans has becoming an institutional arrangement, and the absence of long-term equilibrium between domestic and foreign markets is the premise for government regulation of grain markets (Vitanov et al., 2007; Yang et al., 2008; Guo, 2010; Cummings, 2012).

Additionally, a GSC can be divided into three stages: grain production; grain circulation; and grain sale. In grain production stage, measures like crop insurance, subsidies, and minimum purchase price are used to protect a farmer. In the circulation stage, legislative intervention by a government is frequently utilized to regularize the behavior of grain operators who procure, store, transport, process and sell grain. In the grain sale stage, the government acts as a macro-control regulator controlling the quantity of grain in final markets. Especially in times of shortage, the government will flood the market with grain to ensure that demand is met (Fan et al., 1994; Yang et al., 2008). Therefore, the government can also be regarded as a "backup supplier" for GSC members, helping them overcome the adverse effects of SC disruption. However, to date, few studies have directly investigated the function of government aid in terms of GSC resilience.

This study introduces the concept of resilience based on its framework by Bruneau et al. (2003) and further extension by Zobel (2010). Resilience is the ability of a system to return to its original state or move to a new and more desirable state after being disturbed, or to adapt existing resources and skills to new situations and operating conditions, in order to survive despite withstanding a severe and enduring impact (Comfort, 1999; Christopher et al., 2004; Asbjørnslett, 2008). Bruneau et al. (2003) presented a conceptual framework to define seismic resilience of communities, which consists of robustness, redundancy, resourcefulness, and rapidity. Zobel (2010) extended the concept of resilience and introduced a new approach to visualize and represent the underlying relationship between the two primary characteristics of resilience: robustness against initial loss, and rapidity of the recovery process, and described different combinations of robustness and rapidity as a guide for decision making. Brandon-Jones et al. (2014) discussed the relationship between specific resources, capabilities, and performance in terms of supply chain resilience and robustness from a contingent resource-based view perspective. In this study, the resilience of GSC refers to the ability to response to supply chain disruption caused by natural disasters, and robustness and rapidity of the resilience mentioned in Zobel (2010) are considered in the analysis of the GSC resilience. Moreover, it differs from that of Bruneau et al. (2003) and Zobel (2010): it extends the research boundary from a single firm to a two-stage SC. Bueno-Solano and Cedillo-Campos (2014) built a system dynamics model to analyze the effects of the propagation of disruptions produced by terrorist acts on global supply chains performance, which shows the impact only on inventory levels in the supply chain. This study mainly considers the effect of different recovery levels of upstream member (grain processor) on the profit of downstream member (grain retailer).

3. Problem description

3.1. A typical GSC

Consider a typical GSC composed of an inputs supplier, a grain producer, an intermediate organization, a grain processor, a grain retailer and a consumer. The inputs supplier provides agricultural materials such as seeds, chemical fertilizers,

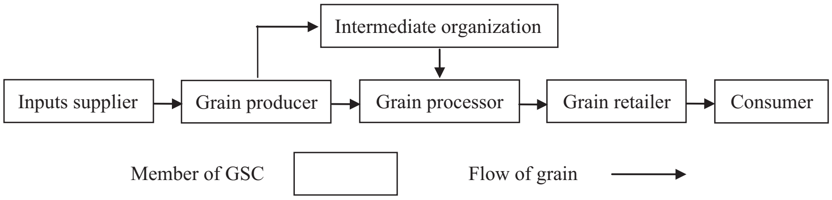

Fig. 1. Illustration of a typical GSC.

pesticides, and agricultural machinery. The grain producer, including individual farmers, and grain growing cooperatives or organizations, purchases agricultural supplies upstream, then grows crops such as maize, wheat, rice, and soybean, and further sells grain downstream. The grain processor is a company that specializes in transforming raw (or unprocessed or unhusked) grain into refined grain through a series of processes, including outer shell removal, grinding, purifying, and drying. Processed grain is then sold to the grain retailer, who sells grain to consumers directly. Notably, an intermediate organization exists between the grain producer and grain processor. This organization collects and stores grain from the farmer and then sells it on the grain market. Recall that Section 1 stated that minimum purchase prices for grain exists for grain producers, and the government intervenes in a volatile grain market by purchasing and selling grain. In China, these collection and storage enterprises, the representative of which is the China Grain Reserves Corporation, are always appointed by the government. Fig. 1 shows a typical GSC.

The grain processor is the central member and plays a critical role in the operation of the GSC. When a natural disaster occurs, yield reduction is inevitable for the grain producer, which directly leads to insufficient supply for grain processor. We assume that the producer/farmer experiences a partial loss of her productive capability and does not completely collapse in case of a disruption. If no measures are adopted, the scarce supply will run upstream to downstream in the GSC, resulting in high prices for the consumer. As discussed in Section 1, the resilience of the grain processor is considered. The grain processor typically purchases grain from its main supplier, which is directly upstream, *i.e.*, grain producer in its region or near its corporation. If the main supplier cannot provide a sufficient amount of grain to the processor after a natural disaster, the processor will purchase grain either from the backup supplier, which may be located outside the disaster area or far from its location, or from the government, which always releases grain onto the market to prevent grain prices from increasing after natural disasters.

Either or both ways can be used by the grain processor. Usually, the backup supplier provides grain to the grain processor at a price higher than that in the grain market, since the backup supplier is the dominant one when dealing with the grain processor in the specific situation, while the final transaction price of grain sold on the market by the government via public auction is always lower than market price during the same period, mainly for price stabilization (Yang et al., 2008). Here, the phrase "recovery cost" is used to indicate that the money should be paid to the backup supplier or the government by the grain processor if it wants to get recovery. The "unit recovery cost" includes the unit price of grain, transportation cost, and transaction cost per unit of grain. That is, the unit recovery cost is the money the grain processor must pay to obtain a unit of grain. On the basis of Bruneau et al. (2003) and Zobel (2010), we learn that if the processor wants to get recovery more quickly, *i.e.*, in a shorter time, it has to pay more to its provider, *i.e.*, the backup supplier or the government. This is mainly because it costs the backup supplier extra time to cope with the processor's additional request if the processor wants a quicker recovery. For example, the backup supplier has to spend on quick preparation for grains and advanced shipment arrangement, thus some additional costs, such as redeployment cost of grain, overtime work cost for staff, and emergency transportation cost, will be yielded. Otherwise it only needs to pay less. Therefore, both methods have a common point: the recovery cost is proportional to the recovery rate of a method, *i.e.*, the speed of recovery and the recovery cost are correlated.

We make the following assumptions before resilience process is analyzed and the model is built without and with government aid. First, only the recovery process of the grain processor, not the grain retailer, is considered in this study when there is supply disruption due to natural disaster. Second, it is a single period model. The period starts when a natural disaster occurs, and the grain provider (i.e., the farmer) will be affected, which shows in that the order from the downstream (i.e., the processor) will not be fulfilled. Then the grain processor will try to procure grain from its backup supplier or the government to make itself have sufficient grain supply to the downstream (i.e., the retailer). Third, there is no stockout and no excess inventory in normal circumstance. That is to say, the member in the upstream of the GSC can just fulfill the order from the downstream when the system is disruption free. Moreover, only one disruption is considered in this single period model. Fourth, government is taken as a grain supplier for the GSC member in this study, and therefore the related societal cost is not introduced into the model. Finally, information sharing exists between the GSC members and their partners, and therefore if disruption occurs in any stage of the GSC, members can prepare to take recovery actions timely. Note that the inputs supplier's role in the overall problem's consideration as well as in the associated model's analysis is negligible.

3.2. Resilience process of the grain processor without government aid

Without government aid, the resilience process of the grain processor *via* only the backup supplier is shown in Fig. 2.

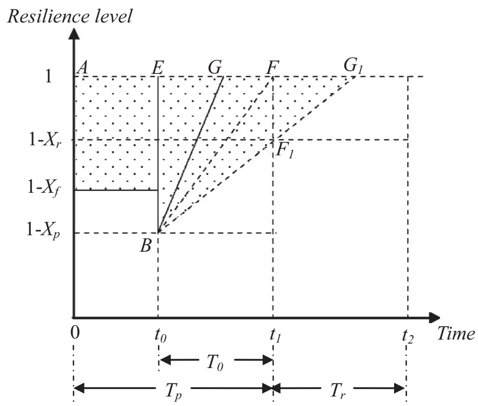

Fig. 2. The resilience process of the grain processor *via* only the backup supplier.

According to Bruneau et al. (2003), Cimellaro et al. (2010) and Zobel (2010), we define the relevant parameters as follows. The vertical axis represents the resilience level (i.e., total functionality) of the GSC members. When the resilience level is equal to 1, it means that the upstream member can fulfill the order from the downstream member; when the resilience level is equal to 0, it means that the upstream member is totally unable to provide any grain to the downstream member. X represents the initial loss of SC members, measured as a percentage of total functionality, and is a fraction in the range of 0–1; that is, X_f, X_p, and X_r represent initial loss of a farmer (or producer) due to a natural disaster, loss of a processor due to the farmer's loss, and loss of a retailer due to the processer's loss, respectively. Here, "initial loss" or "loss" means the loss of order fill rate for the upstream to the downstream, which can also be interpreted as the proportion of unfulfilled orders. While the expression $1 - X$ represents the robustness of SC members. Correspondingly, the expressions $1 - X_f, 1 - X_p$ and $1 - X_r$ represent the robustness of the grain producer, grain processor, and grain retailer, respectively. Note that the farmer is always reluctant to sell grain when its yield drops on expectations that prices will increase or for protection against a bad year. Assume that the coefficient of farmer's reluctance is θ, a relational expression exists for X_p and X_f, *i.e.*, $X_p = 1 - (1 - \theta)(1 - X_f)$; thus, $X_p > X_f$. This study defines the robustness of SC members as the ability of an upstream supplier to satisfy the order from a downstream customer.

The horizontal axis represents the time of the sequence of events happened. That is, a natural disaster occurs at time 0, and causes an initial loss of X_f to the producer. The processor's recovery strategy will begin after the natural disaster occurs. Since the recovery process takes some time, the grain processor must take recovery action before the end of the order lead time, t_1. Assume that the processor begins to take recovery action at time t_0. Time t_1 and t_2 represent the time of delivery to the processor and the retailer, respectively. If the processor can fully recover before time t_1, the retailer will not be affected. Otherwise, the retailer will encounter a stockout. T_p, T_r, and T_0 represents order lead time of the processor, order lead time of the retailer, and the time interval between the time at which the processor takes recovery action and the end of the order lead time of the processor, respectively, measured in a relevant time unit such as weeks. Since the processor's recovery action always happens after a natural disaster occurs, $T_0 \leqslant T_p$ is true. Assume that the recovery rate (i.e., rapidity) of the grain processor when using the backup supplier is β_{p1}, with a unit recovery cost of C_{p1}.

From Fig. 2, the following relationships between parameters are obtained. The length of line segment EB represents X_p; the slope of lines BG, BF, BG$_1$ represents β_{p1}, which are three representatives recovery rates of the processor; the length of line segments EG, EF, EG$_1$ represents the recovery time for the processor, which is expressed as $T_{p1} = \frac{X_p}{\beta_{p1}}$; the length of line segment AF represents T_p; and the length of line segment EF represents T_0.

3.3. Resilience process of the grain processor with government aid

With government aid, the resilience process of the grain processor *via* both the backup supplier and the government is shown in Fig. 3.

Thus, the grain processor can choose to procure grain from either the backup supplier or the government. Therefore, different from that in Fig. 2, the loss of the grain processor, X_p, in Fig. 3 is deconstructed into two parts in a proportion of $\alpha_p (0 \leqslant \alpha_p \leqslant 1)$, meaning that the loss, $\alpha_p X_p$, is recovered *via* the backup supplier, and $(1 - \alpha_p)X_p$ is recovered by government aid. Assume that the recovery rate of the grain processor when using the backup supplier and the government is β_{p1} and β_{p2}, with a unit recovery cost of C_{p1} and C_{p2}, respectively.

