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Three essays on food safety and foodborne illness

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ABSTRACT

This dissertation explores economic impacts of food related illness on agricultural industries and models the performance of food safety programs on supply chain participants. Three stand-alone studies are dedicated to economic analysis on food safety issues from different approaches analytically, empirically, and in simulation.

In response to recent outbreaks of food-borne illness, the fresh produce and fruit industries have adopted marketing agreements to ensure the consistency of food safety. Chapter 2 presents a theoretical framework and simulation analysis to illustrate farmers' behavior on implementing Good Agricultural Practices (GAPs), and the design of monitoring strategies in setting marketing agreements. It reveals that, if the monitoring resources are not high enough to achieve full compliance on GAPs, the general rule is to allocate resources so that the total amount of decreased fraud in terms of safety effort is the same for all farms. When auditing resources are very low, the size effect is dominant and larger farms are inspected first; when auditing resources are large enough, the cost effect is dominant and smaller farms are inspected first. The optimal auditing probability for smaller farms increases faster than that for larger farms.

Contracts now are widely used between processors and growers to specify product quality and safety attributes. Chapter 3 employs a multitask principal-agent model to analyze the optimal incentive structure in contract food production. It offers guidance on understanding contractual relations for both food quality and food safety, and how the inclusion of a traceability system influences the provisions of the contract.

Recent outbreaks of highly pathogenic avian influenza (HPAI) in Asia, Europe, and Africa have caused severe impacts on the broiler sector through production loss, trade restrictions and negative demand shocks. Chapter 4 presents a multimarket econometric model to conduct simulation analyses on the spread and market implications of a potential HPAI outbreak in U.S. broiler industry. It takes into account market power that might exist within the livestock and meat sectors and makes endogenous the optimal production conditions in the model system. Findings from the analysis imply that the HPAI shocks impact prices at different marketing levels unequally and change the price margin along the supply chain with the existence of market power. However, the change in the price margin is quite small in absolute value.

CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Numerous food scares and crises have occurred over the past few years in the US food supply chain, even though it is considered one of the safest in the world. Failure to protect the safety of food leads to a decline in consumer confidence in the safety of many food products and threatens the economic vitality of agricultural industries through economic relationships. Thus, the need to evaluate economic losses associated with food safety problems and to develop strategies to improve food safety throughout the supply chain has become a concern for both the government and agricultural industries. As a consequence, many programs have been developed by industry organizations or government agencies to reduce the risk of food contamination. Individual growers have also responded to increased concerns about foodborne illness by implementing food safety improving activities. The main theme of this dissertation is to understand the economic impacts of food related illness on agricultural industries and the performance of food safety programs on supply chain participants.

To reduce foodborne illness in fruits and vegetables, Good Agricultural Practices (GAPs) have been developed for use by growers to ensure more consistent food safety outcomes. These agricultural practices act as guidelines for many marketing programs. The first topic of this dissertation, presented in Chapter 2, relates to a voluntary marketing agreement which was initialized by Western Growers in California. The agreement requires all signatory handlers to purchase only product from growers who adhere to newly developed Good Agricultural Practices (GAPs). Through regular on-farm control and inspection, third party inspectors (or public regulators) monitor compliance and provide a credible signal to resolve the lack of information in the market. The primary incentive for the farms to join in the program is not to get high price premium but to minimize the risk of potential losses of market share. At the same time, marketing agreements along with Good Agricultural Practices can provide consumers with a substitute for the information and trust they lack.

Marketing agreements, however, are susceptible to opportunistic behaviors. Food safety attributes are credence qualities which cannot be directly ascertained. Although consumers may prefer high-safety products to low-safety ones, they may not be able to tell the difference between the two. Farmers face the use of GAPs as an increased cost of producing the product. The existence of the cost gap between low and high-safety products with no apparent product difference to consumers provides an incentive for farmers not to comply with the full set of requirements. In the meanwhile, the reliability of the marketing agreement on enhancing food security depends on monitoring processes and their implementation. A farmer may decide to shirk in efforts to adopt and apply GAPs when monitoring activity is imperfect and costly. Therefore, the analysis of marketing agreements should account for the possibility of opportunistic behaviors. This study explores the marketing agreement's performance on farmer decisions. The design of an optimal monitoring scheme varies with constraint monitoring resources on heterogeneous farms in terms of farm size.

The analysis of agreements considers a market framework which consists of a continuum of farms with a credence food product. The on-farm inspection of the compliance with GAPs has two possible realizations: a farm either passes the inspection test to get the market price, or fails the test and receives a diverted price. Once a food incident happens, the final consumers' demand will be affected. The negative consequences of a food safety problem affect the industry in a collective way. At the same time, once a farm is traced back as producing unsafe product, it incurs an additional cost which may include the direct cost of liability, product recalls, market-imposed penalties and other fines levied due to the food crisis. The optimal level of effort invested by the farmer and the necessary monitoring rate to guide the farmer to achieve full compliance is derived from the model. Once committed to the agreement, farmers adopt different production decisions according to their individual farm size. Based on the assumption that the objective of the monitoring agency is to maximize total producers' surplus, we obtain a scheme for distributing constrained monitoring resources. For the purposes of illustrating the implications of the model, the market for fresh strawberries in California is simulated.

The fruit and vegetables industry is extensively vertically coordinated in the United States and contracts are widely used between processors and growers. The provisions of a basic processing fruit and vegetables contract may include many issues, and among them product quality usually plays an important role in a contract. Recent outbreaks of food-borne illness related to fruit and vegetables have triggered many industries to identify specific GAPs for adoption by growers on farm level to prevent food contamination. Many retail and foodservice buyers now demand that food suppliers adhere to some performance-based standards or specific criteria and target values for control and monitoring of product. Therefore, the processor pays more attention to food safety attributes and expects the grower to exert effort to make sure food is safe. However, food safety is difficult to observe and measure, and the payoff for improved food safety is poorly contractible.

A potential way to provide the grower an incentive to exert the effort needed to produce safe product is by implementing traceability systems in food supply chains. With a traceability system, the source of unsafe products can be identifiable to some extent. If a grower is identified as the source of a food safety problem, the grower faces costs associated with the failure such as penalties and/or market loss, and the processor faces losses associated with disrupted input supply or market loss due to the safety failure in the processed product. The existence of traceability systems can be looked on as an indirect way to provide safety assurance and thus the provision of product safety can enter into a contract. Although safety is a component of quality, safety improvement activities frequently are not included in quality improvement activities. Activities on improving safety may be independent, complementary, or act as substitutes for quality.

The objective of the second topic of this dissertation, Chapter 3, is to examine how the interaction between safety effort and quality effort influences the grower's incentives, and to identify how a traceability system may affect contract provisions and mitigate the grower's problem of moral hazard.

We first construct a benchmark model in which a traceability system is absent. The processor minimizes the expected compensation by designing a payment scheme to induce high quality effort only. Next, the contract design with fully observable safety effort is examined. The grower performs two activities with respect to quality and safety efforts with the same production process. The two activities affect the stochastic production process simultaneously. Then, the incentive structure with a tractability system is developed that employs a multitask principal-agent model. In this case, the efforts provided by the grower in both quality and safety cannot be directly observed by the processor, and the measured quality level and whether there is a food accident or not is verifiable. A simultaneous shirking deviation along both quality and safety efforts dimensions may occur. For each form of contract we derive the conditions under which the contract is efficient, and examine the distribution of payoffs. We also obtain the extent to which contracts overcome adverse selection problems. The predictions of the theoretical model are given by simulation experiments.

The third topic of this dissertation, Chapter 4, relates to the recent outbreaks of highly pathogenic avian influenza (HPAI) in Asia, Europe, and Africa, an avian disease which has been recognized as a great threat to broiler production, wildlife conservation and public health. Outbreaks of HPAI have caused major changes in demand, additional input use to producers, and price volatility which could induce dramatic market instability. The United States exports more poultry products than any other country in the world. When export markets are taken into account, even a relatively small outbreak has the potential to cause a large welfare loss, especially if trade is restricted. Although mainly affecting the broiler sector and egg sectors, an HPAI shock is expected to influence other related livestock sectors as well.

To understand the potential welfare effects of HPAI, we consider the transmission of HPAI shocks through various stages of the broiler supply chain and through other livestock and related agricultural markets. The impacts of shocks are determined by the behavior of market agents who are involved in the transactions. Price characterizes the linkages between markets. It has been argued that food scares may have differential effects on upstream suppliers and downstream users. Even though the causes of asymmetric price transmission are complicated and multidimensional, market power is a possible important explanation for this differential.

Livestock and meat sectors are increasingly vertically integrated in the United Stated. The linking of successive stages of production and marketing through ownership or contracting is widespread. This vertical integration in the meat industries generally increases market power and could increase welfare loss from an HPAI outbreak. The principle objective of this research is to conduct an HPAI risk and cost analysis while accounting for potential market power within the whole meat supply chain.

A theoretical model is developed to illustrate the potential impacts of market power on the price margin and the distribution of economic welfare following a food scare such as an HPAI outbreak. If market power exists, the exogenous shocks influence the prices on different supply chain stages to varying degrees. As a result, the price margin might be widened or narrowed depending on the demand elasticities as well as interactions of exogenous shifters. We then construct an empirical model to estimate simultaneously the demand for five meat products in the United States. In order to examine the potential impacts of market power on price reaction elasticities, the "integrated" firm's profit maximization conditions are considered to be endogenous in the demand system.

An epidemiological-economic model is developed to simulate the spread and effects of the disease in the poultry and other meat sectors. The economic model is a multimarket partial equilibrium model and provides a complete depiction of key biological and economic relationships within five livestock and meat industries. The simulated market scenarios are classified according to the length and severity of the outbreak, number of birds removed from the market, percentage reduction in domestic and export demand for poultry products, duration of the demand shock, assumptions on diversion, and use of product destined for export markets. Since it is challenging to know in advance the range of an outbreak, this study examines three possible scenarios of the extent of HPAI on broilers and layers: high, medium and low. The data used are obtained from USDA/ERS and NASS. The estimation is based on a sample consisting of 96 quarterly observations that cover the period 1981:1 - 2004:4. The model is also calibrated by dynamic simulation over the same periods. The baseline projections are developed in the first quarter of 2000 and cover the period 2000:1-2004:2. Effects of alternative scenarios are measured relative to this period. The firm-level production impacts and market-level changes in equilibrium prices and output are evaluated.

1.2 Organization of the dissertation

This dissertation carries out the economic analysis of agricultural programs and supply chain dynamics with explicit consideration of food safety issues. While each of these chapters can be viewed as a stand-alone study, they are all dedicated to an examination of the economic impacts of foodborne illnesses. A brief overview of the remainder of this dissertation is outlined as follows:

- Chapter 2 examines the performance of a marketing agreement on the farmer's behavior in implementing Good Agricultural Practices and designs an optimal monitoring scheme for the auditing agency.
- Chapter 3 develops a multitask principal-agent model to examine contractual relations to both food quality and food safety, and how the inclusion of a traceability system in a contract influences the behavior of growers and processors as well as a contract provision to overcome moral hazard problems.
- Chapter 4 conducts an HPAI risk and cost analysis for the United States while accounting for potential market power within the whole meat supply chain.

- Chapter 5 highlights the findings and their implications on the three topics discussed in this dissertation and outlines future directions.

CHAPTER 2. MARKETING AGREEMENTS, OPPORTUISTIC BEHAVIORS AND FOOD SAFETY DETECTION

2.1 Introduction

Recent outbreaks of food-borne illness have raised concern about food safety and their effects on human health. A publicized food scare can damage the consumers' trust in the safety of the affected product, which can lead to a decrease in demand and losses to the industry. For example, contamination of fresh spinach with the bacteria E.coli O157:H7 in Fall 2006 killed three people and made more than 4000 people sick. Spinach sales went down by 30 percent after the break and, for the most part, recovered within six months (Seltzer et al. 2009).

Markets fail to offer the efficient level of safety for several reasons (Unnevehr and Jensen 1996). Since food safety attributes are credence qualities which cannot be directly ascertained through inspection or consumption (Darby and Karni 1973), consumers may not be able to tell the difference between a safe product and an unsafe product although they prefer the safe one. On the supply side, the level of effort exerted to deliver a safe food is private information and the food supplier can shirk in efforts to supply the level of safety consumers would demand with full information.

To reduce food borne illness in fruits and vegetables, Good Agricultural Practices (GAPs) have been used as food safety guidance for growers to adopt on critical production steps to ensure the consistency of food safety. GAPs are designated practices that lead to food or agricultural products with attributes that are valued in the marketplace (Hobbs 2003). According to Hobbs (2003), GAPs can be classified as (i) private industry supply chain GAPs, where suppliers work with a specific processor, exporter or retailer in a closed supply chain; (ii) industry group GAPs, where the GAPs are established by an industry association; (iii) national government-initiated GAPs; and (iv) international agencies-initiated GAPs. To guarantee trust and transparency, GAPs are designed to have detailed production standards covering all aspects of on-farm production activities. These agricultural practices act as guidelines for many voluntary marketing programs.

In response to the spinach outbreak in 2006, Western Growers initiated changes in the California Marketing Agreement. The new agreement requires all signatory leafy greens handlers to purchase only product from growers who adhere to newly developed Leafy Greens Good Agricultural Practices. The standards and practices proposed by the agreement were tighter than those the government already had in place. Under the new marketing agreement, farms can enroll the program voluntarily and be awarded a certification mark for implementing the GAPs. The certification allows the farms to distinguish their output from those without certification. Farms need to communicate product safety to consumers or downstream purchasers, and offer the opportunity to enhance their profit as a differentiated product. From the perspective of downstream suppliers, certification is useful for sourcing vegetable supply from quality farms. Retailers, especially supermarkets, have increasingly turned to the adoption of GAPs with preferred farms (suppliers) as a means to differentiate their fresh produce from that of traditional wholesale markets on the basis of cleanliness and the provision of greater assurance of handling safe products. The assurance that the certification provides ensures consumers of safer food from reliable sources.

Marketing agreements, however, are susceptible to opportunistic behaviors. Despite consumers' increased demand for safe foods, farmers face higher costs through the use of GAPs. Once the farm has committed itself to fulfill the agreement's requirements, the existence of a cost difference between low and high safety foods provides an incentive not to comply with the full set of requirements. Moreover, since all participants in the marketing agreement can benefit from a higher reputation in general, individual farms have an incentive to invest less in safety activities. Farms may choose to partially free-ride on the effort provided by others. Thus, voluntary activities motivated by private incentives provide less safety assurance than would be in the interest of the whole industry; fraudulent behaviors become possible when monitoring activity is imperfect and costly. Free-riding behaviors could alter the credibility of the marketing agreement and even lead to its collapse. Therefore, analysis of marketing agreements should account for the possibility of opportunistic behaviors. However, to date, there has been little discussion about farmers' behavior and the design of management strategies in the setting of marketing agreements.

The objectives of this paper are twofold. First, we use a theoretical model to explore a marketing agreement's effect on farmers' decisions. Second, we examine how the optimal monitoring policy varies with the level of constrained monitoring resources when farms are heterogeneous in terms of farm size.

Our analysis is related to previous literature that addresses the economic implications of food certification programs. Fields of application concern both food safety and the environment. Examples include the role of labeling (Caswell and Padberg 1992; Crespi and Marette 2003; and Golan et al. 2001), financing methods for food safety certification (Crespi and Marette 2001), whether certification systems should be mandatory or voluntary (Segerson 1999), and the welfare impacts of certification policies (Zago and Pick 2004). Although all consider aspects of food certification, these studies make the assumption of perfect certification. Specifically, the approaches used consider that certification can differentiate completely between high safety and low safety products. There are no low safety products in the high safety market. Under this assumption, the process of monitoring and enforcement is not considered explicitly. In contrast to these studies, our model allows for the existence of opportunistic behaviors. Monitoring effort plays an important role in detecting low safety foods disguised as high safety ones, and its inclusion leads to rather different conclusions regarding the market outcomes.

Lack of information or asymmetric information in markets is a major source of market failure. Since the pioneering work of Akerlof (1970) and Klein and Leffler (1981), many studies have investigated the causes and remedies of market failures caused by asymmetric information on product quality. A variety of mechanisms have been proposed to identify the characteristics of products and to obtain suboptimal equilibria resulting from information problems. The mechanisms used include identification of price differences (Shapiro 1983), signaling and reputation (Kreps and Robert 1982; Shapiro 1983), and advertising (Nelson 1970). These types of solutions, however, become problematic for food products which have credence qualities. More recent studies have considered the relationship between food safety and asymmetric information. For example, Elbasha and Riggs (1999) investigate the double moral hazard problem present in food markets. Fox and Hennessy (1999) examine the trade-off between regulation of food quality control and economic damage. Carriquiry and Babcock (2004) develop a repeated purchase model to investigate the different choices of quality assurance systems for producers and the role of reputation.

With asymmetric information, the ability to audit becomes important to the functioning of markets. This aspect has given rise to literature focusing on the problem of imperfect certification and the role of testing (Darby and Karni 1973; De and Nabar 1991; Polinsky and

Shavell 1992; and Starbird 1997). Starbird (2005) examines the impact of inspection policies on consumer and producer's strategies using a principal-agent approach. Marette (2005) addresses the relationship between financing of enforcement and market structure. Mason and Sterbenz (1994) study the effects of an imperfect test of product quality on the strategies of producers and on how adverse selection affects market size. These papers lead to some interesting and different comparative static results for the effects induced by changes in test cost and accuracy compared with those of a perfect test.

Especially relevant to our study are the studies that address how the possibility of fraud affects the producer's behavior and choice of product. This includes whether mechanisms in markets may induce non fraudulent behaviors (Emons 1997; 2000), game-theoretic approaches to making false claims on product quality (McCluskey 2000), and consequences of mislabeling for consumer behavior and welfare (Giannakas 2002). The certifiers' role as intermediary between producers and consumers has also been explored in the certification problem (Biglaiser 1993; Lizzeri 1999; and Nunez 2001).

Fruits and vegetables are different from the other certified (non-food) products in their inelastic supply in a short run. Our study of the marketing agreement and optimal monitoring policy extends extant literature by (1) examining the relationship between the producer's behavior and optimal monitoring policies when monitoring resources are limited; and (2) incorporating into our model the probability of a food safety failure and losses due to traceback. The remainder of this paper is organized as follows. Section 2 sets up the model and presents the results of the monitoring policy's effect on farmers' behaviors under an endogenous detection rate. In Section 3 we develop the optimal monitoring policy for farms with different size. Section 4 provides results from simulations. And finally, Section 5 includes conclusions and summary discussion.

2.2 Background and Model Setup

Our analysis is built around the case of a market framework which consists of a continuum of farms with a single food product. In the second stage, these farms join an industrial marketing agreement voluntarily and commit themselves to adopt GAPs on a regular basis to meet the requirements of the auditing agency. In the first stage, the monitoring agency decides its auditing strategies. When individual farms choose whether to participate in the marketing agreement or not, they weigh their private benefit and cost. Price premiums are a tangible revenue-based incentive for farms to adopt GAPs. However, there is no evidence to indicate that farms can receive higher prices even if they are certified. While direct subsidies provide a direct incentive for farmers to adopt GAPs, experience has shown that they may create a supply response that distorts market signals and results in a budgetary burden for taxpayers.

