Food Control 78 (2017) 443–455

Contents lists available at ScienceDirect

Food Control

journal homepage: www.elsevier.com/locate/foodcont

Modeling a Government-Manufacturer-Farmer game for food supply chain risk management

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ARTICLE INFO

Article history:
Received 29 September 2016
Received in revised form
15 February 2017
Accepted 19 February 2017
Available online 23 February 2017

Keywords:
Food supply chain
Game theory
Decision analysis
Risk management
Regulation

ABSTRACT

Farmers may add chemical additives to crops to enhance their appearances/tastes or decrease their costs, which may also increase the food demand and sales profits. Manufacturers buy products from farmers and sell them to consumers, where the government benefits from tax income based on sales revenues. However, once the contaminated food is consumed, customers could get sick. The government would, thus, be partially responsible for society's health risks from the chemical additives. The punishment policies are set up by the government to regulate and deter farmers' and manufacturers' risky behavior, balancing tax income, punishment income, and society's health risks. Based on the observation of government regulations, the farmers strategically choose the optimal level of chemical additives, and manufacturers pay the appropriate price to farmers. To our knowledge, little work has studied the strategic interactions among the regulating government, manufacturers, and farmers with endogenous customer demand. This paper fills this gap by building a Government-Manufacturer-Farmer model with three decentralized and centralized sub-models. The models are validated and illustrated through applying the 2008 Sanlu food contamination data. Our results show that (a) the higher the food price is, the higher the punishment is needed to deter the use of chemicals; (b) the optimal chemical level increases in the payment to the farmer when it is low and decreases in the government punishment; (c) the manufacturer's payment to the farmer decreases in the government punishment; (d) the chemical level is significantly higher in the centralized model than in the decentralized model especially when the food price and slope for sales amount are high, or the base sales demand, tax rate, and chemical cost are low; and (e) the decentralized model leads to the lowest chemical level at equilibrium. This paper provides some novel policy insights for food supply chain risk management.

1. Introduction

In the field of food supply chain research, there is literature focusing on health and safety. The consumers' perception of potential (food) risks is analyzed in (Liu, Pieniak, Verbeke, 2013; Liu, Pieniak, Verbeke, 2014; Sparks and Shepherd, 1994). Chemical additives are normally added in many processes along the food supply chain by farmers and manufacturers. The food additives are used for a number of purposes, generally for preservation, provision of vitamins or minerals, and enhancement of the food texture, appearance, and flavor. However, food additives could also be harmful. For example, there were more than 100 pet deaths among nearly 500 cases of kidney failure due to a contaminated food additive, “wheat gluten” (which was adulterated with melamine to increase the apparent protein level) in animal food in 2007, involving three companies *Americas Choice*, *Preferred Pet* and *Authority*) (Associated Press, 2007; U S Food and Drug Administration and U S Department of Health & Human Service, 2008). At least six infants were killed due to kidney stones, and the kidneys of 300,000 infants were damaged by industrial chemical melamine in 2008 after using the milk products from Sanlu company (Branigan, 2008). Some children have experienced growth problems due to the contaminated chemical additive 2-ethylhexyl phthalate (DEHP) in food and drinks from 47 Taiwanese companies in 2011 (Galarpe, 2011). The German company, *Harles and Jentzsch*, contaminated 150,000 tons of feed for chickens, turkey, and swine with the cancer-causing additive Dioxin in 2011 (Spiegel Online, 2011).

There are many other cases that follow the same pattern in China. There has been a longstanding concern about farmers using toxic pesticides on vegetables, rice, and other crops in China, where

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http://dx.doi.org/10.1016/j.foodcont.2017.02.047
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the pesticides is meant to kill pests or keep the product fresh (Mail, 2012). Another issue is that the use of poisonous chemical malachite green, which was used for raising mandarin fish to avoid them ill and was found in Hong Kong. It is said that this chemical is harmful for human health risk (CSR C, 2006). About 60 farms in Henan province fed pigs with illegal ractopamine to make more profit, where the ractopamine can speed up the process of muscle building and fat burning to produce leaner pork (Post, 2011).

Multi-stage supply chains in modern economies give anonymity to actors at different stages. The limited transmission of information from suppliers to consumers gives suppliers opportunity to introduce harmful or fraudulent chemicals that raise their profits while harming or defrauding consumers without their knowledge. This strategy benefits individual suppliers in the short run at the expense of consumers. However, market failure similar to a “market for lemons” scenario occurs when consumers become aware of the risk and have no means of gathering reliable information on products. Regulators can gain insights about how to preserve a healthy market by considering the strategic behavior of different actors in the supply chain.

1.1. Risky behavior in food supply chain

A food supply chain process is illustrated in Fig. 1, where raw materials such as raw milk are initially produced by farmers (representing suppliers of raw commodities to manufacturers which include farmers and traders). The raw food is then bought and processed by the manufacturers, and eventually consumed by customers. The government receives the tax income through the manufacturer's sale profit. During the supply chain process, chemical additives could be added by the farmers or manufacturers to preserve the product's freshness or improve its appearance. (In 2008, the contamination of melamine in the aforementioned Sanlu case actually is considered food fraud, and even a food crime, where the farmer added melamine to the raw milk.) The consumers may get sick by consuming the contaminated food. The government inspects and punishes the risky behavior by farmers or manufacturers in the food supply chain and may be considered partially responsible for the societal impacts. The government agencies responsible for inspection and punishment include the U.S. Food and Drug Administration, the European Food Safety Authority, and the Chinese Institute of Food Safety Control and Inspection. This paper focuses on the risky behavior of the farmers, who could be motivated by the low selling profits from manufacturers (Gale & Hu, 2009).

1.2. Motivation for risky behavior by manufacturers or farmers

Chemical additives could preserve the freshness of food and make it more attractive, which is helpful for selling products. Due to considerable sales profits, the manufacturers or farmers may use food additives even though they are harmful (Harrington, 2011). Inspection and punishment policies could deter the manufacturers or farmers' risky behavior. In the Sanlu case, due to low or even no profits from the Sanlu company, farmers had to add melamine to produce milk with high protein, reduce the production costs, and satisfy the demand for the Sanlu company, who was aware of such risky behavior (DeLaurentis, 2009). Appendix provides the influence diagram for the manufacturer's or farmer's risky behavior.

1.3. Motivation for punishment policy by government

The government encourages the sales demand for the manufacturers and farmers (who may add high level of chemicals), which could yield considerable tax incomes from an economic perspective. A conflict tradeoff is generated for the government on how to control the risky behavior. We consider the government as the first mover who sets up punishment, and the farmers or manufacturers as the followers who observe the punishment policy and strategically add chemical additives. The government takes the optimal punishment strategy considering the farmers' and manufacturers' strategic responses, to farmers and manufacturers, respectively. Appendix provides the influence diagram for the government's punishment policy.

1.4. Literature review and contribution

Food contamination incidents could derive from the government's lack of regulations, punishments, and resources to enforce food safety (Ellis & Turner, 2010; Ming, 2006; Zacha, Doyleb, Bierc, & Czuprynskib, 2012). For the safety of the (food) supply chain, many suggestions on government regulations are proposed: (a) the joint use of liability and safety regulation (Shavell, 1984)); (b) fines and corrective taxes (Kambhu, 1990); (c) a higher inspection accuracy and stronger enforcement (Cheung & Zhuang, 2012; Oh, 1995); (d) the imposition of liability for damages (Segerson, 1999); (e) transferring costs and benefits from the government to the manufacturers using penalty contracts (Hobbs & Kerr, 1999); and (f) transferring safety failure costs from the government to the manufacturers (Chen, 2009). This paper focuses on the government's punishment and taxes.

There exists strategic interactions between companies and the regulating government in the existing literature (Tompkin, 2001). For example, (Rose-Ackerman, 1991) suggests direct regulation and product liability that can make incentives for companies to control food quality. (Henson & Caswell, 1999) points out that the expected economic benefits and costs affect a firm's response to the government regulation. The companies' benefits and costs are measured for improving food quality and safety in quality management systems in (Caswell, 1998). (Fares & Rouviere, 2010) finds that the company's decision of using additives depends on its own costs (e.g., food spoilage and risks) and benefits (e.g., productivity enhancement), with or without facing the government regulation.