From Fig. 3, the following relationships between parameters are then given. The length of line segments EJ and JB represents $\alpha_p X_p$ and $(1 - \alpha_p)X_p$, respectively; the slope of lines JJ$_1$, JF, and JJ$_2$ represents β_{p1} in the different situations, and similarly the slope of lines BB$_1$, BF$_2$, and BB$_2$ represents β_{p2}; the length of line segments EJ$_1$, EF, and EJ$_2$ is expressed as $T_{p1} = \frac{\alpha_p X_p}{\beta_{p1}}$, representing the recovery time for the processor *via* the backup supplier; the length of line segments JB$_1$, JF$_2$, and JB$_2$ is

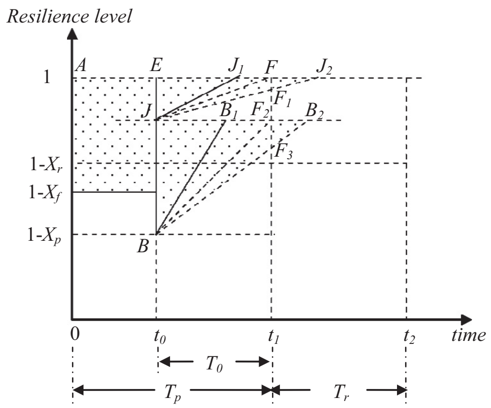

Fig. 3. The resilience process of the grain processor *via* both the backup supplier and the government.

expressed as $T_{p2} = \frac{(1-\alpha_p)X_p}{\beta_{p2}}$, representing the recovery time for the processor *via* the government. Also we note that, the length of line segments FF_1 and F_2F_3, denoted by X_{r1} and X_{r2}, represents the loss of the retailer due to the processer's loss caused by incomplete recovery from the backup supplier and the government; the length of the line segments J_1F and B_1F_2, denoted by T_{h1} and T_{h2}, represents the extra time to hold the grain before the end of the order lead time for processor when using the backup supplier and the government, respectively.

In both the resilience processes of the grain processor without and with government aid, the maximum profit of the grain processor is what we aim at. For the processor, the revenue comes from selling refined grain to the retailer at the unit price of C_p; while the cost includes the following aspects: (1) procurement cost. The processor mainly purchases raw grain from the upstream producer, and pays procurement cost to it at the unit price of C_f; (2) recovery cost. If there is supply disruption caused by natural disaster and the processor takes recovery action, recovery cost from the backup supplier or the government will exist, at the unit recovery cost of C_{p1} and C_{p2}, respectively; (3) shortage cost. If the processor cannot achieve timely full recovery, it must pay a shortage cost to the grain retailer, with the unit shortage cost of C_{sp}; and (4) additional storage (or holding) cost. If the grain processor achieves full recovery earlier than the end of the order lead time, it must store grain for an additional period, with the unit holding cost of C_h. In addition, Q_p and Q_r represent the order quantity of the processor and retailer, respectively. Table 1 summarizes the notation.

Table 1
List of notation.

Notation	Definition
X_f	The initial loss of the farmer (or producer), measured as a percentage of total functionality
X_p	The loss of the processor, affected by the farmer (or producer)
X_r	The loss of the retailer, affected by the processor
X_{r1}	The loss of the retailer caused by the processor's recovery *via* the backup supplier
X_{r2}	The loss of the retailer caused by the processor's recovery *via* the government
C_f	The unit sale price of the farmer (or producer)
C_p	The unit sale price of the processor
C_r	The unit sale price of the retailer
C_{p1}	The unit recovery cost of the processor when using the backup supplier
C_{p2}	The unit recovery cost of the processor when using the government
C_{sp}	The unit stockout cost of the processor
C_{sr}	The unit stockout cost of the retailer
C_h	The unit storage (or holding) cost of the processor
Q_p	The order quantity of the processor
Q_r	The order quantity of the retailer
θ	The coefficient of the farmer's reluctance to sell grain, ranges from 0 to 1
α_p	The proportion of the processor's loss allocated to the backup supplier
$1-\alpha_p$	The proportion of the processor's loss allocated to the government
β_{p1}	The recovery rate of the processor when using the backup supplier
β_{p2}	The recovery rate of the processor when using the government
T_p	The order lead time of the processor
T_0	The time interval between the time at which the processor takes recovery action and the end of the order lead time of the processor
T_{p1}	The time needed for the processor's recovery *via* the backup supplier
T_{p2}	The time needed for the processor's recovery *via* the government
T_{h1}	The extra time to hold the products (before the end of the order lead time) for processor when using the backup supplier
T_{h2}	The extra time to hold the products (before the end of the order lead time) for processor when using the government

4. Model analysis

In this agricultural SC, the grain processor acts as the leader, and the grain retailer acts as the follower. The retailer can be influenced only by the processor. Both pursue profit maximization. Two scenarios are discussed: (1) without government aid (Scenario 1); and (2) with government aid (Scenario 2). By comparing the profit functions of the processor and retailer in different scenarios, the optimal choice of the processor regarding his recovery behavior, as well as the maximum profit of the processor and retailer, can be identified.

4.1. Scenario 1: Without government aid

If the government does not intervene, the processor can depend only on the backup supplier for recovery. From Fig. 2, we know that the recovery rate of the processor determines the profits of both the processor and retailer. As is assumed, different recovery rates of the processor have different recovery costs.

4.1.1. Profit and decision making of the processor

Based on the analysis in Section 3.2, the profit function of the processor is given as follows:

$$\Pi_p = C_p(1-X_r)Q_r - C_f(1-X_p)Q_p - X_pQ_rC_{p1}\beta_{p1} - C_hX_pQ_rT_{h1} - C_{sp}X_rQ_r \tag{1}$$

where $C_p(1-X_r)Q_r$ is the revenue of the processor selling refined grains to the retailer at the unit price of C_p when the retailer's order quantity is Q_r units and the proportion of stockout is X_r; $C_f(1-X_p)Q_p$ is the cost of the processor purchasing raw grains from the producer at the unit price of C_f when the processor's order quantity is Q_p units and the proportion of stockout is X_p; and $X_pQ_rC_{p1}\beta_{p1}$ is recovery cost paid by the processor when using the backup supplier for recovery at the recovery rate of β_{p1}. Since the government does not intervene, the loss of the processor due to the producer, X_p, should be recovered by purchasing grain from the backup supplier at the unit cost of C_{p1}. $C_hX_pQ_rT_{h1}$ is additional storage (or holding) cost when the processor gains full recovery earlier than the end of the order lead time at the time interval of T_{h1}. $C_{sp}X_rQ_r$ is stockout cost that must be paid to the retailer when the processor cannot fully recover. The fourth and fifth items in Eq. (1) cannot exist simultaneously.

Then T_{p1} and T_0 are compared to determine which of the five components should be included in the profit function, Eq. (1). Three cases exist: (1) $T_{p1} = T_0$; (2) $T_{p1} < T_0$; and (3) $T_{p1} > T_0$. Correspondingly, Eq. (1) can be rewritten in the following three different forms: Π_p^1, Π_p^2, and Π_p^3. See Appendix A for the expressions and specific calculations of each profit function.

The following analytical result shows that the optimal profit of the processor, Π_p^*, is related to its unit recovery cost, C_{p1}.

Proposition 1. *The maximum profit of the processor, Π_p^*, and the optimal recovery rate, β_{p1}^*, are determined as follows.*

(a) *if* $C_{p1} < \frac{(C_p+C_{sp})T_0}{X_p}$, *then* $\beta_{p1}^* = \frac{X_p}{T_0}$ *and* $\Pi_p^* = C_pQ_r - C_f(1-X_p)Q_p - \frac{(X_p)^2Q_rC_{p1}}{T_0}$.

(b) *if* $C_{p1} \geqslant \frac{(C_p+C_{sp})T_0}{X_p}$, *then* $\beta_{p1}^* = 0$ *and* $\Pi_p^* = C_pQ_r - C_f(1-X_p)Q_p - (C_p + C_{sp})X_pQ_r$.

Proof for Proposition 1. See Appendix A.

Proposition 1 shows that the unit recovery cost determines the recovery rate and the maximum profit of the processor. On one hand, if the unit recovery cost of the processor when using the backup supplier is low, choosing rapid recovery to avoid stockout is best. Intuitively, if full recovery is achieved earlier than the end of the order lead time, the processor must store products for an extra time. Therefore, as recovery time decreases, recovery cost increases, and holding cost for the processor increases. Hence, as long as the processor can recover not later than the end of the order lead time, it will not be motivated to accelerate recovery. On the other hand, if unit recovery cost of the processor when using the backup supplier is excessively high, choosing not to recover is best for the processor, because recovery cost exceeds benefit derived by recovery of the processor, *i.e.*, the processor would rather bear stockout cost than pay recovery cost.

4.1.2. Profit of the retailer

As to the retailer, the revenue comes from selling refined grains to the consumer at the unit price of C_r; while the cost includes two aspects: (1) procurement cost. The retailer mainly purchases refined grain from the processor at the unit price of C_p; and (2) shortage cost. If the processor cannot achieve timely full recovery, the order of the retailer will not be fulfilled. Therefore, the retailer will encounter a stockout and has to pay shortage cost at the unit cost of C_{sr}.

Since the recovery process of the retailer is out of consideration, the profit of the retailer depends on the recovery of the processor, which can be expressed as follows:

$$\Pi_r = C_r(1-X_r)Q_r - C_p(1-X_r)Q_r - C_{sr}X_rQ_r \tag{2}$$

where $C_r(1-X_r)Q_r$ is the revenue of the retailer selling refined grains to the consumer at the unit price of C_r; $C_p(1-X_r)Q_r$ is the cost of the retailer purchasing grains from the processor at unit price of C_p; $C_{sr}X_rQ_r$ is the shortage cost of the retailer due to incomplete recovery of the processor.

The retailer can only accept, passively, the decision made by the processor. Based on this analysis and Proposition 1, the profit of the retailer is derived as follows.

Proposition 2. *When the optimal recovery rate of the processor is β^*_{p1}, the profit of the retailer, Π_r, is as follows.*

(a) *when* $\beta^*_{p1}=\frac{X_p}{T_0}, \Pi_r=(C_r-C_p)Q_r$.
(b) *when* $\beta^*_{p1}=0, \Pi_r=\left[(C_r-C_p)(1-X_p)-C_{sr}X_p\right]Q_r$.

Proof for Proposition 2. If $\beta^*_{p1}=\frac{X_p}{T_0}$, then $X_r=0$. Inserting $X_r=0$ into Eq. (2) yields Proposition 2(a). If $\beta^*_{p1}=0$, then $X_r=X_p$. Inserting $X_r=X_p$ into Eq. (2) yields Proposition 2(b).

Proposition 2 determines the profit of the retailer under two choices by the processor. If the processor chooses full recovery at the end of the order lead time, the retailer will not be affected by a supply disruption upstream. Thus, the retailer will not lack stock. If the processor chooses not to recover because of the high cost, the retailer will encounter stockout and must pay a shortage cost.

4.2. Scenario 2: With government aid

With government aid, the processor can choose to get grain from the backup supplier or the government. From Fig. 3, we know that the decision problem of the processor is associated with allocating purchase quantities to the two parties.

4.2.1. Profit and decision making of the processor

Based on the analysis in Section 3.3, the profit function of the processor is given by the following expression:

$$\begin{aligned}\Pi_p = {} & C_p(1-X_{r1}-X_{r2})Q_r - C_f(1-X_p)Q_p - \alpha_pX_pQ_rC_{p1}\beta_{p1} - (1-\alpha_p)X_pQ_rC_{p2}\beta_{p2}\\ & - C_h\left[(\alpha_pX_pQ_rT_{h1}) + (1-\alpha_p)X_pQ_rT_{h2}\right] - C_{sp}(X_{r1}+X_{r2})Q_r\end{aligned} \tag{3}$$

where $C_p(1-X_{r1}-X_{r2})Q_r$ is the revenue of the processor selling refined grains to the retailer at the unit price of C_p when the retailer's order quantity is Q_r units and the proportion of stockout is $(X_{r1}+X_{r2})$, where X_{r1} and X_{r2} represent the loss of the retailer caused by processor's recovery *via* the backup supplier and the government, respectively; $C_f(1-X_p)Q_p$ is the cost of the processor purchasing raw grains from the producer at the unit price of C_f when the processor's order quantity is Q_p units and the proportion of stockout is X_p; $\alpha_pX_pQ_rC_{p1}\beta_{p1}$ and $(1-\alpha_p)X_pQ_rC_{p2}\beta_{p2}$ are recovery costs paid by the processor when using the backup supplier and the government for recovery at the recovery rate of β_{p1} and β_{p2}, respectively, and the unit recovery cost of each route is C_{p1} and C_{p2}; $C_h\left[(\alpha_pX_pQ_rT_{h1}) + (1-\alpha_p)X_pQ_rT_{h2}\right]$ is extra storage (or holding) cost when the processor fully recover earlier than the end of the order lead time at the time interval of T_{h1} and T_{h2} for the two recovery paths; $C_{sp}(X_{r1}+X_{r2})Q_r$ is stockout cost that should be paid to the retailer when the processor does not achieve full recovery.