Two important motivations for farms to adopt GAPs are (i) *to minimize the risk of potential market share losses* and (ii) *to reduce the probability of food incidents*. With respect to the first motivation, an outbreak incident may have severe impacts on market share and prices of a food item associated with the outbreak. Processors or retailers seek farms that have participated in the marketing agreement although they need not pay more for the food. For example, in 2003 after hepatitis A outbreaks in the United States associated with green onions from Mexico, the sales of those growers who were not GAPs compliant declined to about half the normal volume, while shipments of growers with third-party audits of compliance with GAPs fell just a bit (Calvin et al. 2004). With respect to the second motivation, applying GAPs can help farms to increase the level of food safety and hence reduce the chance of being linked with a failure or outbreak incident. Farms are interested in both the level of their revenue and its stability over time. Reducing uncertainty over market access assists in stabilizing revenues over the long-run.

2.2.1 Supply and size

To start, farms are assumed to be homogeneous and the total number of the farms is n. The more complex and realistic case that the farms are heterogeneous will be discussed in next section. Let $\bar{y}$ denote farm size in terms of its productive capacity. Farm size is determined by the numbers of acres and the yield per acre, i.e., $\bar{y}$ implies the maximum output of a farm. We assume that the output level chosen by a farmer is his or her predetermined farm size $\bar{y}$ in this study. As Johnson and colleagues (2006) indicated, it is difficult for a farmer to change the level of output in a short run as far as many agronomic and economic constraints are concerned. These constraints may include investing in irrigation and capital investment, hiring more expensive labor to harvest the crop, and developing marketing contacts with processors, etc. Therefore, the total supply of the product is $n\bar{y}$ which is exogenous in the current market period. The more complicated case that supply response changes in the long run are not considered in this analysis.

2.2.2 Monitoring

The strength of the farmer's incentive to invest in GAPs is highly dependent on the ability of the monitoring agency to separate GAP and non-GAP produce. Markets do not always work smoothly for all goods. Imperfect information, which exists when buyers and farmers cannot identify certain characteristics of a product, may reduce the farmer's incentive to adopt GAPs by hindering the development of different levels of food safety. Thus, the provision of credible third party monitoring is crucial to the success of a marketing agreement.

The delineation between private and public monitoring agency has become blurred. In the United States, many auditing agencies are established by an industry association, like the Western Growers, for individual product sectors. The federal government agencies such as the Food and Drug Administration (FDA) and the US Department of Agriculture (USDA) also act as the third party verifier to carry out on-farm audits. A third party may monitor the level of safety effort that the farm implements through inspections of individual farms. We assume the farms participating in monitoring do not generate any externalities on the non-participants. Once committed to a third party agreement, the farm can choose an effort level to meet standards on improving food safety.

2.2.3 Detection and market effects

We assume that safety control is not error-free. If a farm is selected for testing, the level of safety effort is only partly observable in the results the farm has implemented. Let $\rho\left(0<\rho\leq 1\right)$ denote the fixed detection rate of not meeting safety standards. The rate ρ is the conditional probability of detection given that a monitoring event occurs, and it can be considered as detection efficiency. Higher ρ means easier detection. We treat ρ as common knowledge and assume it is same for all farms. Moreover, the detection probability of non compliance with GAPs decreases with the safety effort that the farm has exerted. Parameter $\omega \in [0,1]$ is a measure of the monitoring probability selected by the monitoring agency and it is assumed to have linear, negative relationship with the effort level θ. Therefore, $\rho\omega(1-\theta)$ is the true probability that non-compliance is detected.

Once a food incident happens, the final consumers' demand will be affected. The negative consequences of a food safety problem affect the industry in a collective way. Linear equation $D = (d_0 - d_1 p_g)(1 - h(\varepsilon))$ is specified to represent the demand for the product, where p_g denotes the grower's price and ε denotes the possibility of a food incident. The impact of the shock on the demand is captured by $h(\varepsilon)$, where $h^{'}(\varepsilon) > 0$. The equilibrium price p_g can be solved for by the market clearing process $D = n\bar{y}$. The effectiveness of the marketing agreement depends on how it can reduce the outbreak possibility ε and its severity. We assume $\varepsilon = \varepsilon(\bar{\theta})$, implying that the probability of an incident is determined by the average effort level applied in implementing GAPs in the market. The average effort level $\bar{\theta}$ is assumed to be exogenous and the farms take it as given. All farms can benefit from the marketing agreement by increasing the average level of safety effort in the market and reducing the possibility of food-related risks and the negative demand shock that would follow.

Consider the simplest possible case in which inspection has two possible realizations: the farm either passes an inspection test on compliance with GAPs to get grower's price p_g or fails the test. If a safety failure is detected, the farm will lose its entire market share. Chalfant et al. (2002) indicated that high safety vegetables and fruits are sold for fresh consumption, whereas low safety produce is diverted for manufacturing uses and can only get the diverted price. We denote p_p as the diverted price. Note that p_p may be zero if the product cannot be sold. We measure the price difference p, p_g relative to p_p, by defining $p = p_g - p_p$. The substitution of the demand function in prices p and $p^{'}$ leads to the expected price difference

$$\overline{p} = (1-\varepsilon)\,p + \varepsilon\,p^{'} = (1-\varepsilon)\left(\frac{d_0 - n\overline{y}}{d_1} - p_p\right) + \varepsilon\left(\frac{d_0 - n\overline{y}/\big(1-h(\varepsilon)\big)}{d_1} - p_p\right) \qquad (2.1)$$

where p and $p^{'}$ imply the price difference under the case of an incident and no incident, respectively. Based on the above assumptions, the representative farmer's expected revenue can be expressed as

$$TR = \left(p_p + \overline{p} - \overline{p}\rho\omega(1-\theta)\right)\overline{y} \qquad (2.2)$$

which means the true market value to the farmer of growing one unit of product is the expected market price minus the loss from a detection failure.

2.2.4 Costs

Under the marketing agreement, the costs of an individual farm include two parts. The first part is production costs which are not dependent on safety effort. In reality, production costs include both fixed costs and variable costs. Fixed costs include mainly machinery ownership costs and some labor costs. The labor that is accounted for a fixed cost is supplied by the operator, family, or it is permanent hired labor. The variable costs include expenses on seed, fertilizer, chemicals, fuel, insurance, and variable (hourly) labor. The production cost is assumed to subject to the rule of diminishing returns for production and is specified as a quadratic form $c_a\bar{y}^2/2$.

The second part is compliance costs for GAPs which include recurrent and non-recurrent costs. The major components of non-recurrent costs are investments in harvesting and storage equipment, energy and waste management or investments to improve farmer worker safety. The recurrent compliance costs mainly include higher labor requirements such as training workers to improve hygiene in the fields, upgrading recordkeeping systems, etc. Survey results (Chemnitz 2007, Wood et al. 2005) suggest that large farms benefit from economies of scale in terms of compliance costs.

We specify compliance costs in a form similar to that proposed by Marette (2007), $c(\bar{y})\theta^2\bar{y}$, where $c(\bar{y})$ represents the marginal compliance cost and depends on farm size $\bar{y}$. Individual farms also take into account costs related to traceback in the case of an incident. For example, the *E. coli* outbreak in 2006 was quickly traced to the farms in San Benito or Monterey County in California. Once a farm is identified as producing unsafe product, it causes an additional cost per unit of value f which includes the direct cost of liability, product recalls, market-imposed penalties and other fines levied due to a safety outbreak. Let $\bar{z}(1-\theta)$ be the probability of being identified as a possible source when an incident happens, where $\bar{z}$ is exogenous and can be treated as traceability efficiency.

Obviously, higher safety effort level reduces the chance of being identified as a source and taking responsibility. Thus, the overall cost of traceback for an individual farm is $f\varepsilon\bar{z}(1-\theta)\bar{y}$. Taking the assumption that the total costs are completely separable, the total cost of the farm to participate in the marketing agreement is expressed as

$$TC = c\left(\overline{y}\right)\theta^2\overline{y} + c_a\overline{y}^2 / 2 + f\varepsilon\overline{z}\left(1-\theta\right)\overline{y} \tag{2.3}$$

The farmer takes inspection rate ω and output $\overline{y}$ as given and supplies θ to maximize his or her expected profit. Suppose for the moment that the monitoring agency does not engage in monitoring and enforcement activities $\left(\omega = 0\right)$. The farmer is not afraid of being caught as not complying with GAPs, but he is still afraid of having unsafe produce traced back to his or her operation. The optimal amount of safety effort can be determined as $\theta_n = f\varepsilon\overline{z} / 2c\left(\overline{y}\right)$, which means the farmer adopts GAPs voluntarily to reduce food-borne risk even in the absence of monitoring. Under the environment of monitoring, the farmer can determine the probability that the production process meets the requirements of GAPs. The optimal level of effort invested by the farm is

$$\theta^* = \frac{\overline{p}\rho\omega + f\varepsilon\overline{z}}{2c\left(\overline{y}\right)} \tag{2.4}$$

We can find that the farmer exerts more effort with monitoring compared with the case without monitoring, i.e., $\theta^* > \theta_n$. Equation (2.2)-(2.4) indicate that the increase in safety effort generates two opposing effects. On one hand, it increases expected revenue by enhancing the chance for passing the on-farm examination and reducing the probability of being traced with a safety problem; on the other hand, the increase of safety effort brings higher compliance cost.

With the increase in monitoring rate, the farmer implements more safety effort. Thus the monitoring activities have a deterrent effect on fraudulent behavior. From equation (2.4), the necessary monitoring rate to guide the farm to achieve perfect compliance is

$$\omega_1 = \frac{2c\left(\overline{y}\right) - f\varepsilon\overline{z}}{\rho\overline{p}} \tag{2.5}$$

What we should mention here is that full compliance production can be obtained only if the exogenous detection satisfies $\rho \geq \rho^c = \left(2c\left(\overline{y}\right) - f\varepsilon\overline{z}\right)/\,\overline{p}$ to guarantee that the inspection probability is less than 1.

2.3 Farms differ in their size

Farmers adopt GAPs if expected benefits exceed expected costs. However, not all farmers make the same decision with respect to production strategies. Once committed to an agreement, farmers would adopt different production decisions according to their individual characteristics. As relative returns change along with farm size, market conditions, technological advancement, or government policies, land use and safety investment patterns tend to adjust according. Among these factors, farm size is an important one that influences the farmer's decision on safety effort level. In this study, we only consider heterogeneity in terms of farm size and assume that farms are homogenous in other factors.

Concerns have been raised regarding the potential effect of GAPs on small farms. The fear is that strict requirements of GAPs could impose disproportionately higher cost on small farms and hence marginalize them. Meanwhile, due to the low demand for land and high labor requirements, the fruits and vegetable sector is often seen as a sector where small producers have a chance to participate. In this section we will examine the optimal type-specific monitoring policy with endogenous detection on a fixed set of farms which are heterogeneous in terms of size.

Let $\alpha\bar{y}$ denote the level of farm size. Parameter α reflects differences in size and is assumed to be a continuous index and distributed over the interval $\left[\underline{\alpha},\bar{\alpha}\right]$ according to density function $g\left(\alpha\right)$ and distribution function $G\left(\alpha\right)$, with $G\left(\underline{\alpha}\right)=0$ and $G\left(\bar{\alpha}\right)=1$. Let $c(\alpha\bar{y})$ represent the marginal compliance costs which include non-recurrent costs and marginal recurrent costs.

Recall the previous discussion that the supply elasticity of fruits and vegetables is zero in the short run; each farmer chooses to harvest all his planted land $\alpha\bar{y}$. If there is no constraint on monitoring resources, the maximum high-safety production in the whole market is $Y\left(\alpha\right)=\int_{\underline{\alpha}}^{\bar{\alpha}}\alpha\bar{y}g\left(\alpha\right)d\alpha$. The farm with parameter α will achieve perfect compliance $\left(\theta=1\right)$ if and only if the monitoring probability is higher or equal to $\omega_1\left(\alpha\right)=\dfrac{2c\left(\alpha\bar{y}\right)-f\varepsilon\bar{z}}{\rho\bar{p}}$. We normalize the unit cost of inspection to be one, and then the necessary monitoring resource in terms of dollars to achieve $Y\left(\alpha\right)$ is

$$R\left(\alpha\right)=\int_{\underline{\alpha}}^{\bar{\alpha}}\omega_1\left(\alpha\right)g\left(\alpha\right)d\alpha \tag{2.6}$$

To guide the farmers to invest in more safety effort, the monitoring agency should intensify the frequency of inspections on a farm. However, monitoring resources are not always large enough to cover the necessary monitoring costs to achieve $Y\left(\alpha\right)$.[1] Theoretically, the monitoring agency can impose a per unit user fee to cover expenditures for the

[1] There are some studies have examined the financing method of food certification. According to Crespi and Marette (2001), certification costs can be financed through public action, i.e., a lump-sum tax by all tax payers or a user fee to the farms who participate in the certification program. Because all taxation will create fiscal distortion and result in economic inefficiency, the tax rate for the certification cannot be too high in order to avoid large opportunity costs. In this case, the collected tax may not cover the compliance cost. The more realistic and efficient financing method is to collect per-unit user fee for all certified product.

administration of this agreement. However, a high certification fee may harm many small scale farms and drive them out of the market. Thus, a more modest certification fee may be imposed that would allow the small farms to stay in the market and participate the marketing agreement. However, a small user fee may mean that monitoring costs cannot be covered. Further research on how to determine an efficient user fee would be useful to inform this question.

In this paper, we take the monitoring resource as given and do not address the question of how the resource is decided. Thus, in addition to the relationship of monitoring effort and the production strategies discussed above, we are also interested in the question of how the monitoring agency should distribute monitoring effort among heterogeneous farms when resources are constrained. Taking the farmer's production strategies into account, we move now to the first stage and try to examine how the monitoring agency allocates the constrained enforcement resource efficiently among the farms.

We should highlight the fact that the private incentive to invest in food safety does not reflect the industry wide or public benefit of these actions. In other words, safety level choices that are optimal for an individual farm may not be optimal for society. In the case specified here, we assume that the monitoring agency's objective is to maximize producers' surplus which is defined by the sum of all the producers' profits. An alternative objective would be to obtain the maximum food safety given the agency budget constraint. The marketing agreement discussed here is initialized by an industry group.

Without heterogeneity in farm size, there is no advantage to discriminate among the farms in monitoring effort and it is meaningless to study efficient strategies to allocate resources. Two identical farms would be inspected with the same probability. However, if two farms of different size are audited with the same probability and the same enforcement effort is applied to each, the amounts of the safety level they choose will be different. Thus, when the farms differ, the agency has an incentive to discriminate among farms.

The auditing costs depend on the testing practices, labor requirements, operation size and the other factors. If the monitoring agency's resource is large enough to obtain full compliance, i.e., $R \geq R(\alpha)$, then all farms are audited with probability $\omega_1(\alpha)$. If the monitoring resource is not enough to cover $R(\alpha)$, given that the monitoring agency's resource is just exhausted, the rule for distributing the monitoring effort is given in the next proposition.

Proposition 1. When $R < R(\alpha)$, the general rule of allocating inspection resources is that the total amount of decreased fraud in terms of safety effort should be same for all the farms.

$$-\left(1-\theta_j^*\right)\alpha_j\bar{y} = -\left(1-\theta_k^*\right)\alpha_k\bar{y}$$

Proof: see Appendix A.1.

The result has strong policy implications: when the monitoring agency does not have necessary resources to achieve the socially optimal output, it should use size differences among the farms to guide the decision about distributing monitoring effort among the farms. The result indicates that the total amount of decreased fraud in terms of safety effort $\mathrm{E} = -\left(1-\theta\right)\alpha\bar{y}$ should be same for all farms. Farm size has two opposing effects: (1) a size effect, and (2) a cost effect. The size effect means that larger farms imply a larger absolute value of E, and should be allocated more audits. The cost effect implies that smaller farms have higher compliance costs and more incentive to shirk on effort. Intuitively, smaller farms can be easily deterred with stricter monitoring. Thus, the necessary monitoring rate to obtain same safety level for small farms is lower than for large farms, and the monitoring agency should apply more intense monitoring effort to farms with smaller size.

Corollary 1. The optimal auditing probability for small farms increases faster than that for large farms with an increase of monitoring resources. When $R \le R^*$ the agency first inspects farms with larger size; when $R > R^*$ the agency first inspects farms with smaller size, where $R^* = 4(\alpha_k - \alpha_j) / \rho\bar{p}\left(\frac{\alpha_k}{c_k} - \frac{\alpha_j}{c_j}\right) - 2f\varepsilon\bar{z} / \rho\bar{p}$, $c_i = c(\alpha_i \bar{y})$ and $\alpha_k > \alpha_j$.

Proof: see Appendix A.2.

When monitoring resources are not large enough and less than R^*, the size effect dominates and smaller farms will be inspected with a lower rate or may not even be inspected at all. With the increase of monitoring resources, the cost effect becomes stronger and size effect becomes weaker. After $R > R^*$, the cost effect dominates and the allocated monitoring rate is higher for smaller farms. Because all farms' allocated monitoring rate is less or equal to $\omega_1(\alpha)$, they will make some effort to enhance food safety. Corollary 2 complements the proposition by stating the existence of the fact.

Corollary 2. The size effect and cost effect of audits always have opposite signs.

This fact implies that the changing patterns of monitoring rates for heterogeneous farms are robust.

Proof: see Appendix A.3.

2.4 Simulation analysis

We now construct a simulation model to illustrate our comparative statics results for the fresh strawberries market in California. California supplies more than 85 percent of the total market for fresh strawberries and leads the country in yield per acre (Woods et al. 2005). The main objective in using this example is to examine how monitoring strategies and farm behavior for providing safety effort are affected by alternative plausible values of farm size. It is assumed that if the products are detected as failing the safety criteria or practices, they will be sold in the processed market instead of fresh market. Once a farm has been linked to an outbreak of foodborne illness, it causes an additional cost. Given the values of parameters, the optimal inspection rate ω depends on compliance costs of GAPs and farm size. Since compliance costs are also determined by farm size, the differences of inspection rate among the farms can be said to rely on farm size. We treat ω as a parameter to be solved, for various settings of the other parameters.

The prices for fresh and processed strawberry in California in the year of 2004 are equal to 77.3 and 24.9 cents per pound, respectively. Thus the price difference p for fresh product relative to processed product is 52.4 cents per pound. With monitoring activities, the chance of a food accident is assumed to be 0.02 and the incident will lead to a 10 percent reduction in demand. Using historical data for the California fresh strawberry market from year 1989 through year 2006 adjusted to 2004 dollars, we estimate the demand curve as $D = 911 - 315.2 p_g$. Based on the assumption that the supply elasticity is zero in a short run, the grower's price is estimated to drop to 53.8 cents per pound with an incident. Moreover, we assume the additional cost of the firm's failure is equal to the grower's price following a shock. Table 2.1 summarizes the values of parameters used in this example.

Table 2.1. Parameters used in the example

Parameter	Value
p_g	77.3 (cents)
$p_g^{'}$	53.8 (cents)
p_p	24.9 (cents)
p	52.4 (cents)
$p^{'}$	28.9 (cents)
f	53.8 (cents)
ε	0.02
$h(\varepsilon)$	0.10
ρ	1.00
$\overline{z}$	0.10

Five main GAPs are used to represent what a typical strawberry farmer may adopt in the stage of implementation based on a study of GAP costs in fresh strawberries from the report of Woods and Thornsbury (2005).The costs of all the GAPs are listed in Table 2.2.

For the GAP related to packing and cooling practices, the costs of cleaning the holding shed or cooling pad are the primary expenses. Typical costs include weekly cleaning and maintenance of the shed which require two hours of labor for an average size farm (recurrent costs) and cleaning supplies including a sanitizer (non-recurrent cost) (Wood et al. 2005). Smaller growers need to invest on a single use system which is about \$364 per acre. However, large growers do not have to purchase single-use trays since most strawberries moving into the retail market are field packed directly into plastic clamshells or other single use containers. Thus, the average compliance costs for smaller farms are higher than that for larger farms for this practice.