Strategic interactions between companies and the government are not new, e.g., (Pouliot & Sumner, 2008) analyzes the food safety and quality issues from the perspective of traceability in a marketing chain composed of farmers, marketers and consumers.

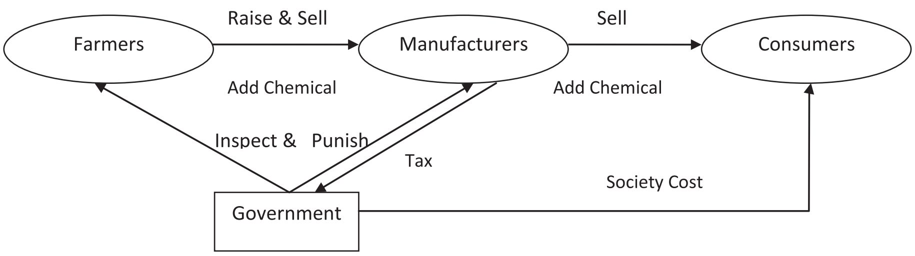

Fig. 1. Risky behavior from the farmers and manufacturers in food supply chain, under potential government regulation, inspection, and punishment.

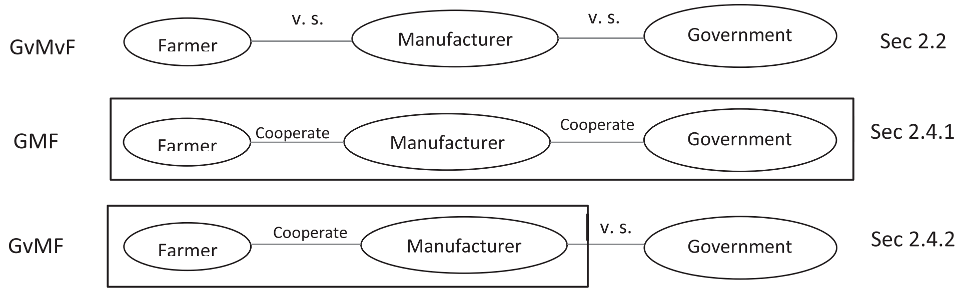

Fig. 2. Illustrating the Relationships between the Three Models Studied in this Paper.

(Song & Zhuang, 2017) studies a two-player government-manufacturer game where the manufacturer could add chemicals. However, in practice there might exist a third player (e.g., farmer) who add chemical additives (see 14). Therefore, this paper extends (Song & Zhuang, 2017) by analyzing the strategic interactions among the regulating government, manufacturers, and farmers considering endogenous customers' demands in the context of food supply chain risk management. Since Sanlu case is considered as food fraud, this paper analyzes the risky behaviors of farmers and manufacturers from an economic way known as economically motivated adulteration (EMA, see (Moore, Spink, & Lipp, 2012)).

In particular, we consider a sequential game where the government, the first player, sets the punishment policies for manufacturers and farmers, balancing tax income, punishment income and societal cost. The manufacturer, as the second mover, pays the farmer based on the observable government punishment information, balancing punishment, tax costs, and sales revenues. The farmer, as the third mover, observes the punishment and payment information and chooses the chemical level, balancing punishment, chemical and production costs, and the sales revenue.

The rest of this paper is organized as follows: Section 2 introduces the optimization problems in a Government-Manufacturer-Farmer model, provides the best responses for the farmers and manufacturers and the optimal solution for the government punishment policy with numerical illustration, studies two types of centralized models, and compares the equilibrium payoffs and strategies between the centralized and decentralized models. In particular, a government against manufacturer against farmer (*GvMvF*) model is introduced in Section 2.2, a centralized Government-Manufacturer-Farmer (*GMF*) model is introduced in Section 2.4.1, and a government against manufacturer and farmer (*GvMF*) model is introduced in Section 2.4.2. Fig. 2 summarizes the relationship and location of all models to be studied in this paper. Section 3 applies the Sanlu case and compares the three models. Section 4 summarizes this paper and provides some future research directions. Appendix provides the proofs for the propositions.

2. A government vs. manufacturer vs. farmer (*GvMvF*) model

In the 2008 tainted Sanlu milk powder accident, the farmer added melamine into raw milk, the manufacturer purchased the raw milk for further processing, and the government was responsible for inspecting and punishing risky behavior of both the manufacturer and farmer (Branigan, 2008). A Government-Manufacturer-Farmer (*GvMvF*) model is studied in this section.

2.1. Notation, sequence of moves, and assumption

Table 1 lists the notations that are used throughout this section, including four decision variables (farmer's payment per unit milk set by the manufacturer P_F, chemical level x, punishment to farmer set by the government β_F, and punishment to the manufacturer set by the government β_M), five utility functions (customer demand $Q(x)$, sickness probability $H(x)$, the government's utility $U_G(x,\beta)$, and the manufacturer's utility $U_M(x,\beta)$, farmer's utility U_F), and thirteen parameters (chemical unit cost p_m, coefficient of health cost c, tax rate γ, basic demand Q_0, slope for customer demand q, unit food price P, and slope for probability of sickness λ, unit production cost for protein c_p, amount of nitrogen in unit protein n_p, amount of nitrogen in unit melamine n_m, total required amount of nitrogen in unit milk powder N, level of protein x_p, and unit protein price p_p).

Stackelberg competition, an economics strategic game, occurs when the first "leader" firm makes a decision and provides the first move of the game. A second"follower" firm moves sequentially based on the leader firm's action. Fig. 3 illustrates the sequence of moves for the government, manufacturer, and farmer with public information. We assume that the government is the first mover who sets the punishment levels β_M for the manufacturer and β_F the farmer. The manufacturer is the second mover, and decides the payment to farmer P_F while considering the punishment level β_M. Finally, the farmer chooses the chemical level x based on the payment P_F, punishment β_F, and consumer demand $Q(x)$. The farmer, the government, and the manufacturer are assumed to be rational and maximize their expected payoffs U_F, U_G, and U_M, respectively.

Table 1
Notation and explanation in the government-manufacturer-farmer (*GvMvF*) model.

Decision Variables	$P_F \geq 0$	Farmer's payment per unit milk set by the manufacturer
	x	Level of chemical additives set by farmer
	$\beta_F \geq 0$	Punishment to the farmer set by the government
	$\beta_M \geq 0$	Punishment to the manufacturer set by the government
Functions	$Q(x) \geq 0$	Consumer demand
	$H(x) \in [0,1]$	Probability of sickness
	$U_G(x,\beta)$	The government's utility function
	$U_M(x,\beta)$	The manufacturer's utility function
	$U_F(P_F,\beta_F)$	Farmer's utility function
Parameters	$p_m \geq 0$	Chemical unit cost
	$[x^-, x^+]$	Chemical level lower bound x^- and upper bound x^+
	$c \geq 0$	Coefficient of health cost per number of sick people
	$\gamma \in [0,1]$	Tax rate
	$Q_0 > 0$	Baseline demand for $Q(X)$
	$q \geq 0$	Slope for $Q(X)$
	$P \geq 0$	Unit food price
	$\lambda \geq 0$	Slope for $H(x)$
	$c_p \geq 0$	Unit production cost for protein
	$c_m \geq 0$	Unit production cost for manufacturer
	$n_p \geq 0$	Amount of nitrogen in unit protein
	$n_m \geq 0$	Amount of nitrogen in unit melamine
	$N \geq 0$	Total required amount of nitrogen in unit milk powder
	$x_p \geq 0$	Level of protein
	$p_p \geq 0$	Unit protein price

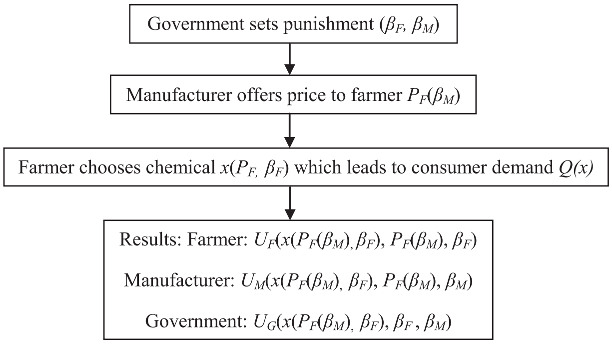

Fig. 3. Sequence of moves for government, manufacturer, and farmer with public information.