Then T_{p1} and T_{p2} are compared with T_0 to determine the specific forms of the profit function, Eq. (3). Nine cases exist: (1) $T_{p1}=T_0$ and $T_{p2}=T_0$; (2) $T_{p1}=T_0$ and $T_{p2}>T_0$; (3) $T_{p1}>T_0$ and $T_{p2}=T_0$; (4) $T_{p1}>T_0$ and $T_{p2}>T_0$; (5) $T_{p1}<T_0$ and $T_{p2}<T_0$; (6) $T_{p1}<T_0$ and $T_{p2}>T_0$; (7) $T_{p1}=T_0$ and $T_{p2}<T_0$; (8) $T_{p1}>T_0$ and $T_{p2}<T_0$; and (9) $T_{p1}<T_0$ and $T_{p2}=T_0$. Correspondingly, Eq. (3) can be rewritten in nine forms as $\Pi^1_p, \Pi^2_p, \Pi^3_p, \Pi^4_p, \Pi^5_p, \Pi^6_p, \Pi^7_p, \Pi^8_p$ and Π^9_p. See Appendix A to find the expressions and specific calculations for each profit function.

Comparing profit in the different situations yields the following result.

Proposition 3. *Based on the nine cases, the possible recovery scenarios for the processor to choose will be only (1), (2), (3) and (4).*

Proof for Proposition 3. See Appendix A.

Proposition 3 indicates that the processor will only choose full recovery at or later than the end of the order lead time. This helps avoid extra holding cost that would be incurred by recovering too early.

To simplify the expressions obtained during subsequent analyses, the following terms are defined:

$$A = C_pQ_r - C_f(1-X_p)Q_p,\quad B=\frac{(X_p)^2Q_r}{T_0},\quad D=X_p(C_p+C_{sp})Q_r,\quad E=\frac{(C_p+C_{sp})^2Q_rT_0}{4},$$

$F=\frac{(C_p+C_{sp})T_0}{2X_p}$, Therefore, $D^2=4EB$ and $D=2BF$.

Proposition 4. *The optimal proportion, α_p^*, and the maximum profit of the processor, Π_p^*, can be derived as follows:*

$$\alpha_p^* = \frac{\lambda_2 C_{p2} + (\lambda_1 - \lambda_2)F}{\lambda_1 C_{p1} + \lambda_2 C_{p2}}, \quad \Pi_p^* = A - \frac{\lambda_1\lambda_2 C_{p1} C_{p2}}{\lambda_1 C_{p1} + \lambda_2 C_{p2}} B - \left(1 - \frac{\lambda_1\lambda_2 (C_{p1} + C_{p2})}{\lambda_1 C_{p1} + \lambda_2 C_{p2}}\right) D + \frac{(\lambda_1 - \lambda_2)^2}{\lambda_1 C_{p1} + \lambda_2 C_{p2}} E.$$

where $0 \leqslant \lambda_1 \leqslant 1$ and $0 \leqslant \lambda_2 \leqslant 1$. At this time, $\beta_{p1} = \lambda_1 \frac{\alpha_p X_p}{T_0}$ and $\beta_{p2} = \lambda_2 \frac{(1-\alpha_p) X_p}{T_0}$.

Proof for Proposition 4. See Appendix A. One can also obtain $\Pi_p^{1*}, \Pi_p^{2*}, \Pi_p^{3*}$ and Π_p^{4*}, which correspond to the four different recovery rate combinations *via* the backup supplier and the government. The following analytical results are easily obtained based on Proposition 4.

Lemma 1. *The maximum profit of the processor, Π_p^*, is determined by the values of λ_1 and λ_2.*

(a) *let* $\lambda_1 = \lambda_2 = 1\left(i.e., \beta_{p1} = \frac{\alpha_p X_p}{T_0}, \beta_{p2} = \frac{(1-\alpha_p) X_p}{T_0}\right)$,

$$\alpha_p^* = \frac{C_{p2}}{C_{p1} + C_{p2}}, \Pi_p^* = \Pi_p^{1*} = A - \frac{C_{p1} C_{p2}}{C_{p1} + C_{p2}} B.$$

At this time, $\beta_{p1}^* = \frac{\alpha_p^* X_p}{T_0}$ *and* $\beta_{p2}^* = \frac{(1-\alpha_p^*) X_p}{T_0}$.

(b) *let* $\lambda_1 = 1$, *when* $\lambda_2^* = 1 - \frac{C_{p1}}{F} (C_{p1} \leqslant F)$ $\left(i.e., \beta_{p1} = \frac{\alpha_p X_p}{T_0}, \beta_{p2}^* = \left(1 - \frac{C_{p1}}{F}\right) \frac{(1-\alpha_p) X_p}{T_0} < \frac{(1-\alpha_p) X_p}{T_0}\right)$,
$\alpha_p^* = 1, \Pi_p^* = \max\left(\Pi_p^{2*}\right) = A - C_{p1} B$. *At this time,* $\beta_{p1}^* = \frac{X_p}{T_0}$ *and* $\beta_{p2}^* = 0$.

(c) *let* $\lambda_2 = 1$, *when* $\lambda_1^* = 1 - \frac{C_{p2}}{F} (C_{p2} \leqslant F)$ $\left(i.e., \beta_{p1}^* = \left(1 - \frac{C_{p2}}{F}\right) \frac{\alpha_p X_p}{T_0} < \frac{\alpha_p X_p}{T_0}, \beta_{p2} = \frac{(1-\alpha_p) X_p}{T_0}\right)$,
$\alpha_p^* = 0, \Pi_p^* = \max\left(\Pi_p^{3*}\right) = A - C_{p2} B$. *At this time,* $\beta_{p1}^* = 0$ *and* $\beta_{p2}^* = \frac{X_p}{T_0}$.

(d) *when* $\lambda_1^* = \lambda_2^* = \lambda (0 \leqslant \lambda < 1)$ *and* $F = \frac{C_{p1} C_{p2}}{2(C_{p1} + C_{p2})}$ $\left(i.e., \beta_{p1}^* = \lambda \frac{\alpha_p X_p}{T_0} < \frac{\alpha_p X_p}{T_0}, \beta_{p2} = \lambda \frac{(1-\alpha_p) X_p}{T_0} < \frac{(1-\alpha_p) X_p}{T_0}\right)$,

$$\alpha_p^* = \frac{C_{p2}}{C_{p1} + C_{p2}}, \quad \Pi_p^* = \max\left(\Pi_p^{4*}\right) = A - \frac{C_{p1} C_{p2}}{C_{p1} + C_{p2}} B = A - D.$$

At this time, $\beta_{p1}^* = \lambda \frac{\alpha_p^* X_p}{T_0}$ *and* $\beta_{p2}^* = \lambda \frac{(1-\alpha_p^*) X_p}{T_0}$.

Proof for Lemma 1. See Appendix A.

The processor's recovery decision making after a natural disaster in the four scenarios is illustrated in Lemma 1. Therein, Lemma 1(a) indicates that the processor can fully recover right at the end of the order lead time; Lemma 1(b) and (c) indicate that one of the two parties could help the processor fully recover and the other cannot; Lemma 1(d) shows that neither party can help the processor fully recover. Notably, the constraint of unit recovery cost associated with the two parties in different scenarios exists. Then we have the following analytical results from Remark 1 to Remark 3, in accordance with Lemma 1(a)–(d).

Remark 1 (*Both sourcing from the backup supplier and the government*). If both the backup supplier and the government, or neither of them, can make the processor fully recover right at the end of the order lead time, then we have the optimal allocation proportion $\alpha_p^* = \frac{C_{p2}}{C_{p1} + C_{p2}}$.

Remark 1 implies that the processor will source from the backup supplier by the proportion α_p^* and from the government by $1 - \alpha_p^*$ for the recovery of grain supply to the retailer if both, or neither, of the two recovery methods can make the processor fully recover right at the end of the order lead time. Therein, the optimal solution (α_p^*) for the backup supply source allocation is determined by the unit recovery costs associated with backup supplier and government (*i.e.*, C_{p1} and C_{p2}, respectively). A decrease in the unit recovery cost from one supply source increases the allocation proportion to the source, *i.e.*, increases the dependence of the processor on this supply source. The optimal profit, $\Pi_p^* = \Pi_p^{1*} = A - \frac{C_{p1} C_{p2}}{C_{p1} + C_{p2}} B$, indicates that a decrease in the unit recovery cost from each source increases the profit of the processor.

Remark 2 (*Solely sourcing from the backup supplier*). If the backup supplier can make the processor fully recover right at the end of the order lead time while the government cannot, then we have the optimal allocation proportion $\alpha_p^* = 1$ on the condition that $\lambda_1 = 1$ *and* $\lambda_2^* = 1 - \frac{C_{p1}}{F}\,(C_{p1} \leqslant F)$ are satisfied.

Remark 2 indicates that the processor will solely sourcing from the backup supplier for grain supply recovery if the backup supplier can make the processor fully recover right at the end of the order lead time while the government cannot. At this time, $\alpha_p^* = 1$, which is not related to the unit recovery costs C_{p1} and C_{p2}.

Remark 3 (*Solely sourcing from the government*). If the government can make the processor fully recover right at the end of the order lead time while the backup supplier cannot, then we have the optimal allocation proportion $\alpha_p^* = 0$ on the condition that $\lambda_2 = 1$ and $\lambda_1^* = 1 - \frac{C_{p2}}{F}\,(C_{p2} \leqslant F)$ are satisfied.

In contrast with Remark 2, Remark 3 implies that the processor will solely sourcing from the government for grain supply recovery if the government can make the processor fully recover right at the end of the order lead time while the backup supplier cannot. At this time, $\alpha_p^* = 0$, which is not related to the unit recovery costs C_{p1} and C_{p2}.

Furthermore, since $\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}} < C_{p1}$ and $\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}} < C_{p2}$ are always true, we can easily derive that the profit gained by Lemma 1(a) is the greatest in all the cases, indicating that multi-sourcing from both the backup supplier and government is the best recovery tactic for the processor, consistent with the claims of Tomlin (2006) and Jain et al. (2013) in multi-sourcing and rerouting for managing SC disruption risks. In this study, whether the processor's recovery from the backup supplier or from the government depends on the comparison of the recovery rate of the processor *via* the different alternatives. This finding provides a supplement to the existing study.

4.2.2. Profit of the retailer

In the following, we provide some generalizations drawn from the above analytical results for the characterization of the profit of the retailer. In this work, the profit function of the retailer can be expressed as follows:

$$\Pi_r = C_r(1 - X_{r1} - X_{r2})Q_r - C_p(1 - X_{r1} - X_{r2})Q_r - C_{sr}(X_{r1} + X_{r2})Q_r \tag{4}$$

where $C_r(1 - X_{r1} - X_{r2})Q_r$ is the revenue of the retailer selling refined grains to the consumer; $C_p(1 - X_{r1} - X_{r2})Q_r$ is the cost of the retailer purchasing grains from the processor; and $C_{sr}(X_{r1} + X_{r2})Q_r$ is the shortage cost of the retailer which is due to incomplete recovery of the processor. As such, the profit of the retailer depends on the optimal solution of the processor for supply recovery. Given the processor adopts the optimal solution for recovering the grain supply to the retailer by Lemma 1, the resulting profit of the retailer then has the following characteristics.

Proposition 5. *The profit of the retailer satisfies the following conditions.*

(a) *when* $\beta_{p1}^* = \frac{\alpha_p^* X_p}{T_0}$ *and* $\beta_{p2}^* = \frac{(1-\alpha_p^*)X_p}{T_0}$, *where* $\alpha_p^* = \frac{C_{p2}}{C_{p1}+C_{p2}}, \Pi_r = (C_r - C_p)Q_r$.