Table 2.2. Cost of Good Agricultural Practices (GAPs)

Farm size (acres)	4.8	30	47
GAPs cost (cents/lb)			
1. Toilet and hand washing facilities	0.08691	0.21349	0.21349
2. Hygiene Training	0.02267	0.04345	0.04156
3. Packing shed and cooling pad sanitation and single use trays for u-picks	0.15681	0.03401	0.04534
4. Monitoring irrigation water	0.01322	0.00945	0.00567
5. Developing a crisis management plan	0.26450	0.04723	0.03023
6. Certification fee	0.33333	0.33333	0.33333
Total	0.87744	0.68095	0.45802

Source: Woods and Thornsbury, 2005.

The main expenses of the other three practices (practices 2, 4 and 5) are labor costs. Labor rate and the time required for each of these GAPs can be used to estimate the compliance costs. The average labor rate is higher for large growers. As example, the wage rate for a hired employee and an operator in large farms is $9.61 and $12.51, respectively, while the wage rate is $7.56 and $9.78 for small farms. From Table 2.2, smaller growers spend less in hygiene training and more in per unit costs of monitoring irrigation water and developing the crisis management plan. In these cases, their benefit from lower labor rates is less than their loss from economies of scale. Finally, the cost of third party certification is about 0.3 cents per pound and does not vary with farm size. With costs as in Table 2.2, smaller farms have higher compliance costs compared with larger farms.

Table 2.3 summarizes the simulation results on critical points (the complete results are presented in appendix Table 2.4). We assume there are only three types of farms in the market (large=47 acres, medium=30 acres and small=4.8 acres) and each size type has same number of farms. For simplicity, we assume the number of farms in each type to be 1, an assumption which will not change the implications of simulation results

Table 2.3. Simulation results on monitoring resources with critical points, R

R	c	$\bar{y}$	ω	θ
0.0050	0.46	47	0.0050	0.4034
	0.68	30	0	0.0808
	0.88	4.8	0	0.0627
0.0186	0.46	47	0.0093	0.6470
	0.68	30	0.0093	0.4351
	0.88	4.8	0	0.0627
0.0340	0.46	47	0.0140	0.9133
	0.68	30	0.0203	0.8543
	0.88	4.8	0	0.0627
0.0517	0.46	47	0.0148	0.9586
	0.68	30	0.0222	0.9267
	0.88	4.8	0.0148	0.5006
0.0616	0.46	47	0.0152	0.9813
	0.68	30	0.0232	0.9648
	0.88	4.8	0.0232	0.7492
0.0670	0.46	47	0.0155	1.0000
	0.68	30	0.0238	0.9877
	0.88	4.8	0.0277	0.8823
0.0700	0.46	47	0.0155	1.0000
	0.68	30	0.0241	1.0000
	0.88	4.8	0.0304	0.9622
0.0713	0.46	47	0.0155	1.0000
	0.68	30	0.0241	1.0000
	0.88	4.8	0.0317	1.0000

We denote by R the monitoring resources (per pound) that the agency can devote to testing. The cost of one test is normalized to be one. For each choice of marginal compliance costs c and farm size $\bar{y}$, we report inspection rate ω and safety effort θ.

Figure 2.1 shows the patterns of optimal inspection rate for each type of farm given different levels of monitoring resources. The simulation results indicate that the optimal inspection rate is an increasing function of monitoring resources. With the increase of monitoring resources, the optimal inspection rate for each type of farm increases but with different speeds. Smaller farms have a higher increasing rate compared to the larger farms, a result which is coincident with the proposition above.

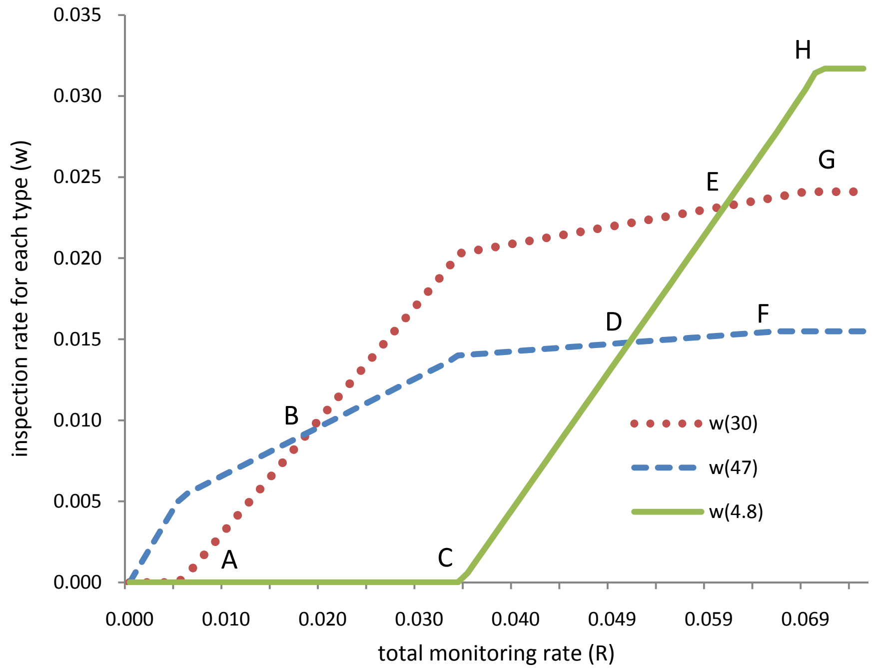

Figure 2.1. Optimal inspection rates with different monitoring resources

When monitoring resources are relatively low, the monitoring agency spends all its resources on the large farms. The small and medium farms are not inspected until point A (R=0.005) – a point with very low monitoring resources; the size effect is dominant in this region. The inspection probability of the medium farm increases faster than that of the large farm and at point B (R=0.0186) the two farms are audited with same probability 0.0093. From then on, the medium farm faces higher inspection rate than the large farm, and the cost effect is more significant compared with size effect. From point C (R=0.034), all farms are inspected but the small farm is inspected with the lowest probability until point D (R=0.052). At point D, the inspection rates for the large farm and the small farm are equal. When the monitoring resource is higher than 0.052 (point D) and lower than 0.062 (point E), the monitoring rate for the small farm is higher than the larger farm but is still lower than the medium farm. At point E, the auditing rate for the medium farm and the small farm is same (= 0.023). With an increase of monitoring resources, the cost effect of monitoring becomes dominant for the small farm. After point E, the inspection rate has a negative relationship with farm size. In this region, increased costs of monitoring food safety effort are associated with a lower level of effort and more easily detected fraudulent behavior in production practices. Thus the necessary monitoring rate to deter fraud decreases.

Correspondingly, the safety effort of the farms changes with their inspection rate. The necessary auditing probability needed to attain full compliance level ($\theta = 1$) is higher for smaller farms. When $R = 0.067$ (point F), the large farm will be inspected with probability 0.0155 and can be induced to exert full effort; the other farms may still shirk their efforts to invest in food safety practices. After point G ($R = 0.070$), both the medium and the large farms will achieve full compliance. After $R = 0.071$ (point H), all farms produce with full compliance.

2.5 Conclusions

This paper provides insight on how and under what conditions, monitoring activities might mitigate the fraudulent activities of food growers under a voluntary marketing agreement. We handled the effect of food safety failure by incorporating the probability of a foodborne illness outbreak into our model. A farm loses from the “bad outcome” by receiving diverted price and/or through traceback being linked with the incident. Our analysis brings out the following results.

First, we show that the farms respond to monitoring and enforcement by increasing safety effort up until perfect compliance is achieved. Meanwhile, farms adopt GAPs voluntarily to reduce their food-borne risk even in absence of monitoring; Second, optimal monitoring policy depends on the exogenous size parameter of the farms. If the monitoring resource is not enough to cover the necessary inspection costs of achieving optimal safety level, the agency will discriminate among farms to maximize total producers' surplus. The general rule of allocating inspection resource is that the total amount of decreased fraud in terms of safety effort for each farm is same. We find when auditing resources are very low, the size effect is dominant and larger farms will be inspected first; when the resources are large enough, the cost effect is dominant and the agency will target small farms first. The optimal auditing probability for small farms has a larger rate of increase than for large farms; the size effect and cost effect cannot have same sign.

There are also several possible extensions for future work. First, we analyze the optimal monitoring policy under the case that all farms are all risk neutral and have same risk preference. A more complicated analysis could be developed when the risk preferences are different. Second, the monitoring resource is assumed to be exogenous in our model. A meaningful extension would be to examine the design of efficient user-fee scheme in a second-best policy setting. Third, the industry's response to food safety failure seems to be dynamic, taking into account the interplay of monitoring policies and the probability of a food incident. More explicit consideration of dynamic response may lead to interesting implications. Fourth, farm size and size distribution are assumed to be predetermined in this study. This assumption is relatively restrictive, but is likely the case in the short run for the produce industry with relatively high capital investments. In the longer run, farms may contemplate existing the industry. Since more supermarkets now require their farms to pass a GAPs audit. If the costs associated with implementing GAPs have a disproportionate impact on smaller farms, the higher costs and requirements of the GAPs may lead to the exit of the smaller farms from the industry. A useful extension of this research would be to allow the size distribution of farms to change with food safety regulation.

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APPENDIX A

A.1. Proof of Proposition 1

The expected return of a farm is:

$$TR = \left(p_p + \overline{p} - \overline{p}\rho\omega_i \left(1-\theta_i\right)\right)\alpha_i \overline{y} \tag{A1}$$

where $\overline{p} = \left(1-\varepsilon\right) p + \varepsilon p^{'}$

The total cost of the farm is:

$$TC = c_i\theta^2\alpha_i\overline{y} + c_a\left(\alpha_i\overline{y}\right)^2/2 + f\,\varepsilon\overline{z}\left(1-\theta_i\right)\alpha_i\overline{y} \tag{A2}$$

where $c_i = c\left(\alpha_i\overline{y}\right)$

The optimal effort level implemented by the farm is

$$\max_{\theta_i} \pi_i = TR - TC \tag{A3}$$

Then we get

$$\theta_i^* = \frac{\overline{p}\rho\omega_i + f\,\varepsilon\overline{z}}{2c_i} \tag{A4}$$

Profit π_i is derived as

$$\pi_i = \left(p_p + \overline{p} - \left(\overline{p}\rho\omega_j + f\,\varepsilon\overline{z}\right) + \frac{\left(\overline{p}\rho\omega_j + f\,\varepsilon\overline{z}\right)^2}{4c_i}\right)\alpha_i\overline{y} - c_a\left(\alpha_i\overline{y}\right)^2/2 \tag{A5}$$

Let us now consider two farms, k and j, such that $\alpha_k > \alpha_j$. With limited resources the agency seeks to maximize the producers' total surplus

$$\max_{\omega_i} \sum_i \pi_i \text{ s.t. } \sum_i \omega_i \le R \quad i = k, j \tag{A6}$$

The first order necessary conditions can be written as

$$\left(-1+\frac{\overline{p}\rho\omega_j^*+f\varepsilon\overline{z}}{2c_j}\right)\alpha_j\overline{y}=\left(-1+\frac{\overline{p}\rho\omega_k^*+f\varepsilon\overline{z}}{2c_k}\right)\alpha_k\overline{y} \tag{A7}$$

Plug (A4) into (A7), we can get

$$-\left(1-\theta_j^*\right)\alpha_j\overline{y}=-\left(1-\theta_k^*\right)\alpha_k\overline{y} \tag{A8}$$

A.2. Proof of Corollary 1

We denote $\overline{y}_j=\alpha_j\overline{y}$ and $\overline{y}_k=\alpha_k\overline{y}$. From the objective function (A6) and the first order condition (A7), the optimal monitoring rate of the farms can be derived as:

$$\begin{aligned}\omega_k^*&=A\left(\frac{\overline{y}_j}{c_j}R+\frac{2}{\rho\overline{p}}\left(\overline{y}_k-\overline{y}_j+\frac{f\varepsilon\overline{z}}{2}\left(\frac{\overline{y}_j}{c_j}-\frac{\overline{y}_k}{c_k}\right)\right)\right)\\ \omega_j^*&=A\left(\frac{\overline{y}_k}{c_k}R-\frac{2}{\rho\overline{p}}\left(\overline{y}_k-\overline{y}_j+\frac{f\varepsilon\overline{z}}{2}\left(\frac{\overline{y}_j}{c_j}-\frac{\overline{y}_k}{c_k}\right)\right)\right)\end{aligned} \tag{A9 }$$

where $A=1/\left(\frac{\overline{y}_j}{c_j}+\frac{\overline{y}_k}{c_k}\right)$

Since $\frac{\partial\omega_k^*}{\partial R}=A\frac{\overline{y}_j}{c_j}<A\frac{\overline{y}_k}{c_k}=\frac{\partial\omega_j^*}{\partial R}$, the optimal auditing probability for the small farm increases faster than that for the large farm.

Correspondingly,

$$\omega_k-\omega_j=A\left(\left(\frac{\overline{y}_j}{c_j}-\frac{\overline{y}_k}{c_k}\right)\left(R+\frac{2f\varepsilon\overline{z}}{\rho\overline{p}}\right)+\frac{4}{\rho\overline{p}}\left(\overline{y}_k-\overline{y}_j\right)\right) \tag{A10}$$

Since $\overline{y}_k>\overline{y}_j$, if $R<R^*, R^*=4\left(\alpha_k-\alpha_j\right)/\rho\overline{p}\left(\frac{\alpha_k}{c_k}-\frac{\alpha_j}{c_j}\right)-2f\varepsilon\overline{z}/\rho\overline{p}$, then $\omega_k-\omega_j>0$, which means the agency first inspects farms with larger size; If $R > R^*, \omega_k - \omega_j < 0$, which means the agency first inspects farms with smaller size.

A.3. Proof of Corollary 2

From (A10) and $\bar{y}_k > \bar{y}_j$, we know size effect $\frac{4}{\rho\bar{p}}\left(\bar{y}_k - \bar{y}_j\right) > 0$. If size effect has same sign with cost effect, then $\frac{\bar{y}_j}{c_j} > \frac{\bar{y}_k}{c_k}$ should be satisfied. Since $c_j > c_k$, $\bar{y}_j / c_j$ is always less than $\bar{y}_k / c_k$, size effect and cost effect always have opposite signs.

Table 2.4. Simulation results on monitoring policies

ω	$\omega(\bar{y}=47)$	$\omega(\bar{y}=30)$	$\omega(\bar{y}=4.8)$
0	0	0	0
0.001	0.00100	0	0
0.002	0.00200	0	0
0.003	0.00300	0	0
0.004	0.00400	0	0
0.005	0.00500	0	0
0.006	0.00550	0.00050	0
0.007	0.00580	0.00120	0
0.008	0.00610	0.00190	0
0.009	0.00640	0.00260	0
0.010	0.00670	0.00330	0
0.011	0.00700	0.00400	0
0.012	0.00730	0.00470	0
0.013	0.00760	0.00540	0
0.014	0.00790	0.00610	0
0.015	0.00820	0.00680	0
0.016	0.00850	0.00750	0
0.017	0.00880	0.00820	0
0.018	0.00910	0.00890	0
0.019	0.00940	0.00960	0
0.020	0.00970	0.01030	0
0.021	0.01000	0.01100	0
0.022	0.01030	0.01170	0
0.023	0.01060	0.01240	0
0.024	0.01090	0.01310	0
0.025	0.01120	0.01380	0
0.026	0.01150	0.01450	0
0.027	0.01180	0.01520	0
0.028	0.01210	0.01590	0
0.029	0.01240	0.01660	0
0.030	0.01270	0.01730	0
0.031	0.01300	0.01800	0
0.032	0.01330	0.01870	0
0.033	0.01360	0.01940	0
0.034	0.01399	0.02029	0
0.035	0.01404	0.02039	0.00057
0.036	0.01408	0.02050	0.00142
0.037	0.01413	0.02060	0.00227
0.038	0.01418	0.02071	0.00312
0.039	0.01422	0.02081	0.00397

Table 2.4. (Continued)

ω	$\omega(\bar{y}=47)$	$\omega(\bar{y}=30)$	$\omega(\bar{y}=4.8)$
0.040	0.01427	0.02092	0.00482
0.041	0.01431	0.02102	0.00567
0.042	0.01436	0.02113	0.00652
0.043	0.01440	0.02123	0.00736
0.044	0.01445	0.02134	0.00821
0.045	0.01449	0.02145	0.00906
0.046	0.01454	0.02155	0.00991
0.047	0.01458	0.02166	0.01076
0.048	0.01463	0.02176	0.01161
0.049	0.01467	0.02187	0.01246
0.050	0.01472	0.02197	0.01331
0.051	0.01476	0.02208	0.01416
0.052	0.01481	0.02218	0.01501
0.053	0.01485	0.02229	0.01586
0.054	0.01490	0.02239	0.01671
0.055	0.01494	0.02250	0.01756
0.056	0.01499	0.02261	0.01841
0.057	0.01504	0.02271	0.01925
0.058	0.01508	0.02282	0.02010
0.059	0.01513	0.02292	0.02095
0.060	0.01517	0.02303	0.02180
0.061	0.01522	0.02313	0.02265
0.062	0.01526	0.02324	0.02350
0.063	0.01531	0.02334	0.02435
0.064	0.01535	0.02345	0.02520
0.065	0.01540	0.02355	0.02605
0.066	0.01544	0.02366	0.02690
0.067	0.01549	0.02377	0.02775
0.068	0.01549	0.02388	0.02864
0.069	0.01549	0.02399	0.02953
0.070	0.01549	0.02410	0.03042
0.071	0.01549	0.02410	0.03142
0.072	0.01549	0.02410	0.03170
0.073	0.01549	0.02410	0.03170
0.074	0.01549	0.02410	0.03170
0.075	0.01549	0.02410	0.03170
0.076	0.01549	0.02410	0.03170

CHAPTER 3. FOOD SAFETY, TRACEABILITY AND CONTRACT DESIGN

3.1 Introduction

Recent outbreaks of food-borne illness related to fruit and vegetables have led to increased concerns about food safety and its effect on human health. Fruits and vegetables are typically grown outdoors and are vulnerable to contamination in the natural environment or in handling and processing after harvest. In order to prevent such contamination, great care should be taken to improve food safety on farm level. For example, many fruit and vegetable industries have identified specific Good Agricultural Practices (GAPs) for adoption by growers at critical production steps to reduce contamination that leads to food safety failures. Many retail and foodservice buyers now require food suppliers to adhere to some performance-based standards or specific criteria for product control and monitoring. As a result, processors now place a higher value on purchasing safe products from their growers than before. Direct relationships with growers are being established on the basis of delivering high safety products and have enabled processors to become much more involved than before in the production practices.

Processors seek to maintain an adequate stream of product to meet production schedules and maintain a low probability of contamination. Safer and higher quality inputs reduce economic losses associated with product recall, public health impacts and consumer’s distrust. In turn, growers seek income stability, market security as well as access to capital and technology. Contracts are used to coordinate exchanges in the production process and to provide contracting parties with a degree of control and risk sharing. Much of the fruit and vegetables industry is vertically coordinated in the United States and where 56.5 % of fruit production and 30% of vegetable production is under marketing contracts (MacDonald et al. 2004).

The provisions of a basic processing fruit and vegetables production contract may include many issues, and the contracts differ substantially across the commodity sectors. Product quantity and quality usually play important roles in a contract. In some markets, contract payment to the grower depends only on measured quantity, while in other markets payment depends on both measured quantity and quality. In order to focus on the effects of quality on contract design, we assume that output is fixed in this research and thus exclude the influence of product quantity.