We assume that consumer demand $Q(x)$ as a function of the chemical level x in Equation (1), has the following properties:

$$Q(x) = Q_0 + qx, \ \forall x \in \left[x^-, x^+\right] \tag{1}$$

$$Q(0) = Q_0; \quad Q'(x) \geq 0; \tag{2}$$

That is, the higher q is, the faster $Q(x)$ increases.

Similarly, we assume that the probability of sickness $H(x)$ as a function of chemical level x, has the following properties:

$$H(x) \in [0,1]; \quad H'(x) \geq 0; \quad H''(x) \leq 0; \tag{3}$$

That is, the higher the chemical level x, the higher the probability of sickness happening. We use parameter λ to model the slope of $H(x)$.

$$H(x) = \lambda x \tag{4}$$

It could be better to use exponential functional forms for the Equations (1) and (4), however, for more analytical results in the later part, we apply linear forms in this section.

2.2. Optimization problems for the decentralized (GvMvF) model

We assume that the farmer's goal is to choose the appropriate level of chemical additives x to maximize expected payoff in Equation (5) below, consisting of: (a) total sales revenue $P_F Q(x)$; (b) expected punishment cost $\beta_F H(x)Q(x)$; (c) chemical purchase cost $p_m x Q(x)$; and (d) protein production cost $c_p x_p Q(x)$. We assume that there is no tax on the farmer.

$$\max_{x \in [x^-, x^+]} U_F(x, P_F, \beta_F) = \underbrace{P_F Q(x)}_{\text{Sales Revenue}} - \underbrace{\beta_F H(x) Q(x)}_{\text{Punishment Cost}} - \underbrace{p_m x Q(x)}_{\text{Chemical Cost}} - \underbrace{c_p x_p Q(x)}_{\text{Production Cost}} \tag{5}$$

From the manufacturer's perspective, the goal is to choose the appropriate payment level to the farmer P_F to maximize the expected payoff shown in Equation (6) below, consisting of three items: (a) sales revenue $(P - P_F)Q(x)$; (b) punishment cost $\beta_M Q(x) H(x)$; (c) tax cost $\gamma P Q(x)$; and (d) production cost $c_m Q(x)$.

$$\max_{P_F \geq 0} U_M(\widehat{x}(P_F, \beta_F), P_F, \beta_M) = \underbrace{(P - P_F)Q(x)}_{\text{Sales Revenue}} - \underbrace{\beta_M Q(x) H(x)}_{\text{Punishment Cost}} - \underbrace{\gamma P Q(x)}_{\text{Tax Cost}} - \underbrace{c_m Q(x)}_{\text{Production Cost}} \tag{6}$$

One of the government's roles is to set the punishment policy to deter manufacturer's and farmer's risky behaviors for the sake of public health, where the corresponding costs of deterrence and implementation are ignored. Another role of the government is to put appropriate economic burdens on the manufacturer's development in order to maintain a stable and healthy economic growth and employment rate. From the government's perspective, the goal is to choose the optimal punishment levels to the farmer β_F and to the manufacturer β_M to maximize the expected payoff shown in Equation (7) below, consisting of three items: (a) health cost $cQ(x)H(x)$; (b) punishment income $(\beta_F + \beta_M)Q(x)H(x)$; and (c) tax income $\gamma P Q(x)$.

$$\max_{\beta_F \geq 0, \beta_M \geq 0} U_G\left(\widehat{x}\left(\widehat{P_F}(\beta_M), \beta_F\right), \beta_F, \beta_M\right) = -\underbrace{cQ(x)H(x)}_{\text{Health Cost}} + \underbrace{(\beta_F + \beta_M)Q(x)H(x)}_{\text{Punishment Income}} + \underbrace{\gamma P Q(x)}_{\text{Tax Income}} \tag{7}$$

Definition 1. *We call a pair of strategy* $(x^*, P_F^*, \beta_F^*, \beta_M^*)$ *a subgame perfect Nash equilibrium (SPNE), or "equilibrium" for the GvMvF model, if and only if Equations (8–10) below are satisfied:*

$$x^* = \widehat{x}(P_F^*, \beta_F^*) \tag{8}$$

$$P_F^* = \widehat{P_F}(\beta_M^*) \tag{9}$$

$$(\beta_F^*, \beta_M^*) = \operatorname*{argmax}_{\beta_F \geq 0, \beta_M \geq 0} U_G\left(\widehat{x}\left(\widehat{P_F}(\beta_M), \beta_F, \beta_F\right), \beta_M\right) \tag{10}$$

where the farmer's and the manufacturer's best responses $\widehat{x}(P_F, \beta_F)$ and $\widehat{P_F}(\beta_M)$ are defined in Equations (11–12), respectively.

$$\widehat{x}(P_F, \beta_F) \equiv \operatorname*{argmax}_{x \in [x^-, x^+]} U_F(x, P_F, \beta_F), \ \forall P_F, \beta_F \geq 0 \tag{11}$$

$$\widehat{P_F}(\beta_M) \equiv \operatorname*{argmax}_{P_F \geq 0} U_M(\widehat{x}(P_F, \beta_F), P_F, \beta_M), \ \forall \beta_M \geq 0 \tag{12}$$

It is hard to test the protein percentage in milk powder, so generally a Kjeldahl determination method is used to test nitrogen amounts, which is used to further calculate the amount of protein in milk powder (Cohen, 1910). In reality, melamine, a fake nitrogen provider, is used to replace protein with less cost. The relationship among nitrogen, melamine, and protein in the Sanlu milk case is as follows:

$$\underbrace{n_p x_p}_{\text{Niotrogen in Protein}} + \underbrace{n_m x}_{\text{Niotrogen in Chemical}} \geq \underbrace{N}_{\text{Required Nitrogen}} \tag{13}$$

That is, Equation (13) details the sources where the nitrogen comes from, including protein and the chemical melamine. It is required by the standard that the total amount of nitrogen in protein meets a certain level (threshold N), where the details will be discussed in Section 3. Based on Equation (13), we have the level of protein $x_p \geq \frac{N-n_m x}{n_p}$. Since the farmer would choose the lowest level of protein to meet the requirement while minimizing the total costs, we have

$$x_p = \frac{N - n_m x}{n_p} \tag{14}$$

2.3. Solution and numerical illustration

Inserting Equations (1), (4) and (14) into Equation (5), the farmer's optimization problem becomes:

$$\begin{aligned} \max_{x \in [x^-, x^+]} U_F(x, P_F, \beta_F) &= \left(-\beta_F \lambda + \frac{c_p n_m}{n_p} - p_m \right) q x^2 \\ &+ \left(P_F q - \beta_F \lambda Q_0 - p_m Q_0 - \frac{c_p N q}{n_p} + \frac{c_p n_m Q_0}{n_p} \right) x \\ &+ P_F Q_0 - \frac{c_p N Q_0}{n_p} \\ &= (a - \beta_F \lambda q) x^2 + (b + P_F q - \beta_F \lambda Q_0) x + P_F Q_0 - \frac{c_p N Q_0}{n_p} \end{aligned} \tag{15}$$

where $a \equiv q\left(\frac{c_p n_m}{n_p} - p_m\right)$, and $b \equiv -p_m Q_0 - \frac{c_p N q}{n_p} + \frac{c_p n_m Q_0}{n_p}$.

Proposition 1. *The solution to the farmer's optimization problem* (Associated Press, 2007) *is given by*

$$\widehat{x}(P_F, \beta_F) = \begin{cases} x^- & \text{if } \beta_F = \frac{a}{\lambda q}, P_F q - \beta_F \lambda Q_0 \leq -b; \text{ or} \\ & \beta_F > \frac{a}{\lambda q}, \frac{b + P_F q - \beta_F \lambda Q_0}{2(\beta_F \lambda q - a)} < x^-; \text{ or} \\ & \beta_F < \frac{a}{\lambda q}, U_F\left(x^-\right) \geq U_F\left(x^+\right) \\ x_{interior} = \frac{b + P_F q - \beta_F \lambda Q_0}{2(\beta_F \lambda q - a)} & \text{if } \beta_F > \frac{a}{\lambda q}, \frac{b + P_F q - \beta_F \lambda Q_0}{2(\beta_F \lambda q - a)} \in \left[x^-, x^+\right] \\ x^+ & \text{if } \beta_F = \frac{a}{\lambda q}, P_F q - \beta_F \lambda Q_0 > -b; \text{ or} \\ & \beta_F > \frac{a}{\lambda q}, \frac{b + P_F q - \beta_F \lambda Q_0}{2(\beta_F \lambda q - a)} > x^+; \text{ or} \\ & \beta_F < \frac{a}{\lambda q}, U_F\left(x^-\right) < U_F\left(x^+\right) \end{cases} \tag{16}$$

Additionally, we have $\frac{\partial \widehat{x}(P_F, \beta_F)}{\partial P_F} = \frac{q}{2(\beta_F \lambda q - a)} \geq 0$ and $\frac{\partial \widehat{x}(P_F, \beta_F)}{\partial \beta_F} = \frac{\lambda Q_0(\beta_F \lambda q - a) + \lambda q(b + P_F q - \beta_F \lambda Q_0)}{2(\beta_F \lambda q - a)^2} < 0$, when $\widehat{x}(P_F, \beta_F) = x_{interior}$, where $b + P_F q - \beta_F \lambda Q_0 > 0$ and $\beta_F \lambda q - a > 0$.