(b) *when* $\beta_{p1}^* = \frac{X_p}{T_0}$ *and* $\beta_{p2}^* = 0$, *where* $\alpha_p^* = 1, \Pi_r = (C_r - C_p)Q_r$.

(c) *when* $\beta_{p1}^* = 0$ *and* $\beta_{p2}^* = \frac{X_p}{T_0}$, *where* $\alpha_p^* = 0, \Pi_r = (C_r - C_p)Q_r$.

(d) *when* $\beta_{p1}^* = \lambda\frac{\alpha_p^* X_p}{T_0}$ *and* $\beta_{p2}^* = \lambda\frac{(1-\alpha_p^*)X_p}{T_0}(0 \leqslant \lambda < 1)$, *where* $\alpha_p^* = \frac{C_{p2}}{C_{p1}+C_{p2}}$,

$$\Pi_r = \left[(C_r - C_p) - (C_r + C_{sr} - C_p)(1 - \lambda)X_p\right]Q_r.$$

Proof for Proposition 5. The optimal recovery rate β_{p1}^* and β_{p2}^* are known, and the optimal allocation proportion, α_p^*, corresponding to each situation in Lemma 1 is also known; therefore, *via* some simple calculations, the analytical results in Proposition 5 are obtained.

From the analytical results with Proposition 5, we conclude that given the processor can recover in time by adopting the recovery tactics suggested in Propositions 5(a)–(c), the retailer is not affected by the event of supply disruption upstream in the GSC. Then, the resulting profit of the retailer is $\Pi_r = (C_r - C_p)Q_r$. However, the processor, sometimes, may adopt the "postponed recovery tactic" meaning that the processor may not recover the supply to the retailer in time, as indicated by Proposition 5(d). Then, the retailer's profit will be affected due to a shortage of grains supplied, thus resulting in a decreased profit given by $\Pi_r = \left[(C_r - C_p) - (C_r + C_{sr} - C_p)(1 - \lambda)X_p\right]Q_r$.

5. Numerical analysis

This section presents the analytical results of a numerical study aiming at the case of rice SC in China using the proposed model and derived principles. The processor purchases unhusked rice from the producer and sells refined rice to the retailer. On the basis of rice prices published in publicly-accessible materials in China (Price Department of Nation Development and Reform Commission, 2011; State Grain Administration, 2011), the selling price of unhusked rice is about US$0.35 per kg, the

Table 2
Parameter base values.

X_p	C_f	C_p	C_r	Q_p	Q_r	T_0	C_{sp}	C_{sr}
0.4	0.35	0.48	0.57	100	73	0.2	0.96	1.14

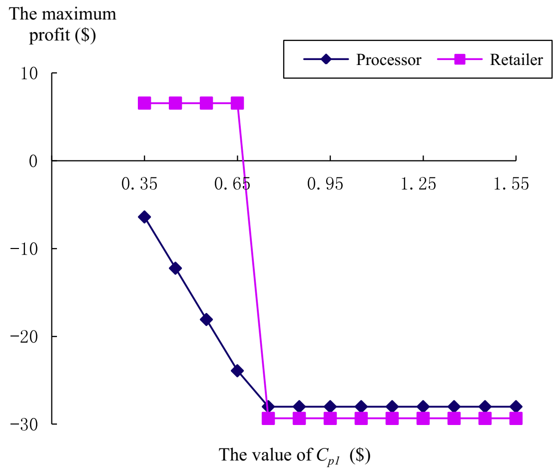

Fig. 4. Maximum profits of the processor and retailer.

wholesale price of refined rice is US$0.48 per kg, and the retail price of refined rice is US$0.57 per kg. According to the processing practices of grain enterprises in China, husked rice processed from unhusked rice is on average 73%, *i.e.*, 1 kg of unhusked rice after processing can be transformed into about 0.73 kg of refined rice. The parameters are therefore assigned appropriate values. Suppose that total loss of the processor by supply disruption is 40%, and stockout cost is twice the sale price. The processor takes recovery action at 0.2 months (i.e., 6 days) before the end of the order lead time. Table 2 lists the base values of the parameters used in the following analysis.

5.1. Without government aid

5.1.1. Numerical illustration

If the government did not intervene after a natural disaster, the processor must purchase unhusked rice from the backup supplier during the agricultural recovery period. Based on Propositions 1 and 2, the following analytical results are acquired.

For the processor, if $C_{p1} < 0.72$, then $\beta^*_{p1} = 2, \Pi^*_p = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.72$, then $\beta^*_{p1} = 0, \Pi^*_p = -28.008$.

For the retailer, when $\beta^*_{p1} = 2, \Pi_r = 6.57$; when $\beta^*_{p1} = 0, \Pi_r = -29.346$.

Recall that in Section 3.1 the unit grain price (C_{p1}) offered by the backup supplier is always higher than that (C_f) by the producer, that is, $C_{p1} \geqslant C_f$. Fig. 4 shows the profits of the processor and retailer gained using the optimal solutions of the proposed model associated with different values of C_{p1}.

Fig. 4 provides the following generalizations of the relationship between the profit and the unit recovery cost. First, as long as the unit recovery cost of the processor when using the backup supplier is less than US$0.72 per kg, the processor will choose full recovery right at the end of the order lead time. Thus, the optimal recovery rate is equal to 2, the recovery time needed for the processor is equal to 0.2 months, and the maximum profit of the processor has a negative linear correlation with the unit recovery cost, *i.e.*, the profit of processor decreases as the value of the unit recovery cost increases within the domain of 0.35–0.72. Being unaffected due to the full recovery of the processor, the retailer obtains a normal profit at a constant value of US$6.57. Second, when the unit recovery cost exceeds US$0.72 per kg, the best choice for the processor is no recovery (i.e., the optimal recovery rate is equal to 0), and the profit will be negative at US$-28.008, the minimum profit of the processor. Since the retailer will encounter a stockout due to the disruption upstream, it will get a negative profit at US$-29.346.

5.1.2. Sensitivity analysis

Specifically, numerical examples are conducted to examine the impact of the key parameters, X_p, T_0, and C_{sp}, on the maximum profit of the processor. When the value of one parameter is changed, the values of the other parameters remain unchanged (Table 2). Figs. 5–7 show plots of maximum profit and the optimal recovery rate of the processor with respect to X_p, T_0, and C_{sp}, respectively.

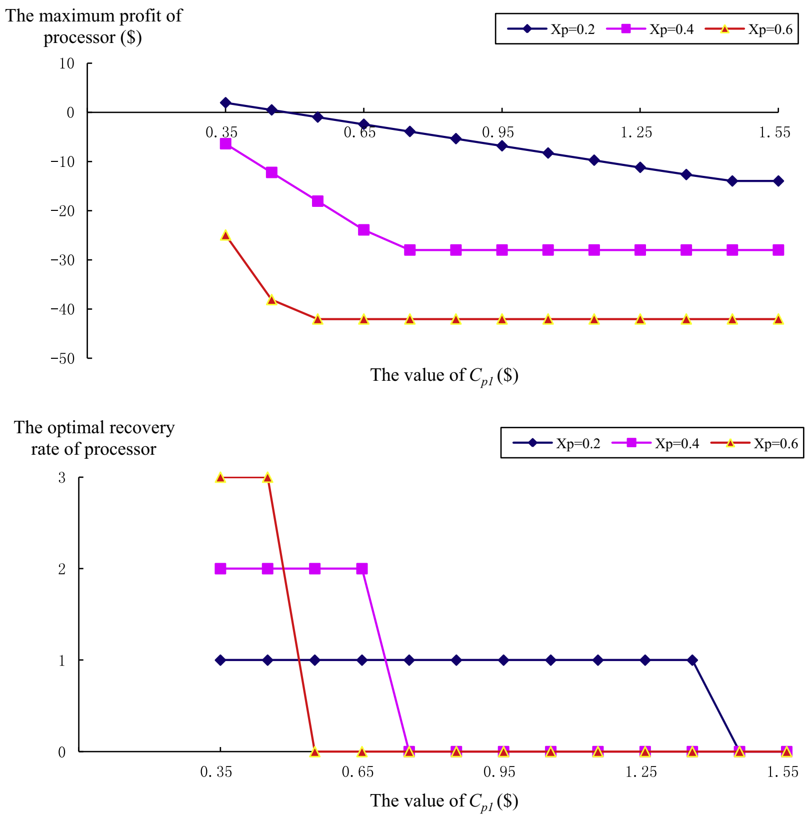

Fig. 5. Profit and the optimal recovery rate of the processor with respect to X_p.

5.1.2.1. The impact of X_p on Π_p^*. Let X_p be equal to 0.2, 0.4, and 0.6 to represent the varying degrees of the processor's loss due to the producer, the following analytical results are obtained.

When $X_p = 0.2$; if $C_{p1} < 1.44$, then $\beta_{p1}^* = 1$ and $\Pi_p^* = 7.04 - 14.6C_{p1}$; if $C_{p1} \geqslant 1.44$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -13.984$.

When $X_p = 0.4$; if $C_{p1} < 0.72$, then $\beta_{p1}^* = 2$ and $\Pi_p^* = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.72$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -28.008$.

When $X_p = 0.6$; if $C_{p1} < 0.48$, then $\beta_{p1}^* = 3$ and $\Pi_p^* = 21.04 - 131.4C_{p1}$; if $C_{p1} \geqslant 0.48$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -42.032$.

Fig. 5 indicates that when the processor's loss, due to the producer's yield reduction in the case of a natural disaster, is low (e.g., $X_p = 0.2$), the processor will choose full recovery within a large value range of the unit recovery cost of the processor (e.g., $C_{p1} < 1.44$), with a slow recovery rate (e.g., $\beta_{p1}^* = 1$). Conversely, when the processor's loss is high (e.g., $X_p = 0.6$), the processor will choose to full recovery within a small value range of the unit recovery cost (e.g., $C_{p1} < 0.48$), with a rapid recovery rate (e.g., $\beta_{p1}^* = 3$). Moreover, with the same unit recovery cost (e.g., $C_{p1} = 0.4$), the processor gains more profit (e.g., $\Pi_p^* = 1.2$) when its loss caused by the producer's yield reduction is lower (e.g., $X_p = 0.2$), compared with the less profit (e.g., $\Pi_p^* = -31.52$) in the case of $X_p = 0.6$. We explain such a finding as that the recovery decision-making will be altered when the processor encounters different level of supply disruption. In the case of full recovery, since the recovery action is taken at the same time, the processor will choose a slow recovery in a situation of lower level of supply disruption to avoid high recovery cost, and a rapid recovery in a situation of higher level of supply disruption to insure quick resilience. In the case of no recovery, an increase in the processor's loss due to the producer decreases the profit of the processor.

5.1.2.2. The impact of T_0 on Π_p^*. Let T_0 be equal to 0.1, 0.2, and 0.3 to represent the different time interval between the time at which the processor takes recovery action and the end of the order lead time, we have the following analytical results.

When $T_0 = 0.1$; if $C_{p1} < 0.36$, then $\beta_{p1}^* = 4$ and $\Pi_p^* = 14.04 - 116.8C_{p1}$; if $C_{p1} \geqslant 0.36$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -28.008$.

When $T_0 = 0.2$; if $C_{p1} < 0.72$, then $\beta_{p1}^* = 2$ and $\Pi_p^* = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.72$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -28.008$.

When $T_0 = 0.3$; if $C_{p1} < 1.08$, then $\beta_{p1}^* = \frac{4}{3}$ and $\Pi_p^* = 14.04 - \frac{116.8}{3}C_{p1}$; if $C_{p1} \geqslant 1.08$, then $\beta_{p1}^* = 0$ and $\Pi_p^* = -28.008$.