Food quality is defined as the totality of features and characteristics of a product (ISO). Often quality can be graded by a third audit party through objective measurements based on its various physical attributes such as appearance, odor, taste, flavor, and nutrition. Grade standards describe the quality requirements for each grade of food products and give industry a common language for buying and selling. In the United States, the USDA Agricultural Marketing Service (USDA-AMS) provides grading services for fresh fruit and vegetables. Growers can improve product quality by investing in efforts by selection of seed and genetics, production and harvest practices and product management.

Food safety is defined as the assurance that the food will not cause harm to consumers when it is prepared and/or eaten according to its intended use (FAO/WHO 1997). Food safety assurance involves reduction of risks which may occur in food products. To improve food safety and reduce contamination, growers should adopt good agricultural practices at various production steps. Those practices may include production site selection, fertilizer usage, grower regulators, the use of veterinary drugs, water quality and usage, pest control, pesticide monitoring and harvesting practices.

Although safety is a component of quality, it differs from many other quality attributes as it is often difficult or very costly to observe the safety outcome. A product can appear to be of high quality but may be unsafe because it is contaminated with undetected (below threshold level of detection) toxic chemicals or other contamination with low probability of detection (or very costly detection) in tests. At the same time, a product that seems to lack many of the visible quality attributes of high quality, such as uniformity in shape, may be safe. Thus, the payoff for higher levels of food safety is difficult to be contractible and the contracts usually do not include conditions on food safety. Instead, the processor is more likely to pay closer attention to food safety indicators and expect the grower to exert effort to assure food safety. However, the grower has incentive to shirk his effort on producing safe product because he or she can be insulated from the risks of social and personal cost of food-borne problems because of the difficulty in product tracing.

A potential way to provide the grower an incentive to exert the effort needed to produce safe product is by implementing traceability systems in food supply chains. With a traceability system in place, the source of unsafe products can more easily be identified. If a grower failing to provide a safe product is identified through traceback, he or she faces costs of failure such as penalties and/or market loss, and the processor faces losses associated with disrupted input supply or market loss due to the safety failure in the processed product. Thus the grower has greater incentive to exert high safety effort during his production process in order to diminish possible losses. In contrast, the processor can benefit from obtaining safer products due to the potential liability incurred by the grower in the case of a food safety failure. The existence of traceability systems can be looked on as an indirect way for providing safety assurance and thus having such a system in place can enter into a contract with conditions designed to improve product safety. Although safety is a component of quality, safety improvement activities frequently are not included in quality improvement activities. In fact, activities on improving quality and safety may be independent, complementary, or substitutes in ensuring safety issues receive appropriate emphasis.

Growers who accept a contract are expected to comply with all of the contract provisions. However, quality and safety information is not full or complete due to the stochastic nature of production. This means greater effort cannot guarantee higher quality and safer product, while reduced effort may generate high quality and safer product. The probability of growers exerting less efforts increases with the profits that can be earned through opportunistic behavior. Furthermore, the effects of a traceability system on mitigating food safety problems rely heavily on its efficiency. Food risks may be caused by poor food safety practices of the grower who knows his production processes but also know the difficulty of trace back to the specific firm.

As a consequence, moral hazard may occur in both quality effort and safety effort. Consideration of the design of a marketing contract needs to account for the impact of both traceability as well as the distribution of payoffs between growers and processors. The objectives of this paper are (1) to analyze the effects of marketing contracts on the behaviors of growers and processors; (2) to examine how the interaction between safety effort and quality effort influences the grower’s incentives and can help to overcome moral hazard problems; and (3) to identify how a traceability system affects contract provisions and mitigates the grower’s moral hazard problem.

3.2 Background

Our analysis is related to previous literature that addresses economic implications of asymmetric information on the failure of agricultural markets. Since the pioneering work of Akerlof (1970) and Grossmann and Hart (1983), the bulk of the literature has considered the causes and remedies of agricultural market failures caused by asymmetric information on product quality and how moral hazard affects producers' behavior and choice of product. For instance, Fraser (2002, 2004) shows that agri-environmental policy reduces the problem of moral hazard and finds a negative relationship between monitoring activities and the extent of fraudulent behaviors by participants. Hennessy et al. (2003) demonstrates the interaction between moral hazard and food safety as a result of systemic failure in the provision of safe food. Caswell et al. (1996) and Crespi et al. (2003) study the effects and role of certification on overcoming adverse selection problems. Starbird (2005) investigates the consequences of inspection policy on food safety and welfare.

Many studies have been conducted to analyze how a traceability system can encourage more food safety efforts and mitigate food-safety related risks as an incentive mechanism. Golan et al. (2004) discuss the implementation of traceability systems in the US and analyzes the motivations for producers to adopt a tractability system. Starbird (2008) constructs a model to analyze the influence of a traceability system on the provision of safe products by incorporating traceability error, sampling error and diagnostic error into the supplier's utility function. Hirschauer and Musshoff (2007) use a game-theoretic approach to address the effects of incomplete inspection on tracing food risks. McEvoy and Monteiro (2008) investigate to what extent an industry voluntary agreement on food traceability can reduce the cost of food-safety related problems. Filho (2007) studies the effects of a traceability system on the raw material supplier's willingness to implement food safety effort. Resende-Filho and Buhr (2008) develop a principal-agent model to examine the optimal expected traceback probability in US fed cattle sector. Souza Monteiro and Caswell (2010) present a network model to analyze the choice of voluntary traceability systems for multi-ingredient foods. In general, the studies show that improved product tracing motivates producers to deliver safer food, and improves product safety through market based incentives.

The general contract perspective has been applied to a variety of incentive problems. Especially relevant to our study are those that address how the marketing contract between processors and growers affects agricultural production. Several studies have explored the effects of contracting using theoretical and empirical approaches. Olesen (2003) analyzes the interaction between the theory and the practice of contracting with heterogeneous growers. Goodhue (2000) examines the impacts of input control and grower heterogeneity on efficient contract design by using a moral hazard-adverse selection approach. Weaver and Kim (2000) demonstrate the potential benefits of supply chain management strategies that use contracts to improve food quality in the supply chain. Ligon (2004) develops an efficient contract which takes account of stochastic production functions from experimental data. Hueth et al. (2002, 2004) examine the relationship between moral hazard problem and contract design within the context of the fruit and vegetable industry.

Although these studies assess the opportunity for supply chain contracting, they only consider the case where the agent performs one task and controls one-dimensional effort. None of these studies evaluates how efficient incentive-compatible contracts can be designed to induce both quality effort and safety effort and how the interaction between quality and safety efforts affects incentives. The contribution of this paper is twofold: First, we examine how incentive considerations affect the optimal mix of efforts along each dimension of the grower's performance. Second, we establish the link between contract design and the traceability system. In particular, we analyze how the grower's behavior decisions are affected by the rate (frequency) of traceability and the effects of traceability on the contract price mechanism.

The remainder of this paper is organized as follows: Section 2 constructs a benchmark model in which a traceability system is absent and develops the baseline analytical results. In the next two sections, contract designs with observable safety effort (section 3) and unobservable safety effort (section 4) in the case of a traceability system are examined, respectively. Section 5 provides results from a numerical experiment, and section 6 provides summary of the findings and conclusions.

3.3 Model Setup and the Strategic Environment

The strategic interaction between the processor and the grower proceeds as follows. First the processor designs and proposes a contract. Second, the grower either accepts or rejects the contract. If the grower rejects the contract, then the game terminates and both parties get their respective reservation payoffs; if the grower accepts, the game moves on to the third stage where the grower chooses whether or not to invest high effort on quality and safety during the production process. Each grower's level of effort on quality and safety is private information. At the end of the cropping season, the outputs are delivered to the processor, and food quality is measured. According to the signed contract, the processor pays the grower based on the product quality measurement. If a food safety problem is detected in following marketing stages and can be traced back to the responsible grower, the grower incurs a penalty; if the grower cannot be identified, he does not face any extra costs at all. The following subsections outline the grower and processor's problems under alternative conditions.

3.3.1 Benchmark model - low safety effort is implemented

In order to better understand the implications of the model, we construct a benchmark model in which the traceability system is absent. Our analysis is based on a monopolistic market framework which consists of multiple growers and one processor. In order to abstract from yield risk, we assume each grower produces a single unit of product. The processor designs a contract with growers specifying payments based on the measured quality of the food product. We assume that the economic value is not large enough for the processor to induce high effort in both tasks, i.e., the processor's objective is to minimize the cost of inducing the growers to implement high effort on quality only. Without explicit incentive, the growers do not exert high effort level on food safety, for example, they do not implement Good Agricultural Practices during their production process.

Though a grower's choice of effort level is continuous, we restrict the effort levels to be a binary choice, *High* or *Low.* As a result, output quality can take only two values, *High* or *Low.* The quality level depends on the effort level chosen by the grower. However, the realized quality level is an imperfect signal of quality effort because despite efforts during production, many fruit and vegetables products are subject to random changes in quality such as stochastic deterioration during the time between shipment and delivery due to their perishable nature. In addition, the grading process at the delivery point is not completely accurate. Thus, this makes it is possible that the choice of effort stochastically determines the grower's output quality. The processor cannot observe the grower's choice of effort on improving quality, but can observe the measured quality level at the delivery point.

We define p as the probability that high quality is realized at the delivery point when high quality effort and low safety effort are implemented during the production process. Consequently, $(1-p)$ is denoted as the probability of being measured as low quality with actual high quality effort. High quality effort leads to higher probability that high quality is realized, i.e., $p > 0.5$. It is assumed that the production technology of high quality product requires that inputs be employed in fixed proportions. The grower incurs cost on high quality effort, given by φ_q.

The processor is assumed to have preferences over lotteries that can be represented by a vonNeumann-Morgenstern utility function U_x for a grower, where x denotes realized quality which can be *high* or *low*. For simplicity, the grower's preference is additively separable in payment and effort cost, and is represented as $V\left(x, \varphi_q\right) = U_x - \varphi_q$. We introduce moral hazard by assuming that observing and monitoring the grower's effort level on improved quality are prohibitively costly. Thus the processor has to offer the grower a contract such that compensation is based on observable output quality. However, the grower will only accept an offer from the processor if it yields at least his reservation payoff, which is normalized to be zero and perfectly certain. Thus, the participation constraint becomes

$$pU_h + (1-p)U_l - \varphi_q \geq 0 \tag{3.1}$$

The risk neutral processor's problem is to design a grower contract that induces the grower to take the best action from the processor's point of view. That is, the goal of the contract is to encourage the grower to deliver high quality products. We denote by αp the probability that high quality is realized at the delivery point associated with low quality effort and low safety effort at the production process, and by $1-\alpha p$ the probability that low quality is realized, where $0<\alpha<1$. Parameter α reflects the likelihood of realizing high quality product given low quality effort relative to that given high quality effort. The processor designs contracts by choosing compensation, or equivalently (U_h, U_l). The incentive compatibility constraint becomes

$$pU_h + (1-p)U_l - \varphi_q \geq \alpha pU_h + (1-\alpha p)U_l \tag{3.2}$$

This constraint ensures that under the contract payment the grower's optimal choice of the quality effort is high. This setting represents a fairly standard principal-agent contracting problem (see for example Laffont and Martimort 2001).

We assume that each processed unit results in one unit output in this analysis. We also assume that the processor is aware of the grower's utility function and the distribution of the grower's effort level. For the processor, inducing high quality effort yields expected revenue $B = pS_h + (1-p)S_l$, where S_h and S_l are the monetary value the processor can get from the high quality product and the low quality product, respectively. We denote h as payment to the grower and assume it has a quadratic expression $h(U) = U + \frac{r}{2}U^2$, where r can be considered as the grower's degree of absolute risk aversion. This assumption ensures a closed-form solution and does not affect the qualitative results. The processor makes the expected payment made to the grower to induce a high quality effort $C = ph(U_h) + (1-p)h(U_l)$.

The processor chooses a payment scheme to minimize the expected compensation subject to the grower's decision rule. Given the above assumptions, the optimal values of U_h and U_l can be derived from the following:

$$\min_{U_h, U_l} C$$

Subject to: (3.1) and (3.2).

For the simplest case of $r = 0$, we obtain the optimal payments to the grower directly by solving (3.1) and (3.2) with equalities:

$$U_h = \frac{\varphi_q}{1-\alpha}\left(\frac{1}{p} - \alpha\right) \tag{3.3}$$

$$U_l = -\varphi_q \frac{\alpha}{1-\alpha} \tag{3.4}$$

The processor makes an expected payment

$$C = ph\left(U_h\right) + (1-p)h\left(U_l\right) = \varphi_q$$

The expected payment to the grower equals the grower's the cost if the processor implements effort to improve quality himself. Thus, the processor can costlessly structure the grower's payments so that the grower has incentive to exert high quality effort. As a general theme of agency theory, moral hazard is not a problem with a risk-neutral farmer despite the fact that the effort is unobservable. In summary, the first-best level of effort on improving quality can be implemented.

When the farmer is risk-averse ($r > 0$), $h(\cdot)$ is strictly convex and the processor's objective function is strictly concave in (U_h, U_l). The constraints are linear and the interior of the constraint set is nonempty. If we let $\left(U_h^*, U_l^*\right)$ denote the maximized value of the payment, we can get optimal payments to the grower from:

$$U_h^* = \varphi_q + \varphi_q \frac{1-p}{p(1-\alpha)} \tag{3.5}$$

$$U_l^* = \varphi_q - \varphi_q \frac{1}{1-\alpha} \tag{3.6}$$

(See Appendix B.1)

The payment to the grower consists of a fixed component, to ensure the grower accepts the compensation contract, and an incentive component that induces high effort on quality improvement. Obviously, $U_h^* > U_l^*$. The grower receives a premium of $\varphi_q \frac{1-p}{p(1-\alpha)}$ in terms of utility when quality is high and a penalty $\varphi_q \frac{1}{1-\alpha}$ when quality is low. From (3.5) and (3.6) we obtain the classical result that the optimal level of payment for high quality is a negative function of the spread ratio of probabilities $1-\alpha$, while for low quality the payment is a positive function of $1-\alpha$. The intuition behind this result is that the processor has less incentive to invest more to differentiate the products if the spread of probabilities is high. Moreover, it becomes harder for the grower to get a higher payment as p increases.

Let us turn to the question of the optimality of inducing a higher quality effort, from the processor's point of view. The expected payment to the grower can be written as

$$C = ph\left(U_h^*\right) + (1-p)h\left(U_l^*\right) \tag{3.7}$$

From (3.3) to (3.6), we can get

$$C = \varphi_q + \frac{r}{2}\varphi_q^2 + \frac{r}{2}\varphi_q^2 \frac{1-p}{p(1-\alpha)^2} \tag{3.8}$$

The first two terms of the right-hand side of (3.8) are first-best costs of implementing quality effort and the last term states the impact of information for the processor. The expected payment given by the processor is thus higher than the first-best costs. We find that the processor's payment increases with the grower's degree of risk aversion r. A higher risk premium must be paid to the risk-averse farmer to induce his participation. Moreover, the expected payment is non-decreasing in α. The smaller is the difference in the probability of being high quality and low quality, the less sensitive is the quality level to effort levels. Thus the observable output is a poor indicator of the grower's effort on improving quality, and higher payments are needed to improve the processor's ability to differentiate high effort from low effort. With low quality effort, the processor instead obtains revenue equal to $B = \alpha p S_h + (1-\alpha p) S_l$. Thus, ΔB is the gain of increasing quality effort from low to high,

$$\Delta B = \left(pS_h + (1-p) S_l \right) - \left(\alpha pS_h + (1-\alpha p) S_l \right) = (1-\alpha) p \Delta S \tag{3.9}$$

where $\Delta S = S_h - S_l$. The gain comes from the fact that high return S_h arises more often when high quality effort is exerted. Had the processor decided to let the grower exert low quality effort, he would make a zero payment to the grower whatever the realization of output. Thus the cost of inducing a high quality effort is equal to C, i.e., $\Delta C = C$.The processor chooses to induce high quality effort when the benefit ΔB is higher than the cost ΔC, i.e.

$$\Delta S \geq \frac{\Delta C}{(1-\alpha) p} = M = \frac{1}{(1-\alpha) p} \left[\varphi_q + \frac{r}{2} \varphi_q^2 + \frac{r}{2} \varphi_q^2 \frac{1-p}{p(1-\alpha)^2} \right] \tag{3.10}$$

where M is unit incremental cost of implementing high quality effort.

3.3.2 Safety effort is observable: high safety effort is implemented

The benchmark model above is extended here to include safety effort. The implicit assumption of this contract is that it is worthwhile for the processor to induce safety effort because its benefit is sufficiently larger than its cost. Thus, the optimal contract provided by the processor should account for this potential effect and adjust the payment schedule accordingly.

Let us first consider the case where the grower's effort is fully observable. It is assumed that food safety problem will not happen if high safety effort is implemented during the production process. Therefore the processor can simply instruct the grower to implement safety effort so that the grower's participation constraint is satisfied with equality. Thus, the optimal choice of safety level for the grower is high. Here, when the grower chooses both high quality and high safety efforts, the probability that high quality is realized at the delivery point is denoted as δp . The probability of output quality depends not only on the level of effort for quality, but also on the level of effort for safety implemented by the same grower. Safety influencing parameter δ denotes the likelihood of obtaining high quality output given high safety effort relative to that given low safety effort. Quality effort and safety effort are independent when $\delta = 1$. When $\delta < 1$, safety effort substitutes for the quality effort by decreasing the marginal productivity of high quality effort. When $\delta > 1$, the efforts are complementary, and higher safety improves the probability that a high quality output realizes. It is assumed that $\delta p \leq 1$ to guarantee that the probability of realizing a high quality is equal to or less than 1.

The processor adopts an incentive scheme to encourage high quality effort, consisting of the payment of U_h when high quality is realized and a payment U_l when the low quality is realized. Given the processor's strategy, the expected utility for the grower is

$\delta pU_h + (1-\delta p)U_l$, where $(1-\delta p)$ is the probability that low quality is realized at the delivery point when the grower actually exerts high efforts on both quality and safety.

It is reasonable to assume that it becomes increasingly difficult for the grower to adopt both quality and safety effort. For the grower to enter into a contract with the processor, the grower faces safety-improving costs which include, for example, investments in harvesting and storage equipment, energy and waste management or investments to improve farm worker conditions (e.g., access to latrines). We denote by φ as the cost when he exerts the two high efforts levels simultaneously, and by φ_s when only high effort on safety occurs. Of course, we have $\varphi > \varphi_s > 0$. Moreover, it is easy to understand, when safety effort and quality effort are independent, $\varphi = \varphi_q + \varphi_s$. When safety effort complements quality effort, $\varphi < \varphi_q + \varphi_s$, which means it is easier to exert quality effort at the margin when safety effort is already performed. When safety effort substitutes for quality effort, $\varphi > \varphi_q + \varphi_s$, which means it is more difficult to exert the quality effort at the margin when the safety effort is already performed.

We denote $B = \delta pS_h + (1-\delta p)S_l$ as the expected revenue of the processor, and denote $C = \delta ph(U_h) + (1-\delta p)h(U_l)$ as the expected payment made to the grower. $\delta\alpha p$ is the probability of high quality that is realized at the delivery point associated with low quality effort and high safety effort at the production process, and $(1-\delta\alpha p)$ is the probability of low quality realized at the delivery point. The parameters satisfy $\delta\alpha p < 1-\delta\alpha p$.