Remark. Proposition 1 shows that the manufacturer's chemical level, in interior solution $\frac{b + P_F q - \beta_F \lambda Q_0}{2(\beta_F \lambda q - a)}$, decreases in the government punishment to the farmer β_F and increases in the payment to the farmer P_F for the intermediate solution.

Inserting Equations (1) and (4) into Equation (6), the manufacturer's optimization problem becomes:

$$\max_{P_F \geq 0} U_M(\widehat{x}(P_F, \beta_F), P_F, \beta_M) = a' P_F^2 + b' P_F + c'$$

where $a' \equiv -\frac{q^2(t + \beta_M \lambda q)}{t^2} \leq 0$, $t = 2(\beta_F \lambda q - a) > 0$, $b' \equiv \frac{t q^2 (1-\gamma) P - Q_0 (t + \beta_M \lambda q) t - 2 q^2 \beta_M \lambda (b - \beta_F \lambda Q_0)}{t^2} - \frac{c_m q^2}{t}$, and $c' \equiv \left[\left(Q_0 + \frac{q(b - \beta_F \lambda Q_0)}{t}\right)\left(\left(1 - \gamma\right) P - \frac{\beta_M \lambda (b - \beta_F \lambda Q_0)}{t}\right)\right] - c_m Q_0 - \frac{c_m q (b - \beta_F \lambda Q_0)}{t}$.
Using the baseline values $\gamma = 0.5$, $P = 1$, $Q_0 = 1$, $q = 2$, $c = 1$, $p_m = 0.5$, $\lambda = 1$, $x^- = 0$, $x^+ = 1$, $c_p = 0.6$, $c_m = 0$, $n_p = 0.16$, $n_m = 0.666$, and $N = 0.0288$, Fig. 4 shows how the manufacturer payment P_F and

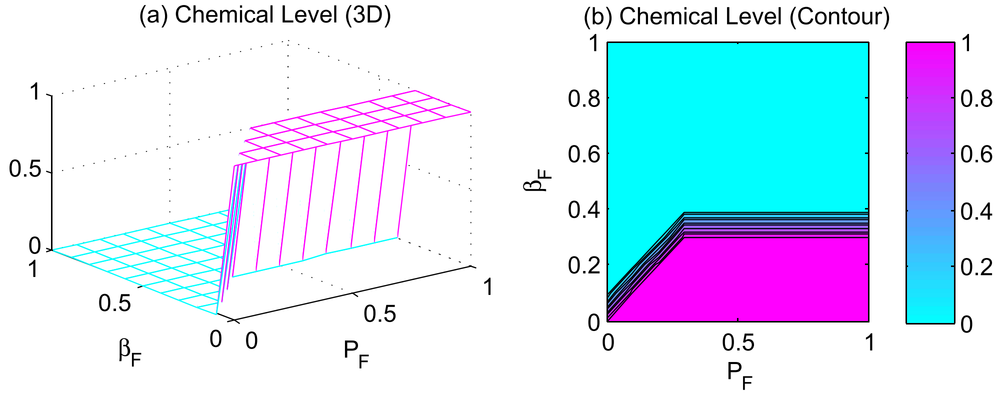

Fig. 4. Illustration of the Farmer's best response chemical level $\widehat{x}$ as functions of the Government's punishment β_F and the Manufacturer's payment P_F in the *GvMvF* model.

punishment β_F affect the farmer's optimal chemical level x. In particular, Fig. 4 shows that the optimal chemical level x increases in P_F and decreases in β_F.

Proposition 2. *The solution to the manufacturer's optimization problem* (Branigan, 2008) *is given by*

$$\widehat{P_F}(\beta_M) = \begin{cases} \dfrac{b'}{-2a'} & \text{if } t>0, \dfrac{b'}{-2a'} \in \left[\dfrac{tx^- - b + \beta_F\lambda Q_0}{q}, \dfrac{tx^+ - b + \beta_F\lambda Q_0}{q}\right] \\ 0 & \text{Otherwise} \end{cases} \tag{17}$$

where a, b, a', b' are defined in Section 2.3 and Proposition 1. In addition, we have $\frac{d\widehat{P_F}(\beta_M)}{d\beta_M} = -\frac{\lambda q^3[2q(b-\beta_F\lambda Q_0)(t+2\beta_M\lambda q)+tq^2(1-\gamma)P]}{2a'^2t^4} \le 0$.

Remark. Proposition 2 shows that at the interior solution the manufacturer's payment to the farmer P_F decreases in the government punishment to the manufacturer β_M.

Fig. 5 shows how the manufacturer's best response P_F is affected by the punishment β_M, when the punishment to the farmer β_F is set at 0.2. In particular, it shows that the optimal manufacturer's payment P_F decreases in punishment β_M until the point $\beta_M = 0.9$. We assume that if the government is indifferent between different punishment levels that lead to the same payoff, the lowest punishment level would be chosen from a mathematical perspective. The analytical solution for the government's optimal strategy is too complex to document in this paper, but it is available upon request.

2.4. *Two centralized models*

In this section, we consider two types of centralized models: the Government-Manufacturer-Farmer (*GMF*) model introduced in Section 2.4.1 and the Government vs. Manufacturer-Farmer (*GvMF*) model introduced in Section 2.4.2. It is rare that the government cooperates with the manufacturer against the farmer, so we do not consider the Government-Manufacturer vs. Farmer (*GMvF*) model.

2.4.1. *Government-Manufacturer-Farmer (GMF) model*

In the *GMF* model, the government, the manufacturer, and the farmer cooperate together to maximize the societal payoff $U(x)$, which equals the summation of the government, the manufacturer, and the farmer's payoffs in Equations (5–7). From Equation (18) shown below, we see that the punishment and payment to the farmer are canceled. The only decision variable is the chemical level x.

$$\begin{aligned} &\max_{x\in[x^-,x^+]} U(x) = U_M + U_F + U_G \\ &= \underbrace{PQ(x) - p_m xQ(x)}_{\text{Sales Revenue}} - \underbrace{c_p x_p Q(x) - c_m Q(x)}_{\text{Production Cost}} - \underbrace{cQ(x)H(x)}_{\text{Health Cost}} \end{aligned} \tag{18}$$

Inserting Equations (1), (4), and (14) into Equation (18), the cooperative optimization problem becomes:

$$\begin{aligned} \max_{x\in[x^-,x^+]} U(x) = -\left(p_m + c\lambda - \frac{c_p n_m}{n_p}\right)qx^2 + \left(\left(P - \frac{c_p N}{n_p} - c_m\right)q \right. \\ \left. - (p_m + c\lambda)Q_0\right)x + (P - c_p x_p - c_m)Q_0 \end{aligned} \tag{19}$$

Solving Equation (19), the optimal chemical level is given by Equation (20).

$$x_{GMF} = \begin{cases} x^- & \text{if } c = \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, P \le \dfrac{c_p N}{n_p} + c_m)q - (p_m + c\lambda)\dfrac{Q_0}{q}; \text{ or} \\ & c > \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \dfrac{\left(P - \frac{c_p N}{n_p} - c_m\right)q - (p_m + c\lambda)Q_0}{2\left(p_m + c\lambda - \frac{c_p n_m}{n_p}\right)q} < x^-; \text{or} \\ & c < \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, U\left(x^-\right) \ge U\left(x^+\right) \\ x_{interior} & \text{if } c > \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \dfrac{\left(P - \frac{c_p N}{n_p} - c_m\right)q - (p_m + c\lambda)Q_0}{2\left(p_m + c\lambda - \frac{c_p n_m}{n_p}\right)q} \in \left[x^-, x^+\right] \\ x^+ & \text{if } c = \dfrac{\frac{c_p N}{n_p} - c_m - p_m}{\lambda}, P > \dfrac{c_p N}{n_p} + c_m)q - (p_m + c\lambda)\dfrac{Q_0}{q} \text{ ; or} \\ & c > \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \dfrac{\left(P - \frac{c_p N}{n_p} - c_m\right)q - (p_m + c\lambda)Q_0}{2\left(p_m + c\lambda - \frac{c_p n_m}{n_p}\right)q} > x^+; \text{or} \\ & c < \dfrac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, U\left(x^-\right) < U\left(x^+\right) \end{cases} \tag{20}$$

where $x_{interior} = \frac{\left(P - \frac{c_p N}{n_p} - c_m\right) q - (p_m + c\lambda) Q_0}{2\left(p_m + c\lambda - \frac{c_p n_m}{n_p}\right) q}$.