Fig. 6 indicates that when the time interval between the time at which the processor takes recovery action and the end of the order lead time is short (e.g., $T_0 = 0.1$), i.e., the processor takes a late recovery action, the processor will choose to full recovery within a small value range of the unit recovery cost of the processor (e.g., $C_{p1} < 0.36$), with a rapid recovery rate (e.g., $\beta_{p1}^* = 4$). Conversely, when the time interval is long (e.g., $T_0 = 0.3$), i.e., the processor takes an early recovery action, the processor will choose to full recovery within a large value range of the unit recovery cost (e.g., $C_{p1} < 1.08$), with a slow

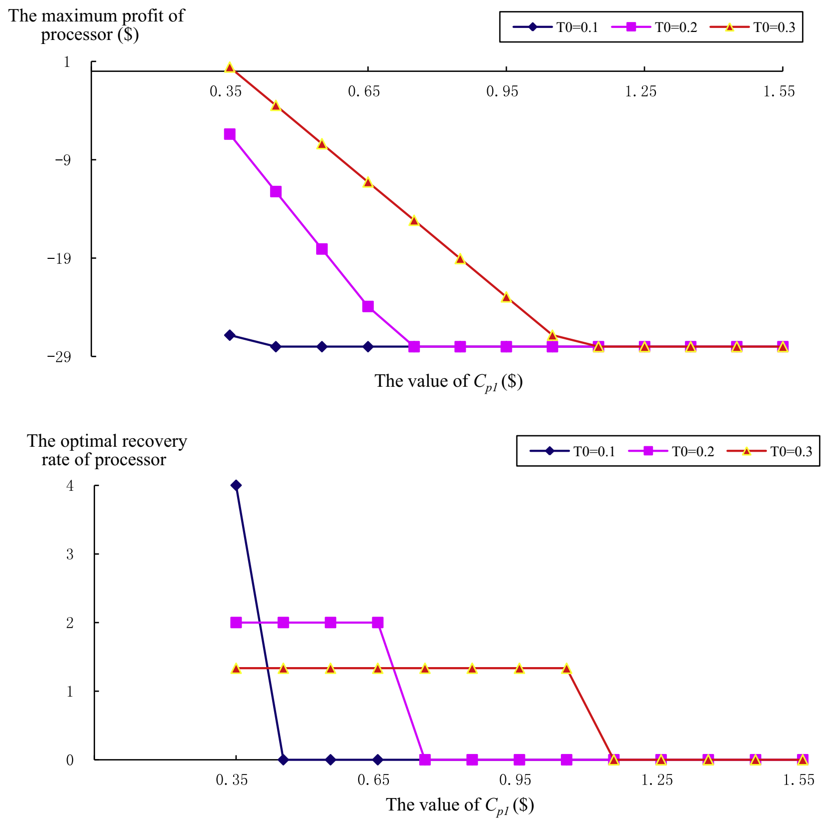

Fig. 6. Profit and the optimal recovery rate of the processor with respect to T_0.

recovery rate (e.g., $\beta^*_{p1} = \frac{4}{3}$). We infer that the time at which the processor begins to take recovery action mainly affects the profit of the processor in full recovery. In the case of full recovery, since the level of supply disruption encountered by the processor is the same, the processor will have less time to recover, which results in a rapid recovery to insure quick resilience, if it takes recovery action late; otherwise, the processor will have more time to take a slow recovery to avoid high recovery cost if it takes recovery action earlier. Meanwhile, at the same unit recovery cost, the processor gains more profit (or pays less loss) when the time interval is longer. In the case of no recovery, the profit keeps at the same level, no matter of the time interval.

5.1.2.3. The impact of C_sp on Π^*_p. Let C_{sp} be equal to 0.48, 0.96, and 1.44 to represent the different size of the unit stockout cost of the processor when recovery is incomplete, the analytical results are as follows.

When $C_{sp} = 0.48$; if $C_{p1} < 0.48$, then $\beta^*_{p1} = 2$ and $\Pi^*_p = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.48$, then $\beta^*_{p1} = 0$ and $\Pi^*_p = -13.992$.

When $C_{sp} = 0.96$; if $C_{p1} < 0.72$, then $\beta^*_{p1} = 2$ and $\Pi^*_p = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.72$, then $\beta^*_{p1} = 0$ and $\Pi^*_p = -28.008$.

When $C_{sp} = 1.44$; if $C_{p1} < 0.96$, then $\beta^*_{p1} = 2$ and $\Pi^*_p = 14.04 - 58.4C_{p1}$; if $C_{p1} \geqslant 0.96$, then $\beta^*_{p1} = 0$ and $\Pi^*_p = -42.024$.

Fig. 7 indicates that when the unit stockout cost for the processor due to incomplete recovery is low (e.g., $C_{sp} = 0.48$), the processor will choose full recovery within a small range of the unit recovery cost (e.g., $C_{p1} < 0.48$). Conversely, when the unit stockout cost is high (e.g., $C_{sp} = 1.44$), the processor will choose full recovery within a large range of the unit recovery cost (e.g., $C_{p1} < 0.96$). In the situation of full recovery, the optimal recovery rates are the same (e.g., $\beta^*_{p1} = 2$) since the recovery rate is determined by the processor's loss, X_p, and the time interval, T_0, i.e., $\beta_{p1} = \frac{X_p}{T_0}$, and at the same unit recovery cost, the maximum profits are also the same, no matter of the value of the unit stockout cost. In the situation of no recovery, the processor gains more profit (or pays less loss) when the unit stockout cost is lower. We believe that the size of unit stockout cost mainly affects the profit of the processor when recovery is incomplete. In the case of full recovery, there is no stockout cost for the processor. Therefore, the profits in different situations are the same. In the case of no recovery, there is stockout cost for the processor, and an increase in the unit stockout cost decreases the maximum profit of the processor.

5.2. With government aid

If the government intervenes in the rice market by selling unhusked rice on the market, the processor can recover by purchasing this unhusked rice or that from the backup supplier. We have given the mathematical expressions of A, B, D, E, and F

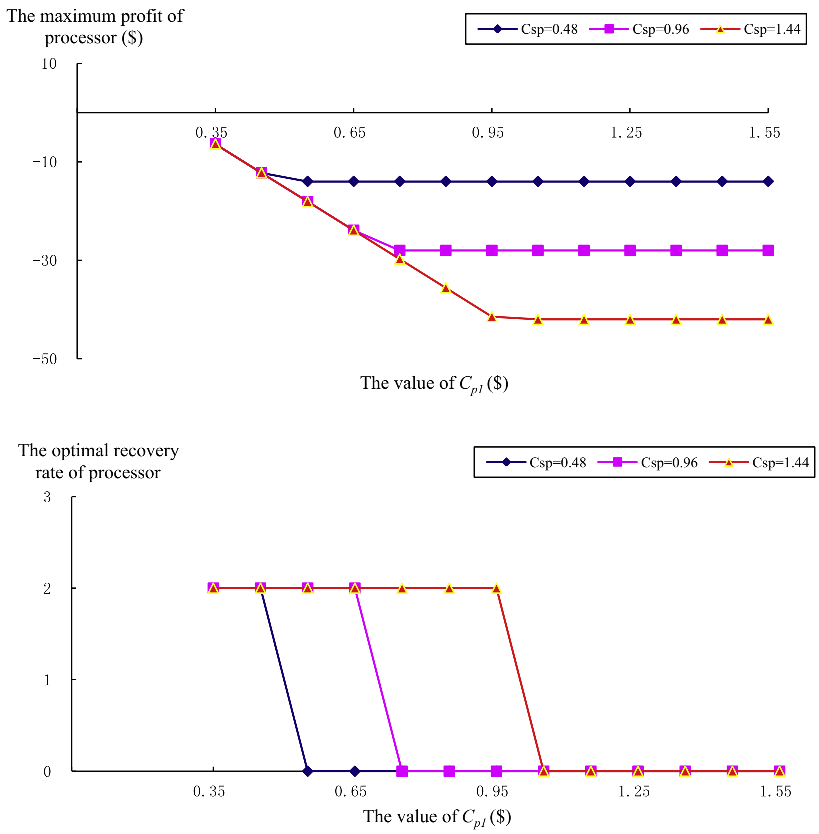

Fig. 7. Profit and the optimal recovery rate of the processor with respect to C_{sp}.

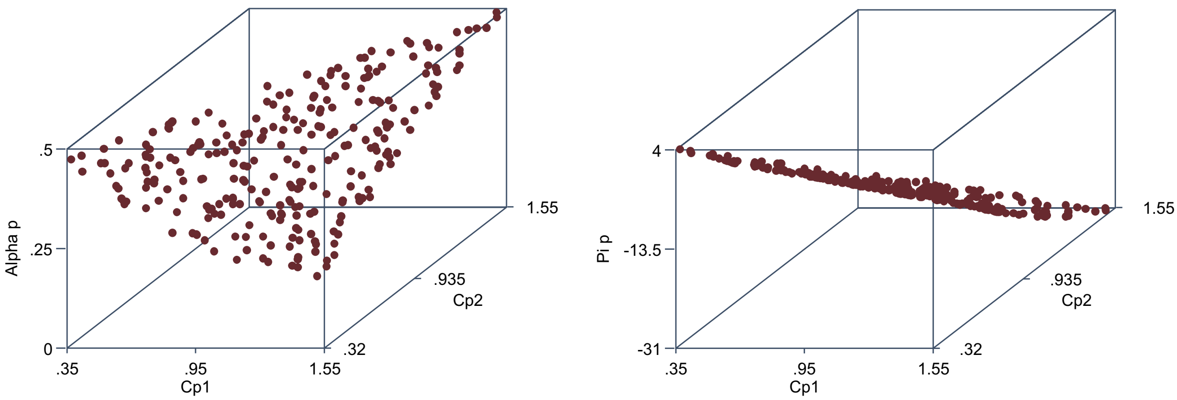

Fig. 8. Changes of α_p^* and Π_p^* with respect to C_{p1} and C_{p2} in the case of $\lambda_1 = \lambda_2 = 1$.

in Section 4.2. After using the values of the parameters in Table 2, we get $A = 14.04, B = 58.4, D = 42.048, E = 7.56864$, and $F = 0.36$. According to China Grain Yearbook (2011), the purchase price of unhusked rice is about US$0.32 per kg. Combining with the analysis in Section 3, we know that the lower bound of C_{p2} is 0.32, and $C_{p2} \leqslant C_{p1}$ is always true. Under Lemma 1, four cases for the processor's recovery exist. Therefore, the following analytical results are obtained.

In the first case $(\lambda_1 = \lambda_2 = 1), \alpha_p^* = \frac{C_{p2}}{C_{p1}+C_{p2}}$ and $\Pi_p^* = 14.04 - 58.4\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}$.

The values of C_{p1} and C_{p2} are assigned at random, and those of α_p^* and Π_p^* will then be determined (Fig. 8).

In the second case $\left(\lambda_1 = 1, \lambda_2^* = 1 - \frac{C_{p1}}{F}\right), \alpha_p^* = 1$ and $\Pi_p^* = 14.04 - 58.4C_{p1}$.

Thus, α_p^* is unrelated to C_{p1}, and Π_p^* is correlated negatively and linearly with C_{p1} (Fig. 9).

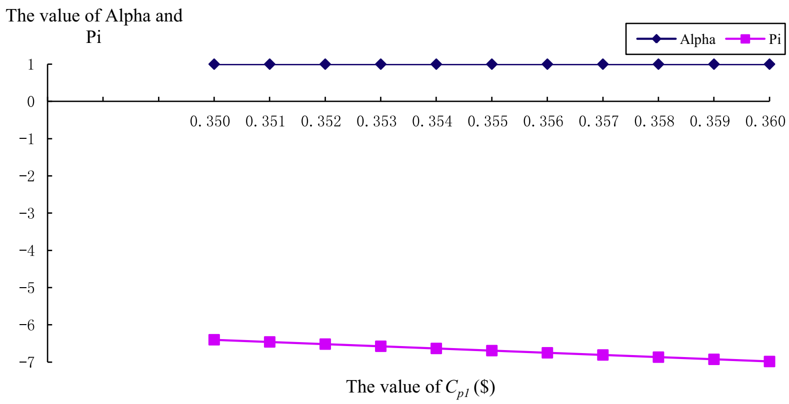

Fig. 9. Changes of α_p^* and Π_p^* with respect to C_{p1} and C_{p2} in the case of $\lambda_1 = 1$, $\lambda_2^* = 1 - \frac{C_{p1}}{F}$.