Similar to the benchmark model, the processor faces the following mechanism design problem:

$$\min_{U_h, U_l} C$$

Subject to

$$\delta p U_h + (1-\delta p) U_l - \varphi \geq 0 \tag{3.11}$$

$$\delta p U_h + (1-\delta p) U_l - \varphi \geq \delta\alpha p U_h + (1-\delta\alpha p) U_l - \varphi_s \tag{3.12}$$

From the above equations, we can obtain the grower's optimal utilities:

$$U_h^* = \varphi + (\varphi - \varphi_s)\frac{1-\delta p}{\delta p(1-\alpha)} \tag{3.13}$$

$$U_l^* = \varphi - (\varphi - \varphi_s)\frac{1}{(1-\alpha)} \tag{3.14}$$

Therefore, the expected payment to a grower is:

$$C = \varphi + \frac{r}{2}\varphi^2 + \frac{r}{2}\left(\varphi - \varphi_q\right)^2 \frac{1-\delta p}{\delta p(1-\alpha)^2} \tag{3.15}$$

Because $\partial C / \partial \delta = -r\left(\varphi - \varphi_q\right)^2 / \left[2 p\delta^2 (1-\alpha)^2\right] < 0$, the expected payment to the grower is decreasing with the safety influencing parameter δ. The processor will pay less when safety effort has a positive effect on the realization of high quality (high δ). When food safety is observable and implemented, the incremental expected benefit from implementing high quality effort can be expressed as ΔB,

$$\Delta B = \left(\delta p S_h + (1-\delta p) S_l\right) - \left(\delta\alpha p S_h + (1-\delta\alpha p) S_l\right) = (1-\alpha)\delta p \Delta S \tag{3.16}$$

The increase in cost of implementing high quality effort is the payment to the growers implementing two high efforts minus the first-best cost of implementing safety effort only.

$$\Delta C = C - h(\varphi_s) = (\varphi - \varphi_s) + \frac{r}{2}\left(\varphi^2 - \varphi_s^2\right) + \frac{r}{2}(\varphi - \varphi_s)^2 \frac{1-\delta p}{\delta p(1-\alpha)^2} \tag{3.17}$$

Similar to the discussion in previous section, the contact is costless to the processor when the farmer is risk-neutral, i.e. $\Delta C = \varphi - \varphi_s$ .The processor prefers to induce effort on both tasks rather than on only safety effort when incremental benefit exceeds the incremental cost, or $\Delta B \geq \Delta C$. That is, when:

$$\Delta S \geq M = \frac{\Delta C}{(1-\alpha)\delta p} \tag{3.18}$$

We denote independent efforts by *ind*, complementary efforts by *com* and substitute efforts by *sub*. The results of the preceding analysis lead to the following characterization of an optimal contract:

Proposition 1. Given that high safety effort is implemented, the processor's willingness to induce high quality effort is increasing with the safety influencing parameter δ when $r \geq 0$, i.e., $M^{com} < M^{ind} < M^{sub}$.

Proof: (See Appendix B.2)

This proposition shows that when the local incentive is binding, it is the easiest to incentivize high quality effort when a high safety effort is exerted under complementary conditions, and it is the most difficult to incentivize high quality effort when the efforts are substitutes. The intuition behind proposition 1 is that under complementary conditions, the payment inducing high quality effort produces a spillover effect which also encourages the grower to exert high effort on safety. Therefore, the unit incremental cost of inducing quality effort under complementary conditions increases less quickly than the cost under unrelated or substitute conditions as one goes from one effort to two efforts. We should note that this finding continues to hold for both risk-neutral and risk-averse growers.

Proposition 2. When safety effort is fully observable, if the processor finds it is valuable to induce high quality effort, he has

1) no incentive to induce high safety effort voluntarily under a substitute condition when $r \geq 0$;
2) no incentive to induce high safety effort voluntarily under an independent condition when $r > 0$, and is indifferent to inducing high safety effort or not when $r = 0$;
3) incentive to induce high safety effort voluntarily under a complementary condition when $r = 0$; when $r > 0$, whether he has incentive to adopt high safety effort or not depends on the degree of complementarity of the two efforts.

Proof: (See Appendix B.3)

According to the proof in the Appendix, if the two efforts are substitutes, the critical value for the processor to induce high quality effort given high safety effort is higher than that given low safety effort. This is not surprising because implementing safety effort has a negative effect on improving quality of the product. Therefore, the processor would need to pay more to induce high quality effort.

We find that even if the two efforts are independent, the critical value for the processor to induce high quality effort given high safety effort is higher than that given low safety effort with risk-averse growers. Since efforts on improving quality and safety are technically unrelated, providing incentives on one effort will not affect the cost of incentives on the other effort. However, to implement high safety effort, the processor needs to incur an additional cost $\frac{r\varphi_s\varphi_q}{(1-\alpha)\,p}$ due to the risk sharing. The cost can be treated as efficiency loss because of the grower's risk aversion. Everything else being held equal, it becomes harder for the processor to induce high quality effort as the grower's degree of risk aversion r increases. If the grower is risk neutral ($r=0$), the processor need not pay any additional cost to induce the grower to implement safety effort.

If the two efforts are complements, the processor is more likely to incur quality effort with high safety effort when the grower is risk neutral ($r=0$). It is easier for the grower to accomplish quality effort at the margin when safety effort is implemented simultaneously. With a risk-averse grower, the processor needs to pay a risk premium to induce high safety effort. Thus, whether or not the processor is likely to induce high quality effort with high safety effort is determined by the impacts of parameter r and δ. If the effect of risk parameter r on the critical value is dominant, the processor is willing to induce low safety effort. If the effect of safety influencing parameter δ on the critical value is dominant, the processor prefers high safety effort.

3.3.3 Asymmetric information model with a traceability system

Let us turn to the case of incomplete information on both quality effort and safety effort. As in the previous case, the grower performs two activities with respect to quality effort and safety effort with the same production process. The two activities affect the stochastic production process simultaneously. Different from the previous case, the efforts provided by the grower in both quality and safety cannot be directly observed by the processor, although the measured quality level and whether there is a food safety problem or not is verifiable. Deviation attributed to a simultaneous shirking along both quality effort and safety effort dimensions may occur. Recall Proposition 2, when food safety is non-contractible, the processor implements high safety effort voluntarily if and only if quality and safety efforts are highly complementary. In order to decrease economic losses caused by food safety problems, a traceability system is introduced to the food-supply chain to encourage high safety effort in the production process. Traceability provides product information on the product's origins and can locate the source of the food safety problem. Thus, the processor requires the provision of effort in both quality and safety. In this section we analyze how incentive considerations affect the optimal mix of efforts along each dimension of the agent's performance and how traceability influences the incentives of growers to deliver safe products.

Figure 3.1 describes the possible events that could happen in the supply chain and their probabilities with varying quality and safety effort. A more detailed description of the notation can be found in table 3.7 in the Appendix. Define $\left(e_q, e_s\right)$ as the input pairs in quality effort and safety effort; $\left(y_q, y_s\right)$ are the realized output pairs in quality and safety. We assume that the production externality is asymmetric, which means that the effort level on quality does not influence the probability of safety level. This assumption ensures that high quality effort has no impact on the probability that a safe product is realized. If the grower exerts high safety effort, we denote the probability that his product is safe as t, and the probability that his product is unsafe $1-t$. βt and $1-\beta t$ are defined as the probability that safe product and unsafe product, respectively, are generated by low safety effort, where $0<\beta<1$. Parameter β reflects the likelihood that a safe product results given low safety effort relative to that given from high safety effort.

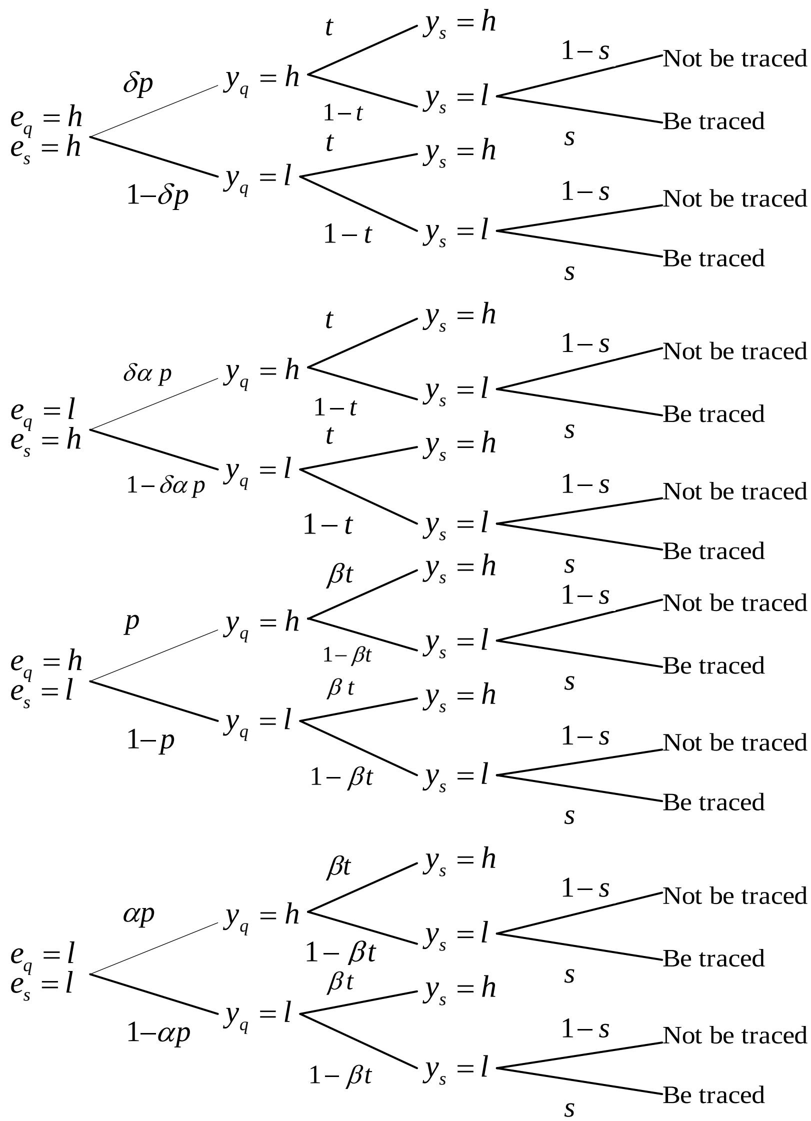

Figure 3.1. Possible efforts and outcomes in the supply chain

If the unsafe lot can be traced back to the responsible grower, the grower will be assessed a penalty. If the unsafe lot cannot be traced to the responsible grower, the grower need not pay any extra costs because of the unsafe food. We denote s as the traceability rate which is the probability that the origin of the unsafe product can be traced to the grower. Then the probability of the product being valued as high safety is the sum of the probability that the product is actually safe, and the probability that an unsafe lot cannot be traced back to the responsible grower. Therefore, the probability of the product being valued as high safety is $\left(t+\left(1-s\right)\left(1-t\right)\right)$ if high safety effort is implemented, and is $\left(\beta t+\left(1-s\right)\left(1-\beta t\right)\right)$ if low safety effort is implemented. This probability depends highly on the traceability rate. Since $s \leq 1$, even if a traceability system were in place, its performance is generally not one hundred percent reliable. Thus, the level of safety effort is only partly observable in the grower's results.

Recall the timeline of the principal-agent game, the contingent income is transferred to the grower based on the measured quality of the product at the delivery point, and then the transaction ends. When a traceability system is in place, it is possible for the processor to associate the unsafe product to the responsible grower with a certain probability success. When the product is detected as unsafe in the subsequent supply stages, the responsible grower is punished even after the transaction has occurred.

Here, we define $U_{ij(i,j=h,l)}$ as the final utility that the grower can obtain from the payment only if realized quality is i and realized safety is j. For example, if the grower implements both high quality effort and high safety effort simultaneously during his production process, the probability of being paid as high quality is δp and the probability of being paid as high safety is $\left(t+\left(1-s\right)\left(1-t\right)\right)$. Therefore, U_{hh} is obtained with probability $\delta p\left(t+\left(1-s\right)\left(1-t\right)\right)$. The probability distribution of output conditional on effort levels are presented in Table 3.1.

Table 3.1. Probability distribution of output conditional on effort level

Probability	$y = hh$	$y = lh$	$y = hl$	$y = ll$
$P(y\mid hh)$	$\delta p\big(t+(1-s)(1-t)\big)$	$(1-\delta p)\big(t+(1-s)(1-t)\big)$	$\delta ps(1-t)$	$(1-\delta p)s(1-t)$
$P(y\mid lh)$	$\delta\alpha p\big(t+(1-s)(1-t)\big)$	$(1-\delta\alpha p)\big(t+(1-s)(1-t)\big)$	$\delta\alpha ps(1-t)$	$(1-\delta\alpha p)s(1-t)$
$P(y\mid hl)$	$p\big(\beta t+(1-s)(1-\beta t)\big)$	$(1-p)\big(\beta t+(1-s)(1-\beta t)\big)$	$ps(1-\beta t)$	$(1-p)s(1-\beta t)$
$P(y\mid ll)$	$\alpha p\big(\beta t+(1-s)(1-\beta t)\big)$	$(1-\alpha p)\big(\beta t+(1-s)(1-\beta t)\big)$	$\alpha ps(1-\beta t)$	$(1-\alpha p)s(1-\beta t)$

When the processor cannot observe the grower's choices of quality effort and safety effort, he has to devise an output contingent contract. His problem is therefore to offer payments so that the grower puts in the two high efforts that maximize the processor's expected return. The grower can choose to exert high effort on both quality and safety, on only quality or only safety, or on no tasks at all. Similar to the previous case, an incentive feasible contract must induce the choice of a high investment on quality if the processor finds it is valuable.

$$\sum_{i,j=h,l} P(ij\mid hh)U_{ij} - \varphi \geq \sum_{i,j=h,l} P(ij\mid lh)U_{ij} - \varphi_s \tag{3.19}$$

Compared to the case with observable safety effort, two new incentive constraints must be added to describe the set of incentive feasible contracts. First, consider the incentive constraint to induce high safety effort:

$$\sum_{i,j=h,l} P(ij\mid hh)U_{ij} - \varphi \geq \sum_{i,j=h,l} P(ij\mid hl)U_{ij} - \varphi_q \tag{3.20}$$

Second, the global constraint prevents the grower from simultaneously reducing both quality and safety efforts.

$$\sum_{i,j=h,l} P(ij \mid hh)U_{ij} - \varphi \geq \sum_{i,j=h,l} P(ij \mid ll)U_{ij} \tag{3.21}$$

Finally, the grower will choose the level of efforts which gives him the largest payoff as long as this maximized value is no less than the reservation cost.

$$\sum_{i,j=h,l} P(ij \mid hh)U_{ij} - \varphi \geq 0 \tag{3.22}$$

The optimal incentive feasible contract is thus a solution to the following problem:

$$\min_{U_{ij}} C = \min \sum_{i,j=h,l} P(ij \mid hh)h(U_{ij}) \tag{3.23}$$

Subject to (3.19) ~ (3.22)

We should stress that there are important interaction effects between the grower's incentive for implementing one effort and the incentive for implementing the other effort. Thus, the two local constraints of the grower need not necessarily bind at the same time.

The optimal contract parameters can be written as follows:

$$U_{ij} = \lambda_1\left(1 - \frac{p(ij \mid lh)}{p(ij \mid hh)}\right) + \lambda_2\left(1 - \frac{p(ij \mid hl)}{p(ij \mid hh)}\right) + \lambda_3\left(1 - \frac{p(ij \mid ll)}{p(ij \mid hh)}\right) + \varphi \tag{3.24}$$

(See Appendix B.4)

The payment to the grower consists of a fixed component and three incentive components. The fixed component φ which is the cost of implementing two high efforts ensures that the grower accepts the contract. The first incentive component induces high effort on quality, the second incentive component induces high effort on safety, and the third one induces both.

Proposition 3. When $\frac{\varphi - \varphi_s}{\varphi - \varphi_q} > \frac{A}{B}$ and $\frac{\varphi - \varphi_s}{\varphi} > \frac{A}{D}$ are satisfied, the traceability system has no effect on the final payments of unsafe products, i.e., $U_{hh} - U_{hl} = 0$ and $U_{lh} - U_{ll} = 0$; otherwise, the processor pays more for safe products than for unsafe products, i.e., $U_{hh} - U_{hl} > 0$ and $U_{lh} - U_{ll} > 0$, where A, B and D are defined in the Appendix.

Proof: (See Appendix B.5)

From the proof in the Appendix B.5, we know $\lambda_2 = \lambda_3 = 0$ when $\frac{\varphi - \varphi_s}{\varphi - \varphi_q} > \frac{A}{B}$ and $\frac{\varphi - \varphi_s}{\varphi} > \frac{A}{D}$ are satisfied. This implies that equation (3.20) and (3.21) are always slack (satisfied) for all possible values of the traceability rate. In other word, for the grower, the benefit of implementing high safety effort is always higher than that of implementing low safety effort. According to the above analysis, this situation may only happen under the condition that quality and safety efforts are highly complementary. In this case, implementing high safety effort has a positive effect on improving the quality of the product, and the grower always chooses high safety effort regardless of the traceability rate. This proposition is very useful for providing guidance on the design of a traceability system. This result is corresponds to the finding of Starbird et al. (2008) which shows that it is possible that the traceability system has no influence on the expected utility of the agent. Except for this case, the payment of a high safety product is higher than that of a low safety product. The difference in the payment can be looked at as the disutility of penalty on delivering unsafe product. However, due to the complex settings, it is hard to characterize the optimal contract in an explicit form. More interesting experimental results will be showed in next section.

3.4 Simulation analysis

We now construct a simulation model to illustrate our comparative statics results for the fresh lettuce market. The main objective is to examine how an efficient contract is affected by alternative plausible values for parameters. To start, we list the values of parameters in table 3.2.

Table 3.2. Parameters used in the numerical example

Parameter	Value		
	Complements	Independence	Substitutes
p	0.85	0.85	0.85
$1-p$	0.15	0.15	0.15
αp	0.05	0.05	0.05
$1-\alpha p$	0.95	0.95	0.95
δp	0.95	0.85	0.75
$1-\delta p$	0.05	0.15	0.25
$\delta\alpha p$	0.06	0.05	0.04
$1-\delta\alpha p$	0.94	0.95	0.96
δ	1.12	1.00	0.88
α	0.06	0.06	0.06
β	0.40	0.40	0.40
t	0.80	0.80	0.80
φ_q	0.18	0.18	0.18
φ_s	0.015	0.015	0.015
φ	0.19	0.195	0.20

The average grower's price for fresh lettuce in the year 2006 was equal to \$ 0.18 per pound (USDA/ERS 2007). We assume that the cost of the main good agricultural practices which improve product safety is about 1.5 cent per pound. When the two efforts are independent, the cost of implementing two efforts simultaneously is the summation of the two effort costs, \$0.195; when the efforts are complements, the cost of implementing two efforts is assumed to be less than the summation and is equal to \$0.19; when the two efforts are substitutes, the cost of implementing two efforts is assumed to be higher than the summation and is equal to \$0.20. Here we assume the likelihood of obtaining high quality $(\alpha = 0.06)$ is far lower than the likelihood of obtaining high safety effort $(\beta = 0.40)$. This is because the performance on quality effort is measured more precisely than on safety effort.

Table 3.3 summarizes the results of our numerical examples where exogenous variables are varied for different scenarios. The first column gives the names of contract parameters. Expected payment to the grower is denoted by C. M is per unit incremental cost, in other word, the critical point that the processor incurs high quality effort. The second column provides the values of optimal contract parameters under the case when low safety effort is implemented. The next three columns give the solutions under the case when high safety effort is implemented and when the safety effort is fully observable.