2.4.2. *The government vs. Manufacturer-Farmer (GvMF) model*

In the *GvMF* model, the manufacturer and farmer cooperate together against the government. The combined manufacturer and farmer utility equals the summation of the respective manufacturer and farmer utilities in Equations (5–6). From Equation (21) below, we see that the payment to the farmer is canceled out.

$$\max_{x \in [x^-, x^+]} U_{FM}(x) = U_M + U_F = \underbrace{PQ(x)}_{\text{Sales Profit}} - \underbrace{p_m x Q(x)}_{\text{Chemical Cost}} \\ \underbrace{- c_p x_p Q(x) + c_m Q(x)}_{\text{Production Cost}} \underbrace{- (\beta_M + \beta_F) Q(x) H(x)}_{\text{Punishment Cost}} \\ \underbrace{- \gamma P Q(x)}_{\text{Tax Cost}} \tag{21}$$

The government's optimization problem remains the same as in Equation (7). Inserting Equations (1), (4), and (14) into Equation (21), the cooperative optimization problem becomes:

$$\max_{x \in [x^-, x^+]} U_{FM}(x) = -\left(p_m + \beta_m \lambda + \beta_F \lambda - \frac{c_p n_m}{n_p}\right) q x^2 \\ + \left(\left(P - \gamma P - \frac{c_p N}{n_p} - c_m\right) q \\ - (p_m + \beta_m \lambda + \beta_F \lambda) Q_0\right) x + (P - c_p x_p - c_m) Q_0 \tag{22}$$

Solving Equation (22), the optimal chemical level is given by Equation (23)

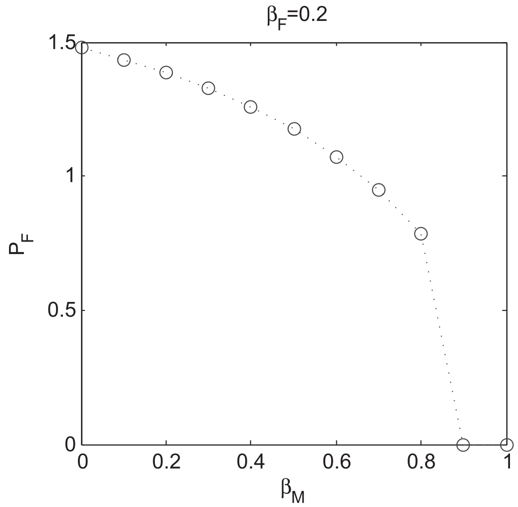

Fig. 5. Illustration of the Manufacturer's Best Response P_F to Punishment β_M in the *GvMvF* Model.

where $x_{interior} = \frac{\left(P - \gamma P - \frac{c_p N}{n_p} - c_m\right) q - (p_m + \beta_m \lambda + \beta_F \lambda) Q_0}{2\left(p_m + \beta_m \lambda + \beta_F \lambda - \frac{c_p n_m}{n_p}\right) q}$.

3. Sanlu case study

3.1. *Data sources*

This paper applies the data from the Sanlu contaminated milk powder case study in 2008 to validate and illustrate the models in Section 2. The Sanlu company, as the manufacturer, took responsibility for the contamination that resulted in the kidney

$$x_{FM} = \begin{cases} x^- & \text{if } \beta_m + \beta_F = \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, P \geq \frac{(\beta_m \lambda + \beta_F \lambda + p_m)\frac{Q_0}{q} + c_m + \frac{c_p N}{n_p}}{1 - \gamma}; \text{ or} \\ & \beta_m + \beta_F > \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \frac{\left(P - \gamma P - \frac{c_p N}{n_p} - c_m\right) q - (p_m + \beta_m \lambda + \beta_F \lambda) Q_0}{2\left(p_m + \beta_m \lambda + \beta_F \lambda - \frac{c_p n_m}{n_p}\right) q} < x^-; \text{ or} \\ & \beta_m + \beta_F < \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, U_{FM}\left(x^-\right) \geq U_{FM}\left(x^+\right) \\ x_{interior} & \text{if } \beta_m + \beta_F > \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \frac{\left(P - \gamma P - \frac{c_p N}{n_p} - c_m\right) q - (p_m + \beta_m \lambda + \beta_F \lambda) Q_0}{2\left(p_m + \beta_m \lambda + \beta_F \lambda - \frac{c_p n_m}{n_p}\right) q} \in \left[x^-, x^+\right] \\ x^+ & \text{if } \beta_m + \beta_F = \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, P < \frac{(\beta_m \lambda + \beta_F \lambda + p_m)\frac{Q_0}{q} + c_m + \frac{c_p N}{n_p}}{1 - \gamma}; \text{ or} \\ & \beta_m + \beta_F > \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, \frac{\left(P - \gamma P - \frac{c_p N}{n_p} - c_m\right) q - (p_m + \beta_m \lambda + \beta_F \lambda) Q_0}{2\left(p_m + \beta_m \lambda + \beta_F \lambda - \frac{c_p n_m}{n_p}\right) q} > x^+; \text{ or} \\ & \beta_m + \beta_F < \frac{\frac{c_p n_m}{n_p} - p_m}{\lambda}, U_{FM}\left(x^-\right) < U_{FM}\left(x^+\right) \end{cases} \tag{23}$$

damages of about 3 million infants by selling the contaminated milk powder. The government charged Sanlu a fine of 49.4 million Chinese RMB (about US$7 million in 2008) (Xinhuanet, 2009) and enforced a 902 million RMB compensation to society (Xinhua, 2009).

We reference the data points (Hau, Kwan, & Li, 2009): $(0, 0)$, $(750, 0.2)$, $(1500, 0.5)$, $(3000, 0.7)$, $(6000, 0.9)$, $(12000, 1)$ to estimate the sickness probability of a human being $H(x)$, where the first number in the bracket is the chemical level x in ppm (parts per million) and the second is the sickness probability of rats $H(x)$. The sickness probability function is exponentially regressed as $H(x) = 1 - \exp^{-\lambda x}$, where $\lambda = 389.7$.

(Southern Metropolis, 2008) roughly estimated the total sales amount is $Q(x) = 700,000$ kg as the chemical level $x = 2563$ ppm $= 2.563{*}10^{-3}$ kg/kg (CCTV com, 2009). Based on the milk powder, price is estimated as $P = 25$ RMB/400 g $= 62.5$ RMB/kg (Bloomberg, 2008), we have the coefficient $q = \frac{Q(x)}{x} = 2.73 \times 10^8$, once we assume $Q_0 = 0$.

From (Food Safety Rapid Detection of Network, 2011), we have the range of the amount of protein required in milk powder as $x_p \in (15\%, 20\%)$, and the amount of nitrogen in protein as $n_p = 16\%$. We average the protein amount as $x_p = 18\%$, and have the total amount of nitrogen in 1 kg milk powder as $N = 0.18{*}0.16 = 0.0288$ kg. The nitrogen density from melamine is $n_m = 66.6\%$. The cost of melamine is one fifth of the cost of protein considering the same amount of protein being produced. Based on that, we have the protein price $p_p = \frac{16\%}{66.6\%} * 5 * p_m = 0.84$ RMB/kg. We also have the unit production cost for protein $c_p = 2.2$ RMB/kg (Gale & Hu, 2009), the melamine cost $p_m = 0.7$ RMB/kg (Wong, 2008), and the tax rate for milk powder estimated as $\gamma = 0.17$ (State Administration of Taxation, 2011).