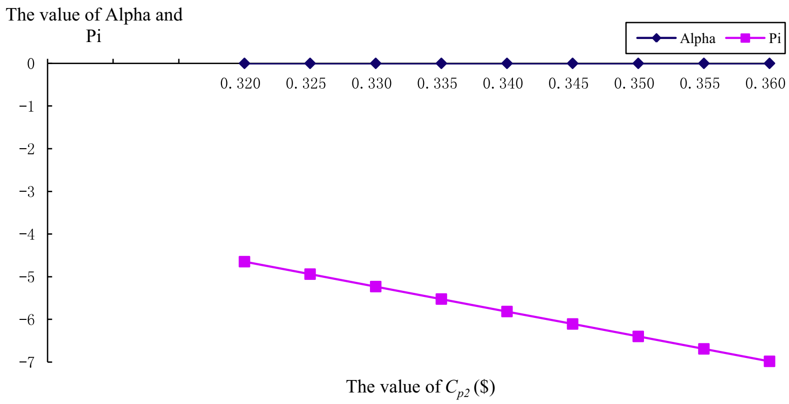

Fig. 10. Changes of α_p^* and Π_p^* with respect to C_{p1} and C_{p2} in the case of $\lambda_1^* = 1 - \frac{C_{p2}}{F}, \lambda_2 = 1$.

In the third case $\left(\lambda_1^* = 1 - \frac{C_{p2}}{F}, \lambda_2 = 1\right), \alpha_p^* = 0$ and $\Pi_p^* = 14.04 - 58.4C_{p2}$.

Thus, α_p^* is unrelated to C_{p2}, and Π_p^* is correlated negatively and linearly with C_{p2} (Fig. 10).

In the fourth case $(\lambda_1^* = \lambda_2^* = \lambda), \alpha_p^* = \frac{C_{p2}}{C_{p1}+C_{p2}}$ and $\Pi_p^* = -28.008$.

The values of C_{p1} and C_{p2} are assigned at random with the constraint of the expression $\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})} = 0.36$; α_p^* will then be decided (Fig. 11).

According to Proposition 5, the profit of the retailer in the first, second, and third cases equals 6.57, indicating that the processor can fully recover in these three cases; hence, the retailer will not be affected and obtain normal profit, US\$6.57. In the fourth case, $\Pi_r = 35.916\lambda - 29.346$, meaning that an increase in the recovery rate of the processor increases the profit of the retailer. Moreover, when $\lambda > 0.817$, the retailer will have a profit. Otherwise, it will have a loss.

5.3. Profit comparison

From Sections 5.1 and 5.2, the profit expressions in various situations are compared (Table 3). Recall that $C_{p2} \leqslant C_{p1}$ is always true. That is, the maximum profit of the processor without government aid is less than that with government aid, as well as the maximum profit of the retailer. We then conclude that government aid is favorable for the profits of both the processor and the retailer, *i.e.*, government aid can help GSC members gain more profits (or pay less loss) from recovery behavior.

Numerical results have several important managerial implications related to the recovery strategy selected by GSC members and the role the government plays in the grain market.

First, government involvement in the recovery process of the grain processor by providing low-cost grain does improve the profits of the processor and retailer after supply disruption. Thus, government aid in the grain market is indispensable for the recovery of agricultural SC members after a natural disaster. For the decision maker in grain processing enterprises, purchasing grain from the government is preferred over that of the backup supplier because it has a lower price.

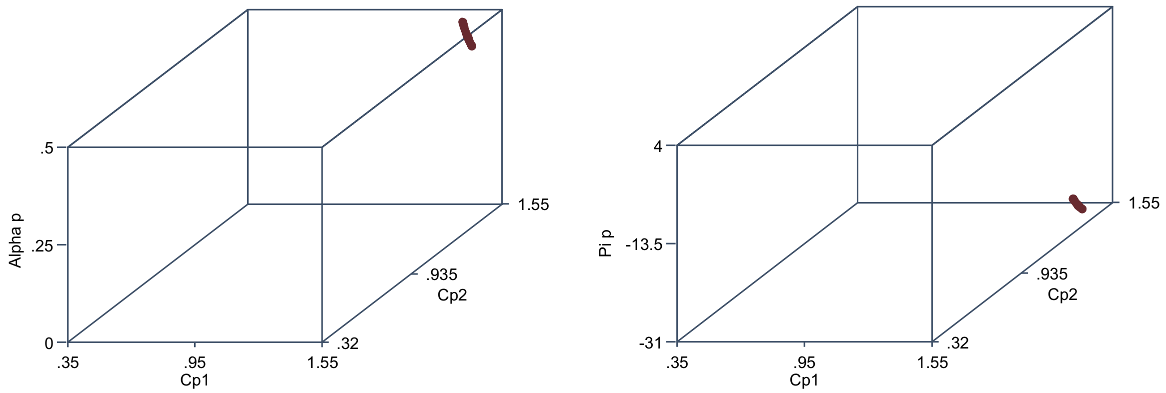

Fig. 11. Changes of α_p^* and Π_p^* with respect to C_{p1} and C_{p2} in the case of $\lambda_1^* = \lambda_2^* = \lambda$.

Table 3
Profit comparison with and without government aid.

If	Without government aid	
$C_{p1} < 0.72$	$\Pi_p^* = 14.04 - 58.4C_{p1}$	$\Pi_r = 6.57$
$C_{p1} \geqslant 0.72$	$\Pi_p^* = -28.008$	$\Pi_r = -29.346$
If	**With government aid**	
$\lambda_1 = \lambda_2 = 1$	$\Pi_p^* = 14.04 - 58.4\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}$	$\Pi_r = 6.57$
$\lambda_1 = 1, \lambda_2^* = 1 - \frac{C_{p1}}{F}$	$\Pi_p^* = 14.04 - 58.4C_{p1}$	
$\lambda_1^* = 1 - \frac{C_{p2}}{F}, \lambda_2 = 1$	$\Pi_p^* = 14.04 - 58.4C_{p2}$	
$\lambda_1^* = \lambda_2^* = \lambda$	$\Pi_p^* = -28.008$	$\Pi_r = 35.916\lambda - 29.346(0 \leqslant \lambda < 1)$

Second, as revealed by the sensitivity analysis, the varying degrees of the processor's loss due to the producer, the time interval between the time at which the processor takes recovery action and the end of order lead time, and the unit stockout cost of the processor in the case of incomplete recovery have a significant effect on the recovery rate decision-making and the profit obtained by the processor and retailer. To increase the profit or reduce the loss, the processor must reduce the impact from the producer upstream as well as the shortage cost paid to the retailer downstream. Measures like stockpiling grain and taking recovery action early are also advised.

Third, to define correctly the role of government in the grain market is critical. Numerical results show that the profit of the processor in the context of full recovery by acquiring grain only from government is less than that from both the backup supplier and the government. In other words, the backup supplier should not be replaced by the government. Therefore, the government should moderately intervene in the grain market after a natural disaster. Over intervention by the government may have adverse effects on profits of SC members (Sheu, 2011). Although putting grain on the market after a natural disaster is essential to stabilize market prices, government aid can only work as a complementary measure, not a substitute for market mechanisms.

6. Concluding remarks

Grain output reduced by natural disasters disrupts flow in the GSC, adversely affecting prices. How to increase the resilience of the SC in this context deserves attention. In this study, profit maximization is the objective function, and simplified and stylized models are constructed for the processor's decision to recover under supply disruption in case of a natural disaster. Several cases of the processor's recovery are examined and the optimal profit and recovery rate for the processor are identified.

Our study indicates that (1) the processor's recovery strategy under the lack of government aid depends on the unit recovery cost from the backup supplier, (2) under government aid, the processor's recovery decision depends on the comparison of the recovery rate from the backup supplier and the government, and the optimal allocation proportion depends on the unit recovery cost in the two situations, (3) various measures like reducing the impact from upstream and shortage cost to downstream can be adopted to enhance the resilience of grain processor, and (4) government aid is a necessary intervention method but not the sole way for grain processor's recovery.

On the basis of systematically analyzing the resilience achieving process of a GSC member, this paper contributes to the literatures by first extending the research boundary from a single organization to a two-stage SC, and considering the effect of different recovery levels of upstream member on the profit of downstream member, which makes improvement for the resilience framework of Bruneau et al. (2003) and Zobel (2010). Second, government aid as a recovery method for grain processor is introduced into the recovery process when natural disasters come, and the role of government in the grain market should be located correctly, just a supplement instead of a substitute. This is rarely detected in the previous literature. Third, this study provides a reference for processor's decision-making when encountering natural disasters, and therefore to some extent it has an application value.

Several directions for future research are suggested. First, consumer behavior in the grain market will change when a natural disaster occurs, such that panic buying and stockpiling may occur. Hence, supply disruption will increase consumer demand (Yu et al., 2009). How to make consumer behavior normalize is an interesting issue for further research. Second, this study only considers the order of the processor that is not fulfilled by the producer when a natural disaster occurs. If the processor is in the disaster area, the processor's capacity might be adversely affected by the disaster. Therefore, recovery of the grain processor should include a self-recovery process. Third, this study defines the main parameters, like the total loss of the processor, as deterministic. To the best of our knowledge, natural disasters may occur unexpectedly, and the resulting loss will be uncertain. Stochastic variables could be introduced into the models to make the results more applicable to actual situations in future studies.

Funding

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Appendix A. Expressions and specific calculations of Π_p^1, Π_p^2 and Π_p^3

Case 1: If $T_{p1} = T_0$, just as the line segment EF existing in Fig. 2, the processor can fully recover at the end of the order lead time.

So, $\beta_{p1} = \frac{X_p}{T_0}$ and $\Pi_p^1 = C_pQ_r - C_f(1-X_p)Q_p - \frac{(X_p)^2 Q_r C_{p1}}{T_0}$.

Case 2: If $T_{p1} < T_0$, just as the line segment EG existing in Fig. 2, the processor can fully recover before the end of the order lead time. At this time, $X_r = 0, T_{h1} = T_0 - \frac{X_p}{\beta_{p1}}$.

Since $\beta_{p1} > \frac{X_p}{T_0}$, let $\beta_{p1} = \lambda_1 \frac{X_p}{T_0}(\lambda_1 > 1)$. Thus, $T_{h1} = \frac{\lambda_1 - 1}{\lambda_1} T_0$.

Therefore, $\Pi_p^2 = C_pQ_r - C_f(1-X_p)Q_p - \frac{\lambda_1 (X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_1 - 1}{\lambda_1} C_h X_p Q_r T_0$.

Case 3: If $T_{p1} > T_0$, just as the line segment EG_1 existing in Fig. 2, the processor cannot get full recovery at the end of the order lead time. At this time, $X_r = X_p - T_0\beta_{p1}, T_{h1} = 0$. The processor will make delivery in a proportion of $1 - X_r$.

Since $\beta_{p1} < \frac{X_p}{T_0}$, let $\beta_{p1} = \lambda_1 \frac{X_p}{T_0}(0 \leqslant \lambda_1 < 1)$. So, $X_r = (1-\lambda_1)X_p$.

And $\Pi_p^3 = C_pQ_r - C_f(1-X_p)Q_p - \frac{\lambda_1 (X_p)^2 Q_r C_{p1}}{T_0} - (C_p + C_{sp})(1-\lambda_1)X_pQ_r$.

Proof for Proposition 1. Compare Π_p^2 and Π_p^1. Since $\lambda_1 > 1, \Pi_p^2 < \Pi_p^1$ is obtained. Therefore, Case 2 is not a good recovery strategy for the processor, and should be abandoned. After some algebra, we can get $\Pi_p^3 = (1-X_p)(C_pQ_r - C_fQ_p) - C_{sp}X_pQ_r + \left[(C_p + C_{sp})X_pQ_r - \frac{(X_p)^2 Q_r C_{p1}}{T_0}\right]\lambda_1$.

When $C_{p1} < \frac{(C_p + C_{sp})T_0}{X_p}, \Pi_p(\lambda_1)$ is a monotonic increasing function. Since $0 \leqslant \lambda_1 < 1$, the value of λ_1 is closer to 1, and the profit of the processor is closer to Π_p^1. At this time, β_{p1} is closer to $\frac{X_p}{T_0}$.