Table 3.3. Simulation results on contract design

Variable	Value			
	With low safety effort	With high safety effort (Safety effort if observable $\beta = 0$ and $t = 1$)		
		Complements	Independence	Substitutes
U_h	0.214	0.199	0.229	0.266
U_l	-0.011	0.004	0.004	0.003
$h(U_h)$	0.225	0.209	0.242	0.284
$h(U_l)$	-0.011	0.004	0.004	0.003
C	0.190	0.199	0.206	0.213
M	0.237	0.223	0.258	0.303

The results in Table 3.3 show first that with high safety effort, the critical point of inducing high quality effort, M, is lowest (0.223) when efforts on improving quality and safety are complements. The critical point is the highest (0.303) when the two efforts are substitutes. Efficiency here requires that the processor pays more to give incentives to the grower to implement high quality effort because implementing high safety effort causes a negative effect on quality improvement.

With low safety effort, the critical point of inducing high quality effort is 0.237. While with high safety effort, the critical point is 0.258 with independent efforts and is 0.303 with substitute efforts. This implies when the two efforts are independent or substitutes, if the processor is willing to induce high quality effort, he prefers to implement low safety effort instead of high safety effort simultaneously. Under complementary conditions, the critical point is 0.223 with high safety effort which is lower than that with low safety effort (0.237). This demonstrates that complementarity between the two efforts can create an externality that can decrease incentive cost. Therefore, it makes the processor prefer taking high safety effort and high quality effort simultaneously.

Now we turn to the question of how the effect of traceability influences optimal contracts and what is the efficient design of the grower contract. From the simulation results, the global incentive constraint (3.21) is more stringent than the local incentive constraint on safety effort (3.20) under complementarity condition. This indicates that it becomes more difficult for the processor to induce the grower to exert high effort on both tasks simultaneously rather than on safety effort alone when both of the efforts are unobservable. When the efforts are substitutes, the local incentive constraint on safety effort (3.20) is more stringent than the global incentive constraint (3.21). This indicates it is more difficult for the processor to induce the grower to exert a high effort on safety alone rather than on both tasks simultaneously. Figure 3.2-3.5 and Tables 3.4-3.6 provide the simulation results.

Figure 3.2 illustrates the impacts of traceability on expected payment to the grower. We find that the expected payment always decreases with the increase of the traceability rate despite the relationship between the two efforts. This is because the traceability system has the effect of punishing growers held responsible for delivering unsafe products and hence of inducing more safety efforts.

Figure 3.2 also shows that the processor needs to pay more when the efforts are substitutes to induce both efforts than with either complementary or independent conditions. The intuition behind this is if the two efforts are substitutes, then providing incentive for high quality effort has a negative effect on the realization of high safety. Given high quality effort, the lower the possibility of high safety decreases the sensitivity of realization of the high safety product to the change in quality effort.

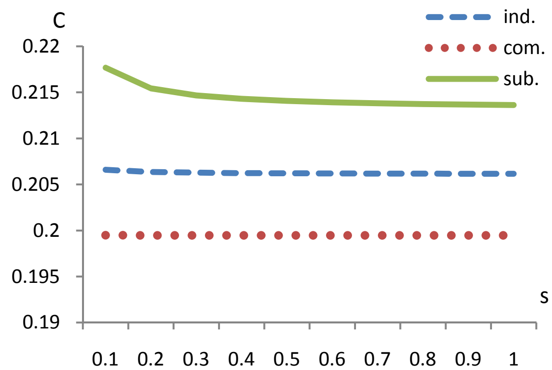

Figure 3.2. Expected payment to growers

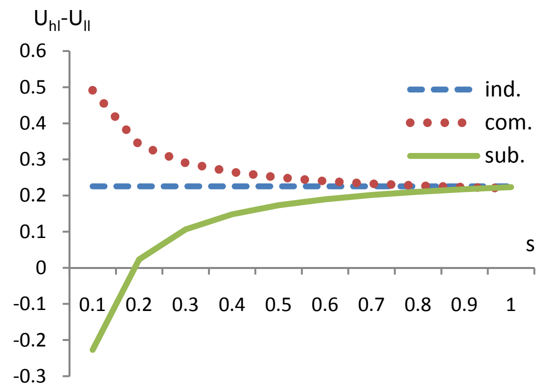

Figure 3.3. Utility difference between high quality and low quality with unsafe product

The simulation results indicate that the change in traceability rate has no influence on the payments to high safety products. Figure 3.3 depicts that if the product is detected as unsafe, with the increase of traceability rate, the payment difference between high quality product and low quality product $(U_{hl} - U_{ll})$ decreases when the efforts are complementary, increases when they are substitutes, and does not change when they are independent. When the two efforts are complements, the effort to improve food quality has a chance of improving food safety. A larger payment difference between high quality and low quality product is needed to encourage high safety effort when s is very small. The existence of a traceability system also has a positive effect on inducing high safety effort, and hence the payment difference is reduced when the traceability rate goes up. When the two efforts are substitutes, the effort on improving food quality makes the realization of safe product become more difficult. The grower has less incentive to implement high quality effort with higher levels of s. Thus the processor needs to increase the payment difference to encourage high quality effort. The fact that the payment difference under independent conditions is not influenced by the traceability rate is because there is no interaction effect between the two efforts.

It should be noted that when the traceability rate is very low $(s = 0.1)$, the payment difference when the efforts are substitutes, $U_{hl} - U_{ll} =$ -0.2273, is less than zero (see Table 3.6). In this case, the processor chooses to induce low safety effort instead of high safety effort. At this time the traceability is too low to differentiate safe and unsafe product. The processor has no incentive to pay extra costs to the grower to induce high safety.

Table 3.4. Simulation results under independent conditions

s	U_{hh}	U_{lh}	U_{hl}	U_{ll}	U_{hl}-U_{11}	U_{hh}-U_{hl}	U_{lh}-U_{ll}	C
0.1	0.2350	0.0098	-0.0775	-0.3027	0.2253	0.3125	0.3125	0.20660
0.2	0.2350	0.0098	0.0788	-0.1465	0.2253	0.1562	0.1563	0.20636
0.3	0.2350	0.0098	0.1309	-0.0944	0.2253	0.1042	0.1042	0.20628
0.4	0.2350	0.0098	0.1569	-0.0684	0.2253	0.0781	0.0781	0.20624
0.5	0.2350	0.0098	0.1725	-0.0527	0.2253	0.0625	0.0625	0.20621
0.6	0.2350	0.0098	0.1830	-0.0423	0.2253	0.0521	0.0521	0.20620
0.7	0.2350	0.0098	0.1904	-0.0349	0.2253	0.0446	0.0446	0.20619
0.8	0.2350	0.0098	0.1960	-0.0293	0.2253	0.0391	0.0391	0.20618
0.9	0.2350	0.0098	0.2003	-0.0250	0.2253	0.0347	0.0347	0.20617
1	0.2350	0.0098	0.2038	-0.0215	0.2253	0.0312	0.0313	0.20616

Table 3.5. Simulation results under complementary conditions

s	U_{hh}	U_{lh}	U_{hl}	U_{ll}	U_{hl}-U_{11}	U_{hh}-U_{hl}	U_{lh}-U_{ll}	C
0.1	0.1994	0.0099	0.19858	-0.2931	0.4917	0.00082	0.3030	0.1994835
0.2	0.1994	0.0099	0.19899	-0.1416	0.3406	0.00041	0.1515	0.1994725
0.3	0.1994	0.0099	0.19913	-0.0911	0.2902	0.00027	0.1010	0.1994688
0.4	0.1994	0.0099	0.19920	-0.0659	0.2651	0.00021	0.0757	0.1994669
0.5	0.1994	0.0099	0.19924	-0.0507	0.2499	0.00016	0.0606	0.1994658
0.6	0.1994	0.0099	0.19927	-0.0406	0.2399	0.00014	0.0505	0.1994651
0.7	0.1994	0.0099	0.19929	-0.0334	0.2327	0.00012	0.0433	0.1994646
0.8	0.1994	0.0099	0.19930	-0.0280	0.2273	0.00010	0.0379	0.1994642
0.9	0.1994	0.0099	0.19931	-0.0238	0.2231	0.00009	0.0337	0.1994639
1	0.1994	0.0099	0.19932	-0.0204	0.2197	0.00008	0.0303	0.1994636

Table 3.6. Simulation results under conditions of substitution

s	U_{hh}	U_{lh}	U_{hl}	U_{ll}	U_{hl}-U_{11}	U_{hh}-U_{hl}	U_{lh}-U_{ll}	C
0.1	0.2873	0.0142	-0.7635	-0.5362	-0.2273	1.0508	0.5504	0.21768
0.2	0.2873	0.0142	-0.2381	-0.2610	0.0229	0.5254	0.2752	0.21543
0.3	0.2873	0.0142	-0.0630	-0.1693	0.1063	0.3503	0.1835	0.21468
0.4	0.2873	0.0142	0.0246	-0.1234	0.1480	0.2627	0.1376	0.21430
0.5	0.2873	0.0142	0.0772	-0.0959	0.1730	0.2102	0.1101	0.21407
0.6	0.2873	0.0142	0.1122	-0.0775	0.1897	0.1751	0.0917	0.21392
0.7	0.2873	0.0142	0.1372	-0.0644	0.2016	0.1501	0.0786	0.21382
0.8	0.2873	0.0142	0.1560	-0.0546	0.2106	0.1314	0.0688	0.21373
0.9	0.2873	0.0142	0.1706	-0.0470	0.2175	0.1168	0.0612	0.21367
1	0.2873	0.0142	0.1822	-0.0408	0.2231	0.1051	0.0550	0.21362

Figure 3.4 and 3.5 show that the penalty on unsafe product is always decreasing with the increase of traceability rate in both high quality $U_{hh} - U_{hl}$ and low quality $U_{lh} - U_{ll}$ cases.

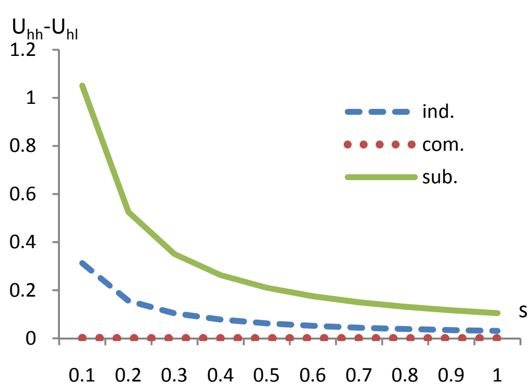

Figure 3.4. Penalty on low safety with high quality effort

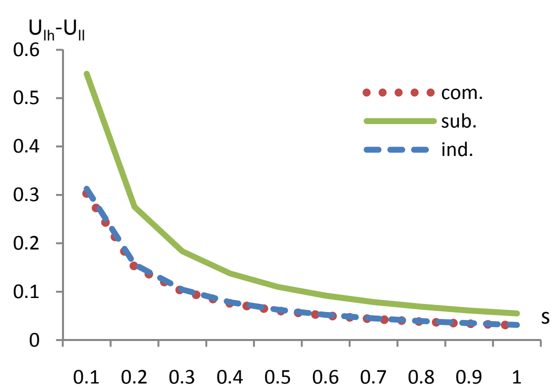

Figure 3.5. Penalty on low safety with low quality effort

It is not surprising because traceability has a positive effect on inducing high safety effort. Furthermore, the penalty is always highest when the two efforts are substitutes. This is because of the fact that the grower is not willing to exert high safety effort due to its negative effect on the realization of high quality, and the penalty should be high enough to induce high safety effort when s is very small.

3.5 Conclusions

The rise of food-safety related problems has received attention recently. In this paper, we present a discussion on the implications of the interaction between safety effort and quality effort on the behavior of the grower as well as contract design. The incentive structure with a tractability system is developed employing a multitask principal-agent model. The predictions of the theoretical model are given by simulation experiments. The primary contribution of this research is that we incorporate traceability into the analysis of contract design and investigate contractual relations for both food quality and food safety.

The model and simulation results show that 1) when high safety effort occurs, the processor induces high quality effort with lowest cost when quality and safety efforts are complements, and with highest cost when the two efforts are substitutes; 2) with complete information on safety effort, if the processor finds inducing high quality effort is valuable, he or she has no incentive to encourage high safety effort simultaneously when the two efforts are independent or substitutes; 3) If safety effort is unobservable and traceability is in place, the final payment to unsafe product is not higher than that to safe product; 4) The expected payments to the grower always decrease with an increase in the traceability rate. The expected payment is lowest when the efforts are complementary, and highest when they are substitutes; 5) The change in traceability rate does not influence payments for safe products; 6) If the product is detected as unsafe, with the increase of traceability, the payment difference between high quality product and low quality product decreases when the efforts are complementary, increases when they are substitutes, and does not change when they are independent; and finally, 7) The penalty on unsafe product decreases with the increase of traceability rate, and it is always highest when the two efforts are substitutes.

The findings of this research are interesting, but the validity of results is limited by the set of assumptions. Further research is suggested to assess the robustness of the results. Since real-world contracts between a processor and a grower may contain a provision on quantity of product, quantity is yet to be incorporated in the model and a complete menu of contract payments need to be evaluated. A traceability system will incur a variety of costs which may include investments in identifying devices, data recording and administrative fees. The cost could be passed to growers, recovered from added value to the final product, and/or be shared among all participants in the supply chain. With slight modification to the model, we can incorporate traceability costs into the model and analyze its effects on optimal contract design. Moreover, since the realization of quality level maybe more than two possible levels, or is characterized as a continuous variable, measurement of quality should to be examined if these settings have any effect on the incentive provisions.

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APPENDIX B

B.1. Deducing $\left\{U_h^*, U_l^*, h\left(U_h^*\right), h\left(U_l^*\right)\right\}$-safety effort is observable

From equation (3.2), we get

$$(1-\alpha)\,p\left(U_h - U_l\right) - \varphi_q \geq 0 \tag{B1}$$

To solve the processor's problem, we form the Lagrangian

$$\begin{aligned} L = {} & ph\left(U_h\right) + (1-p)\,h\left(U_l\right) \\ & + \mu\left(pU_h + (1-p)U_l - \varphi_q\right) + \lambda\left((1-\alpha)\,p\left(U_h - U_l\right) - \varphi_q\right) \end{aligned} \tag{B2}$$

The first-order conditions with respect to U_h and U_l are

$$\mu p + \lambda(1-\alpha)\,p = p\left(1 + rU_h\right) \tag{B3}$$

$$\mu(1-p) - \lambda(1-\alpha)\,p = (1-p)\left(1 + rU_l\right) \tag{B4}$$

From (B3) and (B4) we then have that the multiplier for the participation constraint μ equals to the expected payment to the grower, i.e.

$$\mu = p\left(1 + rU_h\right) + (1-p)\left(1 + rU_l\right) = 1 + rE(U) \tag{B5}$$

From the participation constraint we can get $E(U) = \varphi_q$, and the optimal contract parameters can be derived as follows:

$$U_h = \varphi_q + \frac{\lambda}{r}(1-\alpha) \tag{B6}$$

$$U_l = \varphi_q + \frac{\lambda}{r}\left(1 - \frac{1-\alpha p}{1-p}\right) \tag{B7}$$

Combing (B1), (B6) and (B7) yields the multiplier for the incentive compatibility constraint:

$$\lambda = r\varphi_q \frac{1-p}{p(1-\alpha)^2} \tag{B8}$$

Plug λ into (B6) and (B7), we get

$$U_h^* = \varphi_q + \varphi_q \frac{1-p}{p(1-\alpha)} \tag{B9}$$

$$U_l^* = \varphi_q - \varphi_q \frac{1}{1-\alpha} \tag{B10}$$

B.2. Proof of Proposition 1

Equations (3.16) and (3.18) yield the following results:

$$\Delta C = C - h(\varphi_s) = (\varphi-\varphi_s) + \frac{r}{2}\left(\varphi^2-\varphi_s^2\right) + \frac{r}{2}(\varphi-\varphi_s)^2 \frac{1-\delta p}{\delta p(1-\alpha)^2} \tag{B11}$$

$$\begin{aligned} M &= \frac{\Delta C}{(1-\alpha)\delta p} = \frac{1}{(1-\alpha)\delta p}\left[(\varphi-\varphi_s) + \frac{r}{2}\left(\varphi^2-\varphi_s^2\right) + \frac{r}{2}(\varphi-\varphi_s)^2 \frac{1-\delta p}{\delta p(1-\alpha)^2}\right] \\ &= \underbrace{\frac{\varphi-\varphi_s}{(1-\alpha)\delta p}}_{M_1} + \underbrace{\frac{r}{2}\frac{\varphi^2-\varphi_s^2}{(1-\alpha)\delta p}}_{M_2} + \underbrace{\frac{r}{2}(\varphi-\varphi_s)^2 \frac{1-\delta p}{\delta^2 p^2 (1-\alpha)^3}}_{M_3} \end{aligned} \tag{B12}$$

Since $\varphi^{com} < \varphi^{ind} = \varphi_q + \varphi_s < \varphi^{sub}$ and $\delta^{com} > \delta^{ind} = 1 > \delta^{sub}$, we get

$$M_1^{com} < M_1^{ind} < M_1^{sub}$$

and

$$M_2^{com} < M_2^{ind} < M_2^{sub}$$

Since $\partial M_3 / \partial \delta = \frac{r}{2} \frac{(p\delta-2)(\varphi-\varphi_s)^2}{p^2(1-\alpha)^3\delta^3}$ and $p\delta - 2 < 0$, we get $\partial M_3 / \partial \delta < 0$.

Thus, $M_3^{com} < M_3^{ind} < M_3^{sub}$ is satisfied.