3.2. The Government-Manufacturer-Farmer model in the Sanlu case

3.2.1. Sensitivity analysis of equilibrium strategies

Fig. 6 illustrates the optimal level of chemical x, payment to the farmer P_F, and punishment strategy β with decentralized decision making analyzed as a function of λ, Q_0, c, γ, N, P, n_p, c_p, p_m, n_m and q. It shows that the chemical level x decreases in coefficient of health sickness λ, basic sales demand Q_0, and coefficient of health cost c (Fig. 6 (a, b, c)), while the chemical level x increases in tax rate γ (Fig. 6 (d)). We observe the highest chemical level x, the lowest payment to the farmer by the manufacturer P_F, and the lowest punishment levels β_F and β_M, when there is no health cost. Fig. 6 (d) indicates that the government can leverage the tax rate to reduce the chemical level. The optimal payment to the farmer P_F has the same directional change of x in λ and Q_0. The best punishment strategy to the manufacturer β_M increases in c and λ. The best punishment strategy to the farmer β_F increases in c which demonstrates the government increases punishment β to deter the farmer's risky behavior.

3.2.2. Comparison between the centralized (GMF) and decentralized models (GvMvF)

Figs. 7 and 8 compare the equilibrium chemical levels and societal utilities between the centralized *GMF* model (x_c and U_c, respectively) and the decentralized *GvMvF* model (x_d and U_d, respectively). It demonstrates that x_c is higher than x_d, especially when food price P and slope for sales amount q (Fig. 7 (f, k)) are high, or base sales demand Q_0, tax rate γ, production cost c_p and chemical cost p_m (Fig. 7 (b, d, h, i)) are low. Fig. 8 shows the same conditions hold when U_c is higher than U_d.

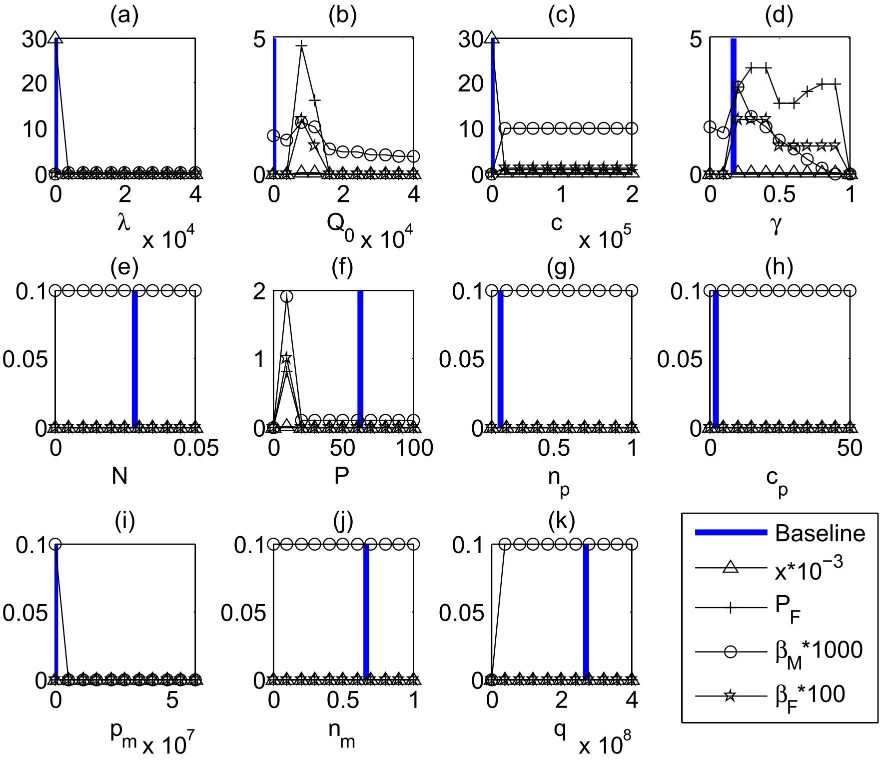

Fig. 6. Optimal Level of Chemical, Payment to Farmer, and Punishment Strategy as Functions of λ, Q_0, c, γ, N, P, n_p, c_p, p_m, n_m and q in the Government-Manufacturer-Farmer Model.

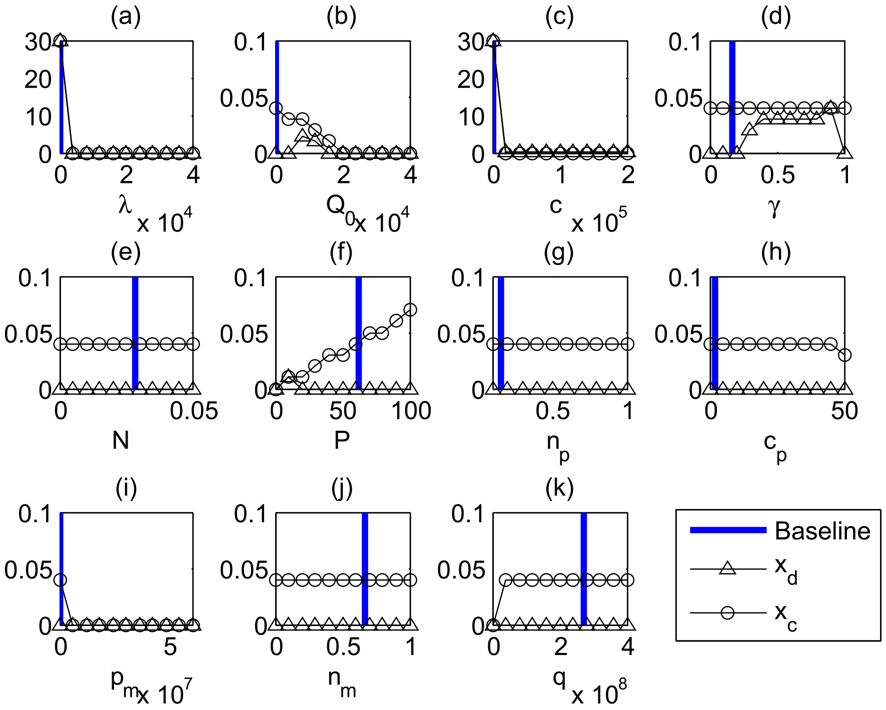

Fig. 7. Comparison between the *GMF* and *GνMνF* models for equilibrium chemical levels.

3.3. *Comparison between the centralized (GνMF) and decentralized (GνMνF) models*

Figs. 9 and 10 compare the equilibrium chemical levels and social utilities between the centralized *GνMF* model (x_c and U_c, respectively) and the decentralized *GνMνF* model (x_d and U_d, respectively). Fig. 9 demonstrates that the chemical level x_c is higher than x_d, especially when food price P and slope for sales amount q (Fig. 9 (f, k)) are high or when sickness slope λ, coefficient of society cost c, tax rate γ, production cost c_p and chemical cost p_m (Fig. 9 (a, c, d, h, i)) are low. Fig. 10 demonstrates that the social utility U_c is higher than U_d, especially when tax rate γ, food price P, and slope for sales amount q (Fig. 10 (d, f, k)) are high or when the sickness slope λ, coefficient for health cost c, production cost c_p and chemical cost p_m (Fig. 10 (a, c, h, i)) are low.