When $C_{p1} > \frac{(C_p + C_{sp})T_0}{X_p}, \Pi_p(\lambda_1)$ is a monotonic decreasing function. Since $0 \leqslant \lambda_1 < 1$, when $\lambda_1 = 0$ is satisfied, the processor can reach the maximum profit $\Pi_p^3 = (1-X_p)(C_pQ_r - C_fQ_p) - C_{sp}X_pQ_r = C_pQ_r - C_f(1-X_p)Q_p - (C_p + C_{sp})X_pQ_r$. At this time, $\beta_{p1} = 0$.

When $C_{p1} = \frac{(C_p + C_{sp})T_0}{X_p}, \Pi_p^3$ is unrelated to λ_1. The processor can get a fix profit, which is $\Pi_p^3 = (1-X_p)(C_pQ_r - C_fQ_p) - C_{sp}X_pQ_r = C_pQ_r - C_f(1-X_p)Q_p - (C_p + C_{sp})X_pQ_r$.

From the analysis above, we can obtain the following results.

If $C_{p1} < \frac{(C_p + C_{sp})T_0}{X_p}, \beta_{p1}^* = \frac{X_p}{T_0}, \Pi_p^* = C_pQ_r - C_f(1-X_p)Q_p - \frac{(X_p)^2 Q_r C_{p1}}{T_0}$.

If $C_{p1} \geqslant \frac{(C_p + C_{sp})T_0}{X_p}, \beta_{p1}^* = 0, \Pi_p^* = C_pQ_r - C_f(1-X_p)Q_p - (C_p + C_{sp})X_pQ_r$.

A.1. Expressions and specific calculation of Π_p^1, Π_p^2, Π_p^3, Π_p^4, Π_p^5, Π_p^6, Π_p^7, Π_p^8 and Π_p^9

Case 1: If $T_{p1} = T_0$ and $T_{p2} = T_0$ are satisfied, just as the line segment EF and JF_2 existing in Fig. 3, the processor can fully recover just at the end of the order lead time. At this time, $X_{r1} = 0, X_{r2} = 0, T_{h1} = 0$ and $T_{h2} = 0$. Then $T_{p1} = \frac{\alpha_p X_p}{\beta_{p1}} = T_0$, and $T_{p2} = \frac{(1-\alpha_p)X_p}{\beta_{p2}} = T_0$. So, $\beta_{p1} = \frac{\alpha_p X_p}{T_0}$, and $\beta_{p2} = \frac{(1-\alpha_p)X_p}{T_0}$. Therefore, the profit of the processor can be expressed as follows: $\Pi_p^1 = C_pQ_r - C_f(1-X_p)Q_p - \frac{(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0}$.

Case 2: If $T_{p1} = T_0$ and $T_{p2} > T_0$ are satisfied, the processor cannot get full recovery before the end of the order lead time. Therefore, stockout cost will occur for the processor. At this time, $X_{r1} = 0, X_{r2} = (1-\alpha_p)X_p - T_0\beta_{p2}$, the length of line segment F_2F_3 in Fig. 3. The processor will make delivery in a proportion of $1 - X_r = 1 - (X_{r1} + X_{r2})$. Because there is no extra stockout cost, $T_{h1} = 0$ and $T_{h2} = 0$. Then, $T_{p1} = \frac{\alpha_p X_p}{\beta_{p1}} = T_0$, and $T_{p2} = \frac{(1-\alpha_p)X_p}{\beta_{p2}} > T_0$. So, $\beta_{p1} = \frac{\alpha_p X_p}{T_0}$, and $\beta_{p2} < \frac{(1-\alpha_p)X_p}{T_0}$. Let $\beta_{p2} = \lambda_2 \frac{(1-\alpha_p)X_p}{T_0} (0 \leqslant \lambda_2 < 1)$. Then $X_{r2} = (1-\lambda_2)(1-\alpha_p)X_p$. Therefore, the profit of the processor can be expressed as follows:

$$\Pi_p^2 = C_p[1-(1-\lambda_2)(1-\alpha_p)X_p]Q_r - C_f(1-X_p)Q_p - \frac{(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_{sp}(1-\lambda_2)(1-\alpha_p)X_p Q_r$$

Case 3: If $T_{p1} > T_0$ and $T_{p2} = T_0$ are satisfied, the processor cannot get full recovery before the end of the order lead time. The same as Case 2, the profit of the processor can be expressed as follows:

$$\Pi_p^3 = C_p[1-(1-\lambda_1)\alpha_p X_p]Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_{sp}(1-\lambda_1)\alpha_p X_p Q_r$$

Case 4: If $T_{p1} > T_0$ and $T_{p2} > T_0$ are satisfied, the processor cannot get full recovery before the end of the order lead time. Therefore, stockout cost will occur for the processor. At this time, $X_{r1} = \alpha_p X_p - T_0\beta_{p1}, X_{r2} = (1-\alpha_p)X_p - T_0\beta_{p2}, T_{h1} = 0$, $T_{h2} = 0$. Then $T_{p1} = \frac{\alpha_p X_p}{\beta_{p1}} > T_0$, and $T_{p2} = \frac{(1-\alpha_p)X_p}{\beta_{p2}} > T_0$. So, $\beta_{p1} < \frac{\alpha_p X_p}{T_0}$, and $\beta_{p2} < \frac{(1-\alpha_p)X_p}{T_0}$. Let $\beta_{p1} = \lambda_1 \frac{\alpha_p X_p}{T_0}, \beta_{p2} = \lambda_2 \frac{(1-\alpha_p)X_p}{T_0} (0 \leqslant \lambda_1 < 1, 0 \leqslant \lambda_2 < 1)$. So, $X_{r1} = (1-\lambda_1)\alpha_p X_p, X_{r2} = (1-\lambda_2)(1-\alpha_p)X_p$. Therefore, the profit of the processor can be expressed as follows:

$$\begin{aligned}\Pi_p^4 = {} & C_p[1-(1-\lambda_1)\alpha_p X_p - (1-\lambda_2)(1-\alpha_p)X_p]Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} \\ & - C_{sp}[(1-\lambda_1)\alpha_p X_p + (1-\lambda_2)(1-\alpha_p)X_p]Q_r\end{aligned}$$

Case 5: If $T_{p1} < T_0$ and $T_{p2} < T_0$ are satisfied, the processor can fully recover before the end of the order lead time. But the processor must hold the grains for a period of time T_{h1} and T_{h2}, the length of line segment J_1F and B_1F_2 in Fig. 3. Thus, there is no stockout cost, while an extra storage cost exists. Thus, $X_{r1} = 0, X_{r2} = 0, T_{h1} = T_0 - T_{p1} = T_0 - \frac{\alpha_p X_p}{\beta_{p1}}$ and $T_{h2} = T_0 - T_{p2} = T_0 - \frac{(1-\alpha_p)X_p}{\beta_{p2}}$. Then $T_{p1} = \frac{\alpha_p X_p}{\beta_{p1}} < T_0$, and $T_{p2} = \frac{(1-\alpha_p)X_p}{\beta_{p2}} < T_0$. So, $\beta_{p1} > \frac{\alpha_p X_p}{T_0}$, and $\beta_{p2} > \frac{(1-\alpha_p)X_p}{T_0}$. Let $\beta_{p1} = \lambda_1 \frac{\alpha_p X_p}{T_0}$ $(\lambda_1 > 1), \beta_{p2} = \lambda_2 \frac{(1-\alpha_p)X_p}{T_0} (\lambda_2 > 1)$. So, $T_{h1} = \frac{\lambda_1 - 1}{\lambda_1} T_0, T_{h2} = \frac{\lambda_2 - 1}{\lambda_2} T_0$. Therefore, the profit of the processor can be expressed as follows:

$$\Pi_p^5 = C_p Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_h\left[\alpha_p X_p Q_r \frac{\lambda_1 - 1}{\lambda_1} T_0 + (1-\alpha_p)X_p Q_r \frac{\lambda_2 - 1}{\lambda_2} T_0\right]$$

Case 6: If $T_{p1} < T_0$ and $T_{p2} > T_0$ are satisfied, the processor cannot get full recovery before the end of the order lead time. The same as Case 4 and Case 5, the profit of the processor can be expressed as follows:

$$\begin{aligned}\Pi_p^6 = {} & C_p[1-(1-\lambda_2)(1-\alpha_p)X_p]Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_h \alpha_p X_p Q_r \frac{\lambda_1 - 1}{\lambda_1} T_0 \\ & - C_{sp}(1-\lambda_2)(1-\alpha_p)X_p Q_r\end{aligned}$$

Case 7: If $T_{p1} = T_0$ and $T_{p2} < T_0$ are satisfied, processor can fully recover before the end of the order lead time. The same as Case 2 and Case 5, the profit of the processor can be expressed as follows:

$$\Pi_p^7 = C_p Q_r - C_f(1-X_p)Q_p - \frac{(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_h(1-\alpha_p)X_p Q_r \frac{\lambda_2 - 1}{\lambda_2} T_0$$

Case 8: If $T_{p1} > T_0$ and $T_{p2} < T_0$ are satisfied, the processor cannot get full recovery before the end of the order lead time. The same as Case 4 and Case 5, the profit of the processor can be expressed as follows:

$$\begin{aligned}\Pi_p^8 = {} & C_p[1-(1-\lambda_1)\alpha_p X_p]Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_h(1-\alpha_p)X_p Q_r \frac{\lambda_2 - 1}{\lambda_2} T_0 \\ & - C_{sp}(1-\lambda_1)\alpha_p X_p Q_r\end{aligned}$$

Case 9: If $T_{p1} < T_0$ and $T_{p2} = T_0$ are satisfied, the processor can fully recover before the end of the order lead time. The same as Case 3 and Case 5, the profit of the processor can be expressed as follows:

$$\Pi_p^9 = C_p Q_r - C_f(1-X_p)Q_p - \frac{\lambda_1(\alpha_p X_p)^2 Q_r C_{p1}}{T_0} - \frac{((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} - C_h \alpha_p X_p Q_r \frac{\lambda_1 - 1}{\lambda_1} T_0$$

Proof for Proposition 3. Compare Π_p^7 and Π_p^1. Since $\lambda_2 > 1, \frac{\lambda_2((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0} > \frac{((1-\alpha_p)X_p)^2 Q_r C_{p2}}{T_0}$ and $\frac{\lambda_2 - 1}{\lambda_2} C_h (1-\alpha_p) X_p Q_r T_0 > 0$, then $\Pi_p^7 < \Pi_p^1$ is obtained. Therefore Case 7 is not a good recovery strategy for the processor, and should be abandoned.

Taking the same approach, we have the following results:

Compare Π_p^9 and $\Pi_p^1, \Pi_p^9 < \Pi_p^1$ as $\lambda_1 > 1$;
Compare Π_p^5 and $\Pi_p^1, \Pi_p^5 < \Pi_p^1$ as $\lambda_1 > 1$ and $\lambda_2 > 1$;
Compare Π_p^6 and $\Pi_p^2, \Pi_p^6 < \Pi_p^2$ as $\lambda_1 > 1$ and $0 \leqslant \lambda_2 < 1$;
Compare Π_p^8 and $\Pi_p^3, \Pi_p^8 < \Pi_p^3$ as $0 \leqslant \lambda_1 < 1$ and $\lambda_2 > 1$.
Processor pursues profit maximization, thus Proposition 3 is proved.

Proof for Proposition 4. Based on Proposition 3, the processor pursues profit maximization. Let $\frac{d\Pi_p^1}{d\alpha_p} = 0, \frac{d\Pi_p^2}{d\alpha_p} = 0, \frac{d\Pi_p^3}{d\alpha_p} = 0, \frac{d\Pi_p^4}{d\alpha_p} = 0$, respectively, then the optimal α_p^* and the maximum profit $\Pi_p^{1*}, \Pi_p^{2*}, \Pi_p^{3*}$ and Π_p^{4*} are achieved as follows.

(1) If $\beta_{p1} = \frac{\alpha_p X_p}{T_0}$ and $\beta_{p2} = \frac{(1-\alpha_p)X_p}{T_0}$, then $\alpha_p^{1*} = \frac{C_{p2}}{C_{p1}+C_{p2}}, \Pi_p^{1*} = A - \frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}} B$.