Finally, we obtain

$$M^{com} < M^{ind} < M^{sub}$$

B.3. Proof of Proposition 2

Without adopting high safety effort, the critical point for the processor to induce high quality effort is

$$M^0 = \frac{1}{(1-\alpha)p}\left[\varphi_q + \frac{r}{2}\varphi_q^2 + \frac{r}{2}\varphi_q^2\frac{1-p}{p(1-\alpha)^2}\right] \tag{B13}$$

With high safety effort, when the two efforts are unrelated, $\delta = 1$, $\varphi^{ind} - \varphi_s = \varphi_q$, and the unit incremental cost is

$$M^{ind} = \frac{1}{(1-\alpha)p}\left[\left(\varphi^{ind} - \varphi_s\right) + \frac{r}{2}\left(\varphi^{ind\,2} - \varphi_s^2\right) + \frac{r}{2}\left(\varphi^{ind} - \varphi_s\right)^2\frac{1-p}{p(1-\alpha)^2}\right] \tag{B14}$$

Thus,

$$\begin{aligned} M^0 - M^{ind} = {} & \frac{1}{(1-\alpha)p}\left[\varphi_q + \frac{r}{2}\varphi_q^2 + \frac{r}{2}\varphi_q^2\frac{1-p}{p(1-\alpha)^2}\right] \\ & - \frac{1}{(1-\alpha)p}\left[\left(\varphi^{ind} - \varphi_s\right) + \frac{r}{2}\left(\varphi^{ind\,2} - \varphi_s^2\right) + \frac{r}{2}\left(\varphi^{ind} - \varphi_s\right)^2\frac{1-p}{p(1-\alpha)^2}\right] \end{aligned} \tag{B15}$$

we get

$$M^0 - M^{ind} = -\frac{r\varphi_s\varphi_q}{(1-\alpha)p} \leq 0, \text{ with } r \geq 0 \tag{B16}$$

When the two efforts are substitutes,

$$\begin{aligned} M^0 - M^{sub} = {} & \frac{1}{(1-\alpha)p}\left[\varphi_q + \frac{r}{2}\varphi_q^2 + \frac{r}{2}\varphi_q^2\frac{1-p}{p(1-\alpha)^2}\right] \\ & - \frac{1}{(1-\alpha)\delta p}\left[\left(\varphi^{sub} - \varphi_s\right) + \frac{r}{2}\left(\varphi^{sub2} - \varphi_s^2\right) + \frac{r}{2}\left(\varphi^{sub} - \varphi_s\right)^2\frac{1-\delta p}{\delta p(1-\alpha)^2}\right] \end{aligned}$$

$$\Rightarrow M^0 - M^{sub} = \underbrace{\left[\frac{\varphi_q}{(1-\alpha)p} - \frac{\varphi^{sub}-\varphi_s}{(1-\alpha)\delta p}\right]}_{\Delta M_1} + \underbrace{\frac{r}{2}\left[\frac{\varphi_q^2}{(1-\alpha)p} - \frac{\varphi^{sub2}-\varphi_s^2}{(1-\alpha)\delta p}\right]}_{\Delta M_2}$$
$$+\underbrace{\frac{r}{2}\left[\varphi_q^2\frac{1-p}{p^2(1-\alpha)^3} - \left(\varphi^{sub}-\varphi_s\right)^2\frac{1-\delta p}{\delta^2 p^2(1-\alpha)^3}\right]}_{\Delta M_3} \tag{B17}$$

Since $\varphi_q < \varphi^{sub} - \varphi_s$ and $\delta < 1$, it is easy to get $\Delta M_1 < 0$ and $\Delta M_2 < 0$ when $r > 0$.

$$\begin{aligned}\Delta M_3 &= \frac{r}{2}\left[\varphi_q^2\frac{1-p}{p^2(1-\alpha)^3} - \left(\varphi^{sub}-\varphi_s\right)^2\frac{1-\delta p}{\delta^2 p^2(1-\alpha)^3}\right]\\ &= \frac{r}{2}\left[\varphi_q^2\frac{\delta^2(1-p)}{p^2\delta^2(1-\alpha)^3} - \left(\varphi^{sub}-\varphi_s\right)^2\frac{1-\delta p}{\delta^2 p^2(1-\alpha)^3}\right]\end{aligned} \tag{B18}$$

Since $\delta^2(1-p) < 1-p < 1-\delta p$, then $\Delta M_3 < 0$ when $r > 0$. Thus, we get $M^0 - M^{sub} < 0$.

With $r = 0$, $M^0 - M^{sub} = \frac{\varphi_q}{(1-\alpha)p} - \frac{\varphi^{sub}-\varphi_s}{(1-\alpha)\delta p} < 0$.

When the two efforts are complements,

$$\begin{aligned}M^0 - M^{com} &= \frac{1}{(1-\alpha)p}\left[\varphi_q + \frac{r}{2}\varphi_q^2 + \frac{r}{2}\varphi_q^2\frac{1-p}{p(1-\alpha)^2}\right]\\ &\quad - \frac{1}{(1-\alpha)\delta p}\left[\left(\varphi^{com}-\varphi_s\right) + \frac{r}{2}\left(\varphi^{com2}-\varphi_s^2\right) + \frac{r}{2}\left(\varphi^{com}-\varphi_s\right)^2\frac{1-\delta p}{\delta p(1-\alpha)^2}\right]\\ &= \underbrace{\left[\frac{\varphi_q}{(1-\alpha)p} - \frac{\varphi^{com}-\varphi_s}{(1-\alpha)\delta p}\right]}_{\Delta M_1} + \underbrace{\frac{r}{2}\left[\frac{\varphi_q^2}{(1-\alpha)p} - \frac{\varphi^{com2}-\varphi_s^2}{(1-\alpha)\delta p}\right]}_{\Delta M_2}\\ &\quad + \underbrace{\frac{r}{2}\left[\varphi_q^2\frac{1-p}{p^2(1-\alpha)^3} - \left(\varphi^{com}-\varphi_s\right)^2\frac{1-\delta p}{\delta^2 p^2(1-\alpha)^3}\right]}_{\Delta M_3}\end{aligned} \tag{B19}$$

Since $\varphi_q > \varphi^{com} - \varphi_s$ and $\delta > 1$, it is easy to get $\Delta M_1 > 0$ when $r > 0$.

$$\begin{aligned}\Delta M_3 &= \frac{r}{2}\left[\varphi_q^2 \frac{1-p}{p^2(1-\alpha)^3} - \left(\varphi^{com} - \varphi_s\right)^2 \frac{1-\delta p}{\delta^2 p^2 (1-\alpha)^3}\right] \\ &= \frac{r}{2}\left[\varphi_q^2 \frac{\delta^2 (1-p)}{p^2 \delta^2 (1-\alpha)^3} - \left(\varphi^{com} - \varphi_s\right)^2 \frac{1-\delta p}{\delta^2 p^2 (1-\alpha)^3}\right]\end{aligned} \tag{B20}$$

Since $\delta^2 (1-p) > 1-p > 1-\delta p$, then $\Delta M_3 > 0$ when $r > 0$.

$$\begin{aligned}\Delta M_2 &= \frac{r}{2}\left[\frac{\varphi_q^2}{(1-\alpha)p} - \frac{\varphi^{com2} - \varphi_s^2}{(1-\alpha)\delta p}\right] = \frac{r}{2}\left[\frac{\delta\varphi_q^2}{(1-\alpha)\delta p} - \frac{\varphi^{com2} - \varphi_s^2}{(1-\alpha)\delta p}\right] \\ &= \frac{r}{2}\left[\frac{\delta\varphi_q^2 + \varphi_s^2 - \varphi^{com2}}{(1-\alpha)\delta p}\right]\end{aligned} \tag{B21}$$

ΔM_2 may be higher, lower than or equal to zero, hence whether M^0 is higher, lower than, or equal to M^{com} is undetermined.

With $r = 0$, $M^0 - M^{com} = \dfrac{\varphi_q}{(1-\alpha)p} - \dfrac{\varphi^{com} - \varphi_s}{(1-\alpha)\delta p} > 0$.

B.4. Deducing $\left\{U_{ij}^*\right\}$ $i, j = h, l$ -safety effort is unobservable

From equation (3.19)-(3.22), we form the Lagrangian

$$\begin{aligned} L = & \sum_{i,j=h,l} P(ij \mid hh) h\left(U_{ij}\right) \\ & + \lambda_1 \left[\sum_{i,j=h,l} \left(P(ij \mid hh) - P(ij \mid lh)\right) U_{ij} - \left(\varphi - \varphi_s\right)\right] \\ & + \lambda_2 \left[\sum_{i,j=h,l} \left(P(ij \mid hh) - P(ij \mid hl)\right) U_{ij} - \left(\varphi - \varphi_q\right)\right] \\ & + \lambda_3 \left[\sum_{i,j=h,l} \left(P(ij \mid hh) - P(ij \mid ll)\right) U_{ij} - \varphi\right] \\ & + \mu \left[\sum_{i,j=h,l} P(ij \mid hh) U_{ij} - \varphi\right] \end{aligned} \tag{B22}$$

From the first-order conditions with respect to U_{ij}, we get $\mu = 1 + rE(U)$. From the participation constraint we obtain $E(U) = \varphi$, and then the optimal contract parameters can be derived as follows:

$$U_{ij} = \lambda_1\left(1 - \frac{p(ij \mid lh)}{p(ij \mid hh)}\right) + \lambda_2\left(1 - \frac{p(ij \mid hl)}{p(ij \mid hh)}\right) + \lambda_3\left(1 - \frac{p(ij \mid ll)}{p(ij \mid hh)}\right) + \varphi \tag{B23}$$

B.5. Proof of Proposition 3

$$\begin{aligned} U_{hh} - U_{hl} = {} & \lambda_1\left[\left(1 - \frac{p(hh \mid lh)}{p(hh \mid hh)}\right) - \left(1 - \frac{p(hl \mid lh)}{p(hl \mid hh)}\right)\right] \\ & + \lambda_2\left[\left(1 - \frac{p(hh \mid hl)}{p(hh \mid hh)}\right) - \left(1 - \frac{p(hl \mid hl)}{p(hl \mid hh)}\right)\right] \\ & + \lambda_3\left[\left(1 - \frac{p(hh \mid ll)}{p(hh \mid hh)}\right) - \left(1 - \frac{p(hl \mid ll)}{p(hl \mid hh)}\right)\right] \end{aligned} \tag{B24}$$

Since $\frac{\beta t + (1-s)(1-\beta t)}{t + (1-s)(1-t)} < \frac{1-\beta t}{1-t}$, we get

$$\begin{aligned} \frac{p(hh \mid lh)}{p(hh \mid hh)} &= \frac{\delta\alpha p\left(t + (1-s)(1-t)\right)}{\delta p\left(t + (1-s)(1-t)\right)} = \frac{\delta\alpha ps(1-t)}{\delta ps(1-t)} = \frac{p(hl \mid lh)}{p(hl \mid hh)} \\ \frac{p(hh \mid hl)}{p(hh \mid hh)} &= \frac{p\left(\beta t + (1-s)(1-\beta t)\right)}{\delta p\left(t + (1-s)(1-t)\right)} < \frac{ps(1-\beta t)}{\delta ps(1-t)} = \frac{p(hl \mid hl)}{p(hl \mid hh)} \\ \frac{p(hh \mid ll)}{p(hh \mid hh)} &= \frac{\alpha p\left(\beta t + (1-s)(1-\beta t)\right)}{\delta p\left(t + (1-s)(1-t)\right)} < \frac{\alpha ps(1-\beta t)}{\delta ps(1-t)} = \frac{p(hl \mid ll)}{p(hl \mid hh)} \end{aligned} \tag{B25}$$

Because high quality is always induced at minimum cost, $\lambda_1 > 0$.

If $\lambda_2 = \lambda_3 = 0$ is satisfied, then $U_{hh} = U_{hl}$; otherwise, $U_{hh} > U_{hl}$.,

Similarly,

$$U_{lh}-U_{ll}=\left[\lambda_1\left(1-\frac{p(lh\,|\,lh)}{p(lh\,|\,hh)}\right)-\left(1-\frac{p(ll\,|\,lh)}{p(ll\,|\,hh)}\right)\right]+\lambda_2\left[\left(1-\frac{p(lh\,|\,hl)}{p(lh\,|\,hh)}\right)-\left(1-\frac{p(ll\,|\,hl)}{p(ll\,|\,hh)}\right)\right]$$
$$+\lambda_3\left[\left(1-\frac{p(lh\,|\,ll)}{p(lh\,|\,hh)}\right)-\left(1-\frac{p(ll\,|\,ll)}{p(ll\,|\,hh)}\right)\right] \tag{B26}$$

Since

$$\begin{aligned}
\frac{p(lh\,|\,lh)}{p(lh\,|\,hh)}&=\frac{(1-\delta\alpha p)\big(t+(1-s)(1-t)\big)}{(1-\delta p)\big(t+(1-s)(1-t)\big)}=\frac{(1-\delta\alpha p)}{(1-\delta p)}=\frac{(1-\delta\alpha p)s(1-t)}{(1-\delta p)s(1-t)}=\frac{p(ll\,|\,lh)}{p(ll\,|\,hh)}\\
\frac{p(lh\,|\,hl)}{p(lh\,|\,hh)}&=\frac{(1-p)\big(\beta t+(1-s)(1-\beta t)\big)}{(1-\delta p)\big(t+(1-s)(1-t)\big)}<\frac{(1-p)s(1-\beta t)}{(1-\delta p)s(1-t)}=\frac{p(ll\,|\,hl)}{p(ll\,|\,hh)}\\
\frac{p(lh\,|\,ll)}{p(lh\,|\,hh)}&=\frac{(1-\alpha p)\big(\beta t+(1-s)(1-\beta t)\big)}{(1-\delta p)\big(t+(1-s)(1-t)\big)}<\frac{(1-\alpha p)s(1-\beta t)}{(1-\delta p)s(1-t)}=\frac{p(ll\,|\,ll)}{p(ll\,|\,hh)}
\end{aligned} \tag{B27}$$

If $\lambda_2=\lambda_3=0$ is satisfied, then $U_{lh}=U_{ll}$; otherwise, $U_{lh}>U_{ll}$.

If $\lambda_2=0$, then (3.20) is slack, plug U_{ij} into (3.21), we get $\dfrac{\varphi-\varphi_s}{\varphi-\varphi_q}>\dfrac{A}{B}$,

where

$$A=\frac{\big(p(hh\,|\,hh)-p(hh\,|\,lh)\big)^2}{p(hh\,|\,hh)}+\frac{\big(p(lh\,|\,hh)-p(lh\,|\,lh)\big)^2}{p(lh\,|\,hh)}+\frac{\big(p(hl\,|\,hh)-p(hl\,|\,lh)\big)^2}{p(hl\,|\,hh)}+\frac{\big(p(ll\,|\,hh)-p(ll\,|\,lh)\big)^2}{p(ll\,|\,hh)}$$

$$\begin{aligned}
B=&\frac{\big(p(hh\,|\,hh)-p(hh\,|\,lh)\big)\big(p(hh\,|\,hh)-p(hh\,|\,ll)\big)}{p(hh\,|\,hh)}\\
&+\frac{\big(p(lh\,|\,hh)-p(lh\,|\,lh)\big)\big(p(lh\,|\,hh)-p(lh\,|\,ll)\big)}{p(lh\,|\,hh)}\\
&+\frac{\big(p(hl\,|\,hh)-p(hl\,|\,lh)\big)\big(p(hl\,|\,hh)-p(hl\,|\,ll)\big)}{p(hl\,|\,hh)}\\
&+\frac{\big(p(ll\,|\,hh)-p(ll\,|\,lh)\big)\big(p(ll\,|\,hh)-p(ll\,|\,ll)\big)}{p(ll\,|\,hh)}
\end{aligned}$$

If $\lambda_3 = 0$, then (3.21) is slack, plug U_{ij} into (3.20), we get $\frac{\varphi - \varphi_s}{\varphi} > \frac{A}{D}$;

where
$$D = \frac{\left(p(hh \mid hh) - p(hh \mid ll)\right)^2}{p(hh \mid hh)} + \frac{\left(p(lh \mid hh) - p(lh \mid ll)\right)^2}{p(lh \mid hh)}$$
$$+ \frac{\left(p(hl \mid hh) - p(hl \mid ll)\right)^2}{p(hl \mid hh)} + \frac{\left(p(ll \mid hh) - p(ll \mid ll)\right)^2}{p(ll \mid hh)}$$

Table 3.7. Notation for the contract model

$p = P(h_q \mid h_q, l_s)$	Probability of high quality generated by high quality effort and low safety effort.
$t = P(h_s \mid h_s)$	Probability of high safety generated by high safety effort.
$\alpha = P(h_q \mid l_q) / P(h_q \mid h_q)$	Likelihood of obtaining high quality given low quality effort relative to that given high quality effort.
$\beta = P(h_s \mid l_s) / P(h_s \mid h_s)$	Likelihood of obtaining high safety given low safety effort relative to that given high safety effort.
$\delta = P(h_q \mid h_q, h_s) / P(h_q \mid h_q, l_s)$	Likelihood of obtaining high quality effort given high quality effort and high safety effort to that given high quality effort and low safety effort.
s	Traceability that responsible growers are traced.
φ_q	Cost of implementing high quality effort.
φ_s	Cost of implementing high safety effort.
φ	Cost of implementing high safety effort and high quality effort
U_{hh}	Utility of payment to the grower when high quality and high safety are realized
U_{lh}	Utility of payment to the grower when low quality and high safety are realized
U_{hl}	Utility of payment to the grower when high quality and low safety are realized
U_{ll}	Utility of payment to the grower when low quality and low safety are realized

CHAPTER 4. POTENTIAL HPAI SHOCKS AND THE WELFARE IMPLICATIONS OF MARKET POWER IN THE U.S. BROILER INDUSTRY

4.1 Introduction

Highly pathogenic avian influenza (HPAI) has been recognized as a great concern for broiler production, wildlife conservation and public health. Between 2003 and August 2009, 62 countries reported HPAI cases in their domestic poultry or wildlife (Narrod 2009). The World Bank estimates that the HPAI disease could cost the world economy between US$800 billion dollars and US$3 trillion dollars (Narrod 2009). HPAI is highly contagious and causes severe illness in poultry with high mortality; it can cause mortality rates of 90% or higher in domesticated poultry within 48 hours of infection (CDC). With concern for transmission to humans, outbreaks of HPAI have caused major changes in demand, led to an increase in costs to producers through additional input use, and caused price volatility which could in turn induce dramatic market instability. The United States exports more poultry product than any other country in the world. When export markets are taken into account, even a relatively small outbreak has the potential to cause large welfare loss, especially if trade is restricted. Although mainly affecting the broiler sector and egg sectors, an HPAI shock is expected to influence other related livestock sectors as well.

To understand the potential welfare effects of HPAI, we consider the transmission of HPAI shocks through various stages of the broiler supply chain and through other livestock and related agricultural markets. The impacts of shocks are determined by the behavior of market agents who are involved in the transactions. Price characterizes the linkages between markets. Food scares can have differential effects on downstream suppliers and upstream suppliers, i.e., the extent to which price adjustments may be asymmetric. As example, both Sanjuán and Dawson (2003) and Lloyd et al. (2006) found that the retail price of beef decreased significantly less than farm level price in response to BSE outbreaks in U.K., and resulted in a substantial increase in the farm-retail margin and widening the food crisis. Even though the causes of asymmetric price transmission are complicated and multidimensional, market power is a possible important explanation for this differential. Under competitive conditions, shocks impact prices at each marketing level equally. "If market power exists then the spread between retail and producer supply prices behaves differently since price setting by the sector with market power will be reflected in the mark down that the firms can earn, and so affects the spread. " (Lloyd et al. 2006).

Livestock, poultry and meat sectors are vertically integrated in the United States. The linking of successive stages of production and marketing through ownership or contracting is widespread. For example, over 90 percent of the total production in broiler industry and more than a third of eggs are under ownership integration and contracts (Martinez 2002). Particularly, the processing industries become much more concentrated. Large processing establishments dominate production in all major meat sectors. In the year of 2005, the four largest processors accounted for 79%, 64% and 53% of purchases in cattle, hog and broiler industry, respectively (USDA 2009). Vertical integration between producing and processing activities in the meat industry results in reduced transaction costs, more uniformed food products and gains in economic efficiency. However, this vertical integration generally increases market power as shown below, and could increase welfare loss from an HPAI outbreak. With the increased importance of vertical integration, local farmers have access to only a few buyers and may be forced to accept a reduced distribution of profit or increased risk. Transportation costs, time of harvest, storage costs, or local specificity could limit the area over which products can be shipped (MacDonald et al. 2004). As MacDonald and colleagues (2004) indicate, contracts may extend market power by deterring entry by potential rivals, limiting price competition among existing rivals and facilitating discriminatory pricing.

In this paper we only focus on monopsony (buyer) market power, a situation which is traditionally more important in livestock and meat industries than monopoly (seller) power. Then the question is: Do the price effects of concentration vary across markets? How would the distribution of economic welfare across levels among agents differ following HPAI shocks under the environment of market power?

Many recent studies have conducted analyses on how Avian Influenza influences the economic outcomes of livestock and meat industries in the United States (Brown et al. 2007, Paarlberg et al. 2007, Djunaidi et al. 2007, and Fabiosa et al. 2007).However, these studies assume that the livestock and meat industries are competitive; none of these studies have accounted for market structure in modeling the price transmission of HPAI shocks. The principle objective of this research is to conduct an HPAI risk and cost analysis that accounts for potential market power within the whole meat supply chain. The paper is organized as follows: We next present the literature review. Then we develop a theoretical model to examine the potential impacts of market power on the distribution of economic welfare following a food scare. We then turn to empirical analysis on measuring the magnitude of market power for U.S. meat sectors. Next, we utilize an epidemiological-economic model to conduct simulation analyses on the potential spread and effects of an HPAI scare in U.S. broiler industry. The final section draws conclusions.