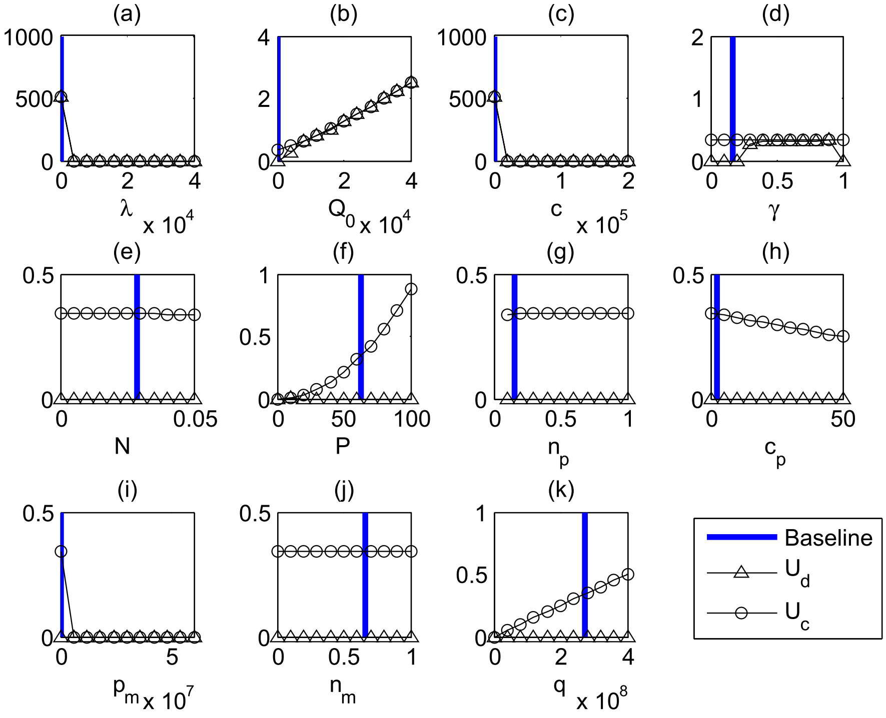

Fig. 8. Comparison between the *GMF* and *GνMνF* models for the social utilities.

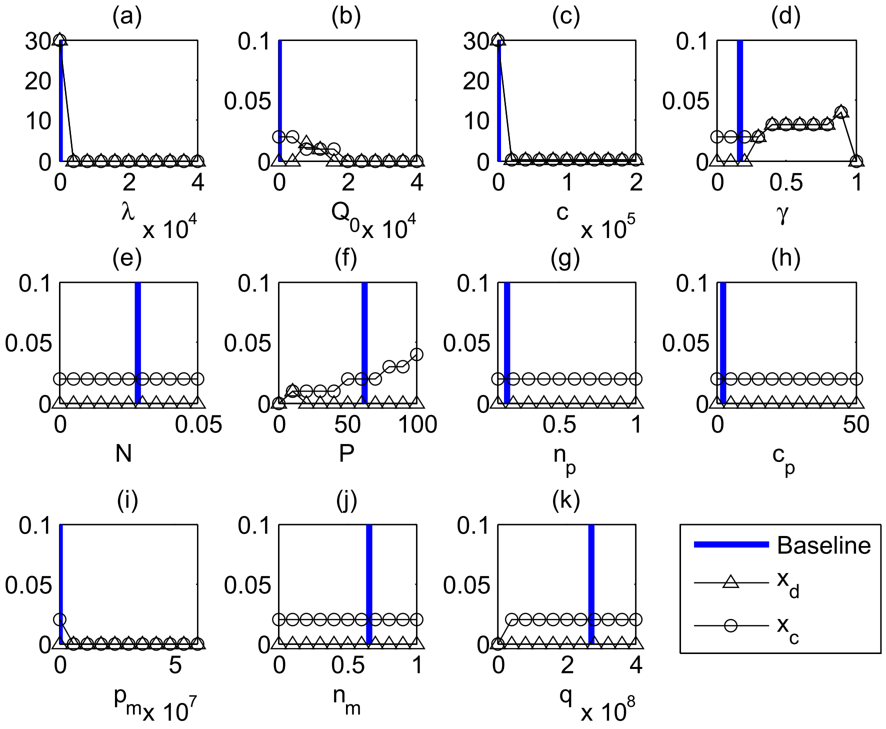

Fig. 9. Comparison between the *GvMF* and *GvMvF* models for equilibrium chemical levels.

3.4. Comparison at all models

Table 2 compares the chemical level x, the punishment to the company β, the social utility U_c, and the government utility U_G among the *GvMvF*, *GMF*, and *GvMF* models. It shows that the *GvMvF* model leads to the lowest chemical level x and sickness probability $H(x)$, the *GvMF* model leads to the highest government utility U_G, and that the *GMF* model leads to the highest social utility U_c and the highest sales amount $Q(x)$.

4. Conclusion and future research directions

In the food supply chain, it is important, but challenging, for the government to regulate the risky behavior of farmers and

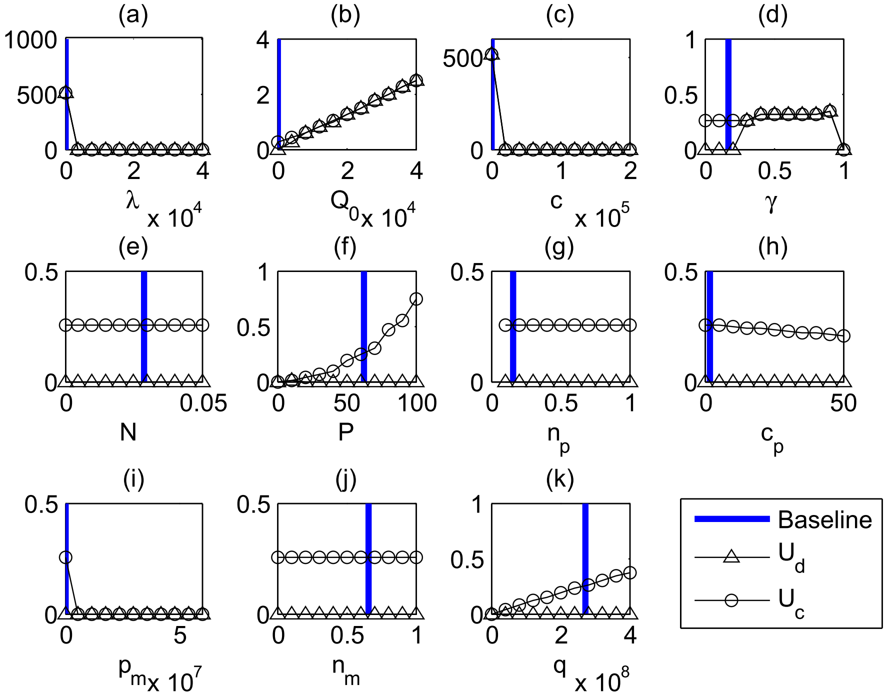

Fig. 10. Comparison between the *GvMF* and *GvMvF* models for the social utilities.

Table 2
Comparison among the *GvMvF*, *GMF*, and *GvMF* models.

	x	β_M	β_F	U_c	U_G	U_F	U_M	$Q(x)$	$H(x)$
GvMvF	0	0	1400	0	0	0	0	0	0
GMF	4×10^{-5}	N/A	N/A	340377	N/A	N/A	N/A	10920	0.015
GvMF	2×10^{-5}	30	4400	254309	159748	N/A	N/A	5460	0.008

manufacturers who may add excessive chemical additives. Such regulations are further complicated by the factors such as sales profit, tax income, punishment income, and consumer health risks. This paper builds up a Government-Manufacturer-Farmer model with three players, which details and quantifies the risky behaviors in the process of supply chain risk management. The analytical solution for farmer's chemical level and manufacturer's payment are provided. The three players' corresponding equilibrium strategies are numerically illustrated, where the chemical level increases in the milk payment to the farmer when it is low, and decreases in the punishment to the farmer. The manufacturer's payment to the farmer decreases in the government punishment policy. At this point, since there are two types of government punishments corresponding to both the farmer and manufacturer, and in order to avoid the farmer's risky behavior, our suggestion is: (a) the punishment to the farmer should not be too low to deter farmer's risky behavior; and (b) the punishment to the manufacturer should not be too high, otherwise it would affect the farmer's benefit from the manufacturer's payment to the farmer, and lead farmer to add chemical additives. The sensitivity analysis of equilibrium strategies indicates that the government can leverage the tax rate to reduce the chemical level.