(2) If $\beta_{p1} = \frac{\alpha_p X_p}{T_0}$ and $\beta_{p2} = \lambda_2 \frac{(1-\alpha_p)X_p}{T_0} (0 \leqslant \lambda_2 < 1)$, then $\alpha_p^{2*} = \frac{\lambda_2 C_{p2} + (1-\lambda_2)F}{C_{p1}+\lambda_2 C_{p2}}, \Pi_p^{2*} = A - \frac{\lambda_2 C_{p1} C_{p2}}{C_{p1}+\lambda_2 C_{p2}} B - \frac{(1-\lambda_2)C_{p1}}{C_{p1}+\lambda_2 C_{p2}} D + \frac{(1-\lambda_2)^2}{C_{p1}+\lambda_2 C_{p2}} E$. Let $0 \leqslant \alpha_p^{2*} \leqslant 1, 1 - \frac{C_{p1}}{F} \leqslant \lambda_2 < 1$ is obtained.

(3) If $\beta_{p1} = \lambda_1 \frac{\alpha_p X_p}{T_0} (0 \leqslant \lambda_1 < 1)$ and $\beta_{p2} = \frac{(1-\alpha_p)X_p}{T_0}$, then $\alpha_p^{3*} = \frac{C_{p2} - (1-\lambda_1)F}{\lambda_1 C_{p1} + C_{p2}}, \Pi_p^{3*} = A - \frac{\lambda_1 C_{p1} C_{p2}}{\lambda_1 C_{p1} + C_{p2}} B - \frac{(1-\lambda_1)C_{p2}}{\lambda_1 C_{p1} + C_{p2}} D + \frac{(1-\lambda_1)^2}{\lambda_1 C_{p1} + C_{p2}} E$. Let $0 \leqslant \alpha_p^{3*} \leqslant 1, 1 - \frac{C_{p2}}{F} \leqslant \lambda_1 < 1$ is obtained.

(4) If $\beta_{p1} = \lambda_1 \frac{\alpha_p X_p}{T_0} (0 \leqslant \lambda_1 < 1)$ and $\beta_{p2} = \lambda_2 \frac{(1-\alpha_p)X_p}{T_0} (0 \leqslant \lambda_2 < 1)$, then $\alpha_p^{4*} = \frac{\lambda_2 C_{p2} + (\lambda_1 - \lambda_2)F}{\lambda_1 C_{p1} + \lambda_2 C_{p2}}, \Pi_p^{4*} = A - \frac{\lambda_1 \lambda_2 C_{p1} C_{p2}}{\lambda_1 C_{p1} + \lambda_2 C_{p2}} B - \left(1 - \frac{\lambda_1 \lambda_2 (C_{p1} + C_{p2})}{\lambda_1 C_{p1} + \lambda_2 C_{p2}}\right) D + \frac{(\lambda_1 - \lambda_2)^2}{\lambda_1 C_{p1} + \lambda_2 C_{p2}} E$. Considering the value of λ_1 and λ_2, the following results can be obtained. If $\lambda_1 > \lambda_2$, let $0 \leqslant \alpha_p^{4*} \leqslant 1$, thus $C_{p1} \geqslant \frac{\lambda_1 - \lambda_2}{\lambda_1} F$; If $\lambda_1 < \lambda_2$, then $C_{p2} \geqslant \frac{\lambda_2 - \lambda_1}{\lambda_2} F$; If $\lambda_1 = \lambda_2 = \lambda$, then $\alpha_p^* = \frac{C_{p2}}{C_{p1}+C_{p2}}$ and $\Pi_p^{4*} = A - \frac{\lambda C_{p1} C_{p2}}{C_{p1}+C_{p2}} B - (1-\lambda) D$.
Note that (1), (2) and (3) in the above are the special cases of (4) if the conditions $\lambda_1 = \lambda_2 = 1, \lambda_1 = 1$ and $0 \leqslant \lambda_2 < 1, 0 \leqslant \lambda_1 < 1$ and $\lambda_2 = 1$, are satisfied, respectively. Thus, let the value of λ range from 0 to 1, we can use (4) to represent all of the above cases. Therefore, Proposition 4 is proved.

Proof for Lemma 1. Let $\frac{\partial \Pi_p^*}{\partial \lambda_1} = 0$ and $\frac{\partial \Pi_p^*}{\partial \lambda_2} = 0, \lambda_1^*$ and λ_2^* is obtained to gain the maximum of Π_p^*.

After some algebra, we get

$$\lambda_1^2 C_{p1} E + 2\lambda_1 \lambda_2 C_{p2} E - \lambda_2^2 \left(C_{p1} C_{p2}^2 B - C_{p1} C_{p2} D - C_{p2}^2 D + 2C_{p2} E + C_{p1} E\right) = 0$$
$$\lambda_2^2 C_{p2} E + 2\lambda_1 \lambda_2 C_{p1} E - \lambda_1^2 \left(C_{p1}^2 C_{p2} B - C_{p1} C_{p2} D - C_{p1}^2 D + 2C_{p1} E + C_{p2} E\right) = 0$$

Therefore, $\lambda_1^* = \left(-\frac{C_{p2}}{C_{p1}} + \left|1 + \frac{C_{p2}}{C_{p1}} - \frac{C_{p2}}{F}\right|\right) \lambda_2$ and $\lambda_2^* = \left(-\frac{C_{p1}}{C_{p2}} + \left|1 + \frac{C_{p1}}{C_{p2}} - \frac{C_{p1}}{F}\right|\right) \lambda_1$.

Now let's analyze the relationship of λ_1^* and λ_2^*.

Firstly, if $\lambda_1 = 1$, we only need to let $\frac{\partial \Pi_p^*}{\partial \lambda_2} = 0$. Through calculating λ_2^*, we gain the maximum of Π_p^*.

From the above, we see that $\lambda_2^* = -\frac{C_{p1}}{C_{p2}} + \left|1 + \frac{C_{p1}}{C_{p2}} - \frac{C_{p1}}{F}\right|$. From the proof of Proposition 4, we know that if $\lambda_1 = 1, 1 - \frac{C_{p1}}{F} \leqslant \lambda_2 < 1$, i.e. $C_{p1} \leqslant F$, thus $\lambda_2^* = -\frac{C_{p1}}{C_{p2}} + 1 + \frac{C_{p1}}{C_{p2}} - \frac{C_{p1}}{F} = 1 - \frac{C_{p1}}{F}$.

Therefore, $\alpha_p^* = \frac{\left(1-\frac{C_{p1}}{F}\right)C_{p2} + \left(1 - 1 + \frac{C_{p1}}{F}\right)F}{C_{p1} + \left(1 - \frac{C_{p1}}{F}\right)C_{p2}} = 1$, and $\Pi_p^* = \max\left(\Pi_p^{2*}\right) = A - C_{p1} B$.

Secondly, if $\lambda_2 = 1$, we only need to let $\frac{\partial \Pi_p^*}{\partial \lambda_1} = 0$. In the same way, we can get $\alpha_p^* = \frac{C_{p2} - \left(1 - 1 + \frac{C_{p2}}{F}\right)F}{\left(1 - \frac{C_{p2}}{F}\right)C_{p1} + C_{p2}} = 0$, and $\Pi_p^* = \max\left(\Pi_p^{3*}\right) = A - C_{p2} B$.

Thirdly, if $0 \leqslant \lambda_1 < 1$ and $0 \leqslant \lambda_2 < 1$, we have got λ_1^* and λ_2^* as above.

We analyze $\lambda_1^* = \left(-\frac{C_{p2}}{C_{p1}} + \left|1 + \frac{C_{p2}}{C_{p1}} - \frac{C_{p2}}{F}\right|\right) \lambda_2$ first.

(1) if $1 + \frac{C_{p2}}{C_{p1}} - \frac{C_{p2}}{F} > 0$, i.e., $F > \frac{C_{p1} C_{p2}}{C_{p1} + C_{p2}}$, then $\lambda_1^* = \left(1 - \frac{C_{p2}}{F}\right) \lambda_2$. Further, let $1 - \frac{C_{p2}}{F} > 0$, i.e., $F > C_{p2}$. Therefore, when $F > C_{p2}, \lambda_1^* = \left(1 - \frac{C_{p2}}{F}\right) \lambda_2$ is satisfied. From it we know $\lambda_1 < \lambda_2$ is always true.

(2) if $1+\frac{C_{p2}}{C_{p1}}-\frac{C_{p2}}{F}<0$, i.e., $F<\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}$, then $\lambda_1^*=\left(\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1\right)\lambda_2$. Further, let $\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1>0$, i.e., $F<\frac{C_{p1}C_{p2}}{C_{p1}+2C_{p2}}$. Therefore, when $F<\frac{C_{p1}C_{p2}}{C_{p1}+2C_{p2}}, \lambda_1^*=\left(\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1\right)\lambda_2$ is satisfied.

(2.1) if $\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1>1$, i.e., $F<\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}, \lambda_1>\lambda_2$.

(2.2) if $\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1=1$, i.e., $F=\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}, \lambda_1=\lambda_2$.

(2.3) if $0<\frac{C_{p2}}{F}-\frac{2C_{p2}}{C_{p1}}-1<1$, i.e., $\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}<F<\frac{C_{p1}C_{p2}}{C_{p1}+2C_{p2}}, \lambda_1<\lambda_2$.

(3) if $1+\frac{C_{p2}}{C_{p1}}-\frac{C_{p2}}{F}=0$, i.e., $F=\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}, \lambda_1^*=\left(-\frac{C_{p2}}{C_{p1}}\right)\lambda_2$. We know this expression is false because λ_1 is a nonnegative number. Then we analyze $\lambda_2^*=\left(-\frac{C_{p1}}{C_{p2}}+\left|1+\frac{C_{p1}}{C_{p2}}-\frac{C_{p1}}{F}\right|\right)\lambda_1$.

(4) if $1+\frac{C_{p1}}{C_{p2}}-\frac{C_{p1}}{F}>0$, i.e., $F>\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}$, then $\lambda_2^*=\left(1-\frac{C_{p1}}{F}\right)\lambda_1$. Further, let $1-\frac{C_{p1}}{F}>0$, i.e., $F>C_{p1}$. Therefore, when $F>C_{p1}, \lambda_2^*=\left(1-\frac{C_{p1}}{F}\right)\lambda_1$ is satisfied. From it we know $\lambda_1>\lambda_2$ is always true.

(5) if $1+\frac{C_{p1}}{C_{p2}}-\frac{C_{p1}}{F}<0$, i.e., $F<\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}$, then $\lambda_2^*=\left(\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1\right)\lambda_1$. Further, let $\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1>0$, i.e., $F<\frac{C_{p1}C_{p2}}{2C_{p1}+C_{p2}}$. Therefore, when $F<\frac{C_{p1}C_{p2}}{2C_{p1}+C_{p2}}, \lambda_2^*=\left(\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1\right)\lambda_1$ is satisfied.

(5.1) if $\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1>1$, i.e., $F<\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}, \lambda_1<\lambda_2$.

(5.2) if $\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1=1$, i.e., $F=\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}, \lambda_1=\lambda_2$.

(5.3) if $0<\frac{C_{p1}}{F}-\frac{2C_{p1}}{C_{p2}}-1<1$, i.e., $\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}<F<\frac{C_{p1}C_{p2}}{2C_{p1}+C_{p2}}, \lambda_1>\lambda_2$.

(6) if $1+\frac{C_{p1}}{C_{p2}}-\frac{C_{p1}}{F}=0$, i.e., $F=\frac{C_{p1}C_{p2}}{C_{p1}+C_{p2}}, \lambda_2^*=\left(-\frac{C_{p1}}{C_{p2}}\right)\lambda_1$. We know this expression is false because λ_2 is a nonnegative number.

To sum up, in order to gain the maximum of Π_p^*, we should make λ_1^* and λ_2^* exist simultaneously. Hence, when $F=\frac{C_{p1}C_{p2}}{2(C_{p1}+C_{p2})}, \lambda_1^*=\lambda_2^*=\lambda(0\leqslant\lambda<1)$. At this time, $\alpha_p^*=\frac{C_{p2}}{C_{p1}+C_{p2}}$ and $\Pi_p^*=\max\left(\Pi_p^{4*}\right)=A-\frac{\lambda C_{p1}C_{p2}}{C_{p1}+C_{p2}}B-(1-\lambda)D=A-\lambda 2FB-(1-\lambda)D=A-D$. Then, Lemma 1 is proved.

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