One decentralized Government vs. Manufacturer vs. Farmer (GvMvF) model and two centralized (Government-Manufacturer-Farmer GMF, and the Government vs. Farmer-Manufacturer GvMF) models are analyzed. This paper applies the real data from the 2008 Sanlu milk powder contamination case to the three models. We demonstrate that (a) the optimal chemical level in the centralized GMF model is higher than that in the decentralized GvMvF model, especially when the food price and the slope for sales amount are high, or the base sales demand, tax rate, production cost, and chemical cost are low; and (b) the optimal chemical level in the centralized GvMF model is higher than that in the decentralized GvMvF model, especially when the food price and the slope for sales amount are high, or when the tax rate, sickness slope, coefficient of society cost, production cost and chemical cost are low. Finally, we compare all three models and find out the decentralized GvMvF model leads to the lowest chemical level and sickness probability, the GvMF model leads to the highest government utility, and the centralized GMF model leads to the highest social utility and the highest sales amount. This means that the government should not cooperate with the farmer for the lower use of chemical additives and sickness probability. Additionally, the farmer should not cooperate with the manufacturer for the lower sickness probability and government's punishment. This paper demonstrates the origin cause of the farmer's risky behavior and direct and indirect effect of the manufacturer and government's behavior decisions. It provides some novel government punishment policy insights and farmer/manufacturer strategies for the food supply chain risk management. It could give some managerial insights for manufacturers on the payment to the farmer and whether to control the quality of milk.

Some future research directions include: (a) considering the government tax policy as a decision variable affecting the manufacturers' and farmers' risky behaviors; (b) modeling the farmers' and manufacturers' non-strategic behaviors; (c) analyzing the competitions between manufacturers or between farmers; and (d) considering the different effects of chemical additives on the food's perishing rate in a dynamic model.

Acknowledgements

This research was partially supported by the United States National Science Foundation (NSF) under award numbers 1200899 and 1334930. This research was also partially supported by the United States Department of Homeland Security (DHS) through the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) under award number 2010-ST-061-RE0001. In addition, this research was partially supported by the Beijing Natural Science Foundation under award number 9174040, Beijing Social Science Foundation under award number 16GLC076 and Science Foundation of China University of Petroleum, Beijing under award numbers 2462014YJRC051 and 2462015YQ0722. However, any opinions, findings, conclusions, or recommendations in this document are those of the authors and do not necessarily reflect views of the sponsors. We thank anonymous reviewers for constructive comments.

A. Appendix

A.1. Influence diagrams for the players

Fig. 11 shows an influence diagram (Clemen & Reilly, 2001) of the manufacturers' or farmers' decisions on food additives affected by chance nodes and intermediate value nodes. One chance node is the “Government Inspects & Punishes,” and another chance node is “Potential Sickness,” where customers could get sick once consuming the contaminated food. Both chance nodes could directly affect the level of penalty cost to manufacturers and farmers. The intermediate values (penalty cost, chemical cost, and sales profit) eventually determine the net profit values.

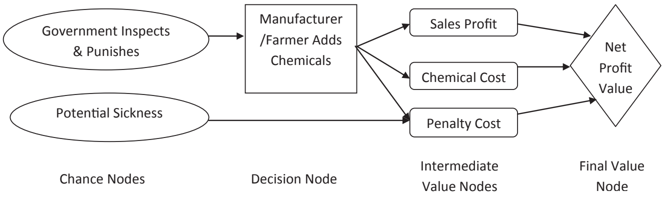

Fig. 11. Influence diagram for the manufacturer's or farmer's risky behavior.

An influence diagram of the government's decision making on the punishment policy to the farmers or manufacturers is shown in Fig. 12. Two chance nodes are “Potential Sickness” and the farmer's or manufacturer's “Chemical Level,” (amount of chemical additive) both affecting the intermediate values (tax income, penalty income, and health cost) that eventually determine the government's net

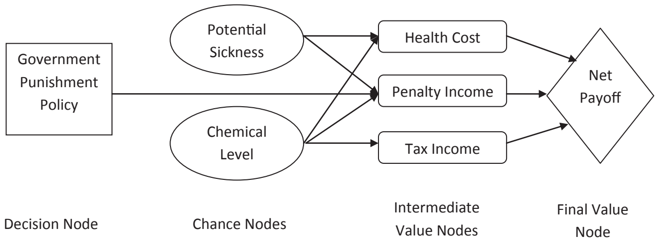

Fig. 12. Influence diagram for the government's punishment policy.

payoff.

A.2. Proof of proposition 1

(i) If $\beta_F > \frac{a}{\lambda q}$ and $\frac{b+P_F q-\beta_F\lambda Q_0}{2(\beta_F\lambda q-a)} \in [x^-, x^+]$, we get the interior point $x_{interior} = \frac{b+P_F q-\beta_F\lambda Q_0}{2(\beta_F\lambda q-a)}$ by setting $\frac{\partial U_F(x)}{\partial x} = 0$.where

$$a = q\left(\frac{c_p n_m}{n_p} - p_m\right)$$

$$b = -p_m Q_0 - \frac{c_p N q}{n_p} + \frac{c_p n_m Q_0}{n_p}$$

If $\frac{b+P_F q-\beta_F\lambda Q_0}{2(\beta_F\lambda q-a)} < x^-$, then $\widehat{x} = x^-$. If $\frac{b+P_F q-\beta_F\lambda Q_0}{2(\beta_F\lambda q-a)} > x^+$, then $\widehat{x} = x^+$.

(ii) If $\beta_F = \frac{a}{\lambda q}$ and $P_F q - \beta_F\lambda Q_0 \le -b$, then $U_F(\widehat{x}(P_F,\beta_F),P_F,\beta_F)) = (b + P_{Fq} - \beta_F\lambda Q_0)x + P_F Q_0 \frac{c_p N Q_0}{n_p}$ is a linear function. When $b + P_F q - \beta_F\lambda Q_0 \le 0$, the optimal x would be at the lower bound x^-, otherwise it would be at the upper bound x^+.

(iii) If $\beta_F < \frac{a}{\lambda q}$, the optimal chemical level would be at the bound that has the highest utility U_F.

A.3. Proof of proposition 2

The manufacturer's utility function is rewritten below:

$$\max_{P_F \ge 0} U_M(\widehat{x}(P_F,\beta_F),P_F,\beta_M) = a'P_F^2 + b'P_F + c'$$

where $t = 2(\beta_F\lambda q - a) > 0$, $a' \equiv -\frac{q^2(t+\beta_M\lambda q)}{t^2} \le 0$, $b' \equiv \frac{tq^2(1-\gamma)P - Q_0(t+\beta_M\lambda q)t - 2q^2\beta_M\lambda(b-\beta_F\lambda Q_0)}{t^2} - \frac{c_m q^2}{t}$, and $c' \equiv \left[\left(Q_0 + \frac{q(b-\beta_F\lambda Q_0)}{t}\right)\left(\left(1-\gamma\right)P - \frac{\beta_M\lambda(b-\beta_F\lambda Q_0)}{t}\right)\right] - c_m Q_0 - \frac{c_m q(b-\beta_F\lambda Q_0)}{t}$.

(i) When $t > 0, \frac{b'}{-2a'} \in \left[\frac{tx^- - b + \beta_F\lambda Q_0}{q}, \frac{tx^+ - b + \beta_F\lambda Q_0}{q}\right]$, then

$\widehat{x} = \frac{b+P_F q-\beta_F\lambda Q_0}{2(\beta_F\lambda q-a)}$. With $\frac{\partial U_M(x)}{\partial P_F} = 2a'P_F + b'$, we can get the interior solution $\widehat{P_F}(\beta) = \frac{b'}{-2a'}$ by setting $\frac{\partial U_M(x)}{\partial P_F} = 0$. The optimal chemical level $\widehat{x}$ could also be at a lower bound x^- or at an upper bound x^+.

(ii) When $\widehat{x} = x^-$, $U_M(P_F) = (P - P_F)Q(x) - \beta_M Q(x)H(x) - \gamma PQ(x) - c_m Q(x) = -P_F(Q_0 + qx^-) + (P - \gamma P - c_m)(Q_0 + qx^-) - \beta_M(Q_0 + qx^-)\lambda x^-$. Since U_M decreases in P_F, we have $\widehat{P_F}(\beta_M) = 0$.

(iii) When $\widehat{x} = x^+$, $U_M(P_F) = (P - P_F)Q(x) - \beta_M Q(x)H(x) - \gamma PQ(x) - c_m Q(x) = -P_F(Q_0 + qx^+) + (P - \gamma P - c_m)(Q_0 + qx^+) - \beta_M(Q_0 + qx^+)\lambda x^+$. Since U_M decreases in P_F, we have $\widehat{P_F}(\beta_M) = 0$.

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