4.2 Review of literature

There has been a long-established interest for professionals in gaining a greater understanding of the potential existence of market power in food sectors. Following the work of Appelbaum (1982), a number of studies have attempted to examine market power in agricultural markets. The GIPSA/USDA study (1996) summarized the findings of previous studies relating to the effects of concentration in the red meat packing industry, and suggested that the results on market power are “mixed” and not consistent across studies. For example, Schroeter (1988) found statistically significant but limited oligopsony and oligopoly market power in beef packing industry; Azzam and Pagoulatos (1990) showed packers to have market power in both livestock procurement and meat sales; whereas Koontz, Garcia, and Hudson (1993) found no evidence of market power in beef industry in 1984-1986. The conflicting results among the studies are mainly because of limitations in the research methods or data. With recent consolidation in the red meat sector, the newer studies may be more relevant. The authors that found evidence of market power in the beef and pork packing industry include Muth and Wohlgenant (1999), Quagrainie, Unterschultz, Veeman and Jeffrey (2003).However, only a few studies have examined the broiler sector to see if buyers exert a significant amount of market power. Bernard and Willett (1996) analyzed asymmetric price relationships in U.S. broiler industry on both the regional and national levels. Vukina and Leegomonchai (2006) illustrated the poultry grower’s hold-up problem. Their results showed moderate empirical evidence that the grower’s under-investment behavior depends on the integrator’s market power in the broiler industry production contract. Key and MacDonald (2008) suggested a “small but economically meaningful effect” of local monopsony power in U.S. broiler industry using farm survey data.

There is a rich of literature investigating the farm-retail price margin and what factors influence price transmission in agricultural economics. High concentration as well as increased vertical dependencies in agricultural sectors is evident in most developed countries. Suppliers may pass only a small fraction of an input cost decrease to output price or pass all of input cost increase to output price (or both) in the environment of potential market power. Thus price signals are allowed to be passed up or down by market agents to capture welfare and profits for themselves relative to the competitive market (Azzam 1999, Meyer and von Cramon-Taubadel 2004, Miller and Hayenga 2001, Lopez, Azzam and Liron-Espana 2002). For meatpacking industries, empirical studies indicated that concentration may limit competition and enable meatpacking firms to exert monopoly power and keep prices low (Azzam 1997, Marion and Geithman 1995, Richards, Patterson and Acharya 2001).

In this study, a major effort is directed to the modeling and analysis of HPAI impacts on livestock industries when taking market power into account. Hence, the estimation and measurement of market power is critical. A number of studies have explored the methods of estimating market power in food industries. The empirical implementation can be classified among several approaches, including: the new empirical industrial organization approach (Baker and Bresnahan 1985); alternative reduced-form or nonparametric approaches (Panzar and Rosse 1987, Hall 1988); and a structural model system (Just and Chern 1980, Bresnahan 1982, Schroeter and Azzam 1990, Liang 1989, Cotterill 1994, Vickuer and Davies 1999). Hyde and Jeffrey (1999) developed a new technique for measuring market power in Australian beef, lamb, and pork markets simultaneously by extending the structural approach which allows estimation for more than one product.

4.3 Theoretical framework

We first develop a theoretical model to illustrate the potential impacts of market power on the price margin and the distribution of economic welfare following a food scare such as an HPAI outbreak. Following the assumption used in Schroeter and Azzam's study (1990), we assume "the existence of fully integrated firms spanning the farm-to-retail meat marketing channel and ignore all vertical relationships within the industry". This implies we do not decompose the farm-retail margin into farm-wholesale and wholesale-retail margins to identify if the exercise of market power occurs at the wholesale level or at the retail level. The model structure includes: producer supply, consumer demand on final product and retail supply. We assume that the final products produced by all firms are homogenous, and the industry technology is characterized by constant return to scale. Furthermore, to concentrate the model on the implications of market power, we simply assume the input-output coefficient to be 1. The food shocks enter into the model by taking the form of exogenous demand and/or supply shifters.

The inverse producer's supply can be expressed as

$$p^0 = f\left(q, Z_s\right) \tag{4.1}$$

where p^0 is the price received by the producer, and q is producer supply. Z_s denotes supply shifter caused by the food scare or outbreak.

The consumer's inverse demand for the retail product is

$$p = D\left(q, Z_d\right) \tag{4.2}$$

where p represents retail price. Z_d denotes demand shifter caused by the food scare.

The representative firm's profit maximization can be expressed as

$$p + \lambda p^{'}(q)q = C^{'}(q) \tag{4.3}$$

where λ represents the level of market power, and the value of λ ranges from zero (perfect competition) to one (monopsony). Values lying between these two extremes imply the presence of an intermediate degree of market power. $C^{'}(q)$ is the marginal cost of the firm and can be assumed as a linear function of producer level price p^0 and marketing cost w.

$$C^{'}(q) = p^0 + w \tag{4.4}$$

Let $\eta = (\partial q / \partial p)(p / q)$ which is less than zero denote the price elasticity of demand in the retail market, then equation (4.3) can be rearranged as

$$p\left(1 + \frac{\lambda}{\eta}\right) = p^0 + w \tag{4.5}$$

In order to obtain the industry-level expression of equation (4.5), we need to aggregate among firms. The industry-level conjectural variation interpreter $\lambda_{industry}$ can be estimated as the weighted average of individual conjectural variation interpreter λ, with firms' market shares as weights. As in many studies of market power (e.g., Azzam and Pagoulatos; Lopez, Wann and Sexton), we simply assume that the market share of each firm on the final market is identical. Thus, the conjectural variation interpreter at the industry level is $\lambda_{industry} = \lambda$.

Using (4.1), (4.2) and (4.5), the endogenous variables (q^*, p^{0*}, p^*) can be derived by implicit solutions. The price spread $r^* = p^* - p^{0*}$ can provide insight on how market power would change the impacts of the shocks. If market power exists, the exogenous shocks influence the prices at different supply chain stages to varying degrees. As a result, the price margin might be widened or narrowed depending on the demand elasticities as well as interactions of exogenous shifters. In the meantime, market power plays a role in determining the magnitude and distribution of welfare impacts. The producer's surplus $V^* = p^* q^*$ can be expressed as a function of price elasticities vector η, marketing cost w and market power parameter λ. In general form, the impacts of a demand shock and a supply shock caused by HPAI can be provided by

$$\frac{dr^*}{dZ_d} = \frac{\partial p(\eta, w, \lambda)}{\partial Z_d} - \frac{\partial p^0(\eta, w, \lambda)}{\partial Z_d} \tag{4.6}$$

$$\frac{dr^*}{dZ_s} = \frac{\partial p(\eta, w, \lambda)}{\partial Z_s} - \frac{\partial p^0(\eta, w, \lambda)}{\partial Z_s} \tag{4.7}$$

and

$$\frac{dV^*}{dZ_d} = \frac{\partial p(\eta, w, \lambda)}{\partial Z_d} \cdot q(\eta, w, \lambda) - p(\eta, w, \lambda) \cdot \frac{\partial q(\eta, w, \lambda)}{\partial Z_d} \tag{4.8}$$

$$\frac{dV^*}{dZ_s} = \frac{\partial p(\eta, w, \lambda)}{\partial Z_s} \cdot q(\eta, w, \lambda) - p(\eta, w, \lambda) \cdot \frac{\partial q(\eta, w, \lambda)}{\partial Z_s} \tag{4.9}$$

respectively.

In the beef and pork industries, marketing contracts are the prevalent method of vertical coordination. The marketing contract mainly specifies delivered quantities, product specification, compensation and quality control (MacDonald et al. 2004). The farmer makes most of his or her decisions which include how much to produce and how to produce. Here p^0 is farm level price, i.e, steer price for the beef industry and barrow-gilt price for the pork industry.

Unlike the beef and pork industries, most farms in the broiler, egg and turkey industries are linked to an integrator through production contracts. In a production contract, the integrator engages in many of the farmer's decisions like providing chicks, feed, veterinary services and retains ownership of important production inputs. In most cases, farmers invest only in production facilities according to the firm's specifications and certain management strategies. Under production contracts, farmers are paid for farming services, not for the products. Therefore, here, the producer's price p^0 is the wholesale level price instead of the farm level price. The impacts of market power will be transmitted along the whole supply chain and result in a different new market equilibrium compared with prefect competition.

4.4 Empirical analysis

4.4.1 Measurement of market power

To examine the impacts of market structure on economic outcomes in the food sector following an HPAI scare, it is important to measure the market power that might exist for each product within the livestock and meat sectors. Our study draws upon the method of Hyde and Jeffrey (1999) who simultaneously estimated an Almost Ideal Demand System (AIDS) model for Australia's retail meat sectors, a market power parameter and a marginal cost function for each product. This approach is more efficient than examining each good in isolation because "it makes use of information obtained from demand theory, such as price homogeneity restriction" (Hyde and Jeffrey 1999). Due to the substitution between meat products on the demand side, the prices of all meat products are included in the demand functions for each meat product. This enables us to capture substitution between meat products by consumers in response to relative price changes, which is important for examining the net impacts on one specific market. We modify Hyde and Jeffrey's model by analyzing market power in the whole supply chain instead of at the retail level only. In our study, the model estimates simultaneously the demand of major meat products: chicken, pork, beef, turkey and egg.

The demand component recognizes that in the very short run, meat production is essentially fixed, and thus price determination is at the retail level. The demand component also recognizes that the consumers' adjustment to changes in relative prices and income is not instantaneous, and consumers of the five meat products have preferences that are weakly separable.

The AIDS model includes expenditure share equations for the meat-poultry products that are related to the logarithm of total expenditure and the logarithms of relative prices. The model can be written as follows:

$$s_i = \alpha_i + \sum_{j=1}^{5} \gamma_{ij} \ln p_j + \beta_i \ln\left(X / P\right) \tag{4.10}$$

where s_i represent the share of commodity i, p_j denotes the retail price of good j, X is the total expenditure on the five meat products, and P is price index which is defined as:

$$\ln P = \alpha_0 + \sum_{i=1}^{5} \ln p_i + \left(1/2\right) \sum_i \sum_j \gamma_{ij} \ln p_i \ln p_j \tag{4.11}$$

The AIDS model satisfies the aggregation restriction $\sum_{i=1}^{5} \alpha_i = 1,\ \sum_{i=1}^{5} \beta_i = 0,$ and homogeneity, $\sum_{j=1}^{5} \gamma_{ij} = 0$, and symmetry, $\gamma_{ij} = \gamma_{ji}$,which can be imposed with parametric restrictions automatically.

In order to examine the potential impacts of market power on price reaction elasticities, the "integrated" firm's profit maximization conditions are considered to be endogenous in the demand system. One of the favorable characteristics of AIDS model is that it is plausible to incorporate theoretical restrictions on the system.

Recall the firm's maximization problem

$$p_i + \lambda_i p_i^{'}(q_i) q_i = C_i^{'}(q_i) \tag{4.12}$$

where $\lambda_i \in [0,1]$ is the parameter that captures market power (conjectural variation). That is, in a competitive market, we expect λ_i is equal to zero.

$C_i^{'}(q_i)$ is the marginal cost of product i. Differing from Hyde and Jeffrey's study, in this study p_i^0 and w denote producer price and marketing cost along the whole supply chain, respectively.

$$C_i^{'}(q_i) = a_i + b_i p_i^0 + d_i w \tag{4.13}$$

By substituting the (4.13) and $p_i^{'}(q_i)$ derived from the AIDS model into (4.12), the first order condition can be rewritten as

$$p_i = \left[a_i + b_i p_i^0 + d_i w - \frac{\lambda_i s_i}{q_i} \sum_{j \neq i} \frac{p_j q_j}{\gamma_{ij} - \beta_i s_j} \right] \times \left(1 - \frac{\lambda_i}{1 - \gamma_{ii} / s_i + \beta_i} \right)^{-1} \tag{4.14}$$

Then the AIDS model is estimated using a double logarithmic demand system by imposing parameter restrictions and the profit maximization restriction (4.14). The market power parameter λ_i can be obtained. The magnitude of price asymmetry depends not only on the level of market power but also on the demand elasticities. The data used in the demand system are obtained from USDA/ERS and NASS. The estimation in this study is based on a sample consisting of 96 quarterly observations that cover the period 1981:1 - 2004:4. The regression results are listed in table 4.1.

Table 4.1. Model estimates

Parameter	Estimate	Parameter	Estimate	Parameter	Estimate
α_1	-0.0012	γ_{44}	-0.0096	d_1	0.0163***
α_2	0.1432***	γ_{45}	0.0000***	d_2	0.0021***
α_3	1.0152***	γ_{55}	0.0393***	d_3	0.0014**
α_4	-0.0016***	β_1	0.1269***	d_4	0.0000***
α_5	-0.1557***	β_2	0.0256***	d_5	0.0001***
γ_{11}	0.0903***	β_3	-0.2123***	a_0	0.0000
γ_{12}	-0.0527***	β_4	0.0054***	λ_1	0.0342***
γ_{13}	-0.0161***	a_1	-0.0060***	λ_2	0.0499***
γ_{14}	0.0378***	a_2	-0.0010***	λ_3	0.1607***
γ_{15}	-0.0594***	a_3	-0.0007	λ_4	-0.0015
γ_{22}	0.0981***	a_4	0.0001*	λ_5	0.00004
γ_{23}	-0.0089***	a_5	0.0033*		
γ_{24}	-0.0373***	b_1	0.00001		
γ_{25}	0.0009***	b_2	0.0000		
γ_{33}	-0.0033	b_3	0.00002**		
γ_{34}	0.0091***	b_4	0.00000		
γ_{35}	0.0192***	b_5	0.00008*		

Note: *** 1% significance level; ** 5% significance; * 10% significance level
1-beef; 2-pork; 3-poultry; 4-turkey; 5-egg

Table 4.1 lists coefficients of statistical inference. Most parameters are statistical significant at the 5% level or less. These findings indicate the estimated market power index λ is statistically significant for the beef, pork and chicken sectors, which suggests that to some extent market power exists in these industries. The results also indicate that the overall concentration on the national level is quite small in terms of magnitude.

4.4.2 Economic impacts of HPAI under market power

4.4.2.1 Economic model

An epidemiological-economic model is developed to simulate the spread and effects of the disease in the poultry and other meat sectors. This approach differs from the study of Lloyd et al. (2006) which adopted a vector autoregressive (VAR) model to verify the influences of BSE disease on the farm-retail margin. Instead, here, a state-transition model of the transmission of Avian Influenza developed by Lawrence Livermore National Laboratory (LLNL) was used along with an economic model. The epidemiological model was developed to incorporate the dynamics of influenza A virus infection with birds and estimate the effect of different risk profiles on the final disease prevalence and infection rate. (Please refer to Fabiosa et al. for further details and references.) The economic model developed by the Center for Agricultural and Rural Development (CARD) at Iowa State University uses parameters generated by the epidemiological model to validate the potential effects of shocks associated with the disease on prices along the supply chain, domestic consumption, export, production and ending stock under different scenarios.

The CARD model is a multimarket partial equilibrium model and provides a complete depiction of key biological and economic relationships within five livestock and meat industries. The modeling effort updates previous work described in Jensen et al. (1989), and Buhr and Hayenga (1994). The model revisions accommodate updated results from re-estimated market models, added livestock sectors, and new technical production parameters. The model allows for components envisioned in the simulations of an Avian Influenza outbreak in broiler and egg industry. The current extended model system includes five meat sectors: broiler and chicken meat; turkey and turkey meat; layer and eggs; beef cattle and beef; and hog and pork. Each market in the model is assumed to be national in scope, and has a single national equilibrium price.

The structure of the model includes live animal supply, meat supply, meat demand, and price margin components. The econometric specification provides an abstraction of a complex system and aids in synthesizing information and causal relationships into a comprehensible form. Aggregate demand and supply can be partitioned to equations that define the behavior relationship between quantities and price and other event factors. The specification of the five supply sectors is based on a partial adjustment-adaptive expectations framework and is driven by the feed cost variable, output price and expected output on particular stages. The processes include biological restrictions inherent in livestock production, the appropriate lags to capture time periods required in production, technical parameters, and accounting identities to ensure consistency in the stock as well as flow variables. Relevant trade flows for the products involved are also modeled. In a word, the supply components of the models are determined by the biological relationship in the production process as well as on the economic considerations of meat producers.

Under the assumption that supply is fixed in the short run (less than one quarter), the meat demand system is estimated by an Almost Ideal Demand System (AIDS) which includes expenditure share equations for the all meat products. The linkage takes the assumption that consumers adjust their purchasing behaviors based on relative retail meat prices and the cross-commodity effects originate on the demand side. The marginal specifications provide a price linkage from the farm market to the retail market. The potential existence of market power and the optimal production condition for each sector are not included in CARD model. In this study, we update the estimation of the AIDS demand system by taking market power and its consequent impacts on economic outcomes into account.

The model has a simultaneous econometric framework where market equilibrium price and quantity for the five livestock sectors are jointly determined. Economic activity is initiated by the breeding decisions of livestock producers, and these are linked recursively to all other variables of the model system and simultaneously interact to determine each other's value. The supply and demand sides of each model are linked by market clearing conditions. Current prices influence future production and current consumption decisions. For this analysis, input markets are assumed to be exogenous. When the scenarios introduce a shock, responses captured through elasticities on the endogenous variables will shift the demand or supply curve, and thus induces price movements. Thereafter supply recovers gradually and stable supply path can be obtained again. A new equilibrium is achieved in which supply and demand are in balance. While a shock on the broiler industry may have an initial impact on the industry itself, the interdependencies between the industries and the supply chain integration ensure that the others are also affected to some extent. The influences of the shocks are different because of the differences in the endogenous variables' elasticities and in the relative variability of the series for the endogenous variables. The effects of market power involve adjustments on demand elasticities, which influence equilibrium prices and quantities, as well as the distribution of social cost through market relationships.

4.4.2.2 Scenarios

Following Fabiosa et al. (2007), the simulated market scenarios are classified according to the length and severity of the outbreak, number of birds removed from the market, percentage reduction in domestic and export demand for poultry products, duration of the demand shock, assumptions on diversion, and use of product destined for export markets. Since it is challenging to know in advance the range of an outbreak, this study examines three possible scenarios of the extent of HPAI on broilers and layers: high, medium and low. The epidemiological model generates data on infection rates and effects on national broiler production required by the economic model. An infection rate of 0.2% and duration of 90 days are generated for the low shock scenario. Infection rate and duration for medium and high shock scenarios are 0.4% and 180 days, 0.7% and 270 days, respectively. There is depopulation of pullets, chicks hatched and slaughter ready birds, applied in equal percentages to each sector spread out during the period of the outbreak.

On the domestic demand side, consumers are assumed to respond to an AI outbreak by decreasing purchase of chicken during the quarter when the outbreak happens. The decreasing level is 5%, 8% and 14% for low, medium and high scenarios, respectively. For the high scenario, the consumption decreases by 10% on the quarter following outbreak, while these is no decline on the following quarters for low and medium scenario.

For export, we assume export would be 50%, 25% and 10% below normal levels for high, medium and low scenarios, and shocks on export market fade over after 135, 270, and 405 days, respectively. A further issue is what happens to product destined for export should it be banned from the export market. If none of the retained product is “diverted” to secondary or alternative markets (e.g., pet food, rendered product, or other country destinations), this is termed 0% diverted, and all the banned export product is consumed in the United States. The product is either exported, consumed domestically, or added to ending stocks (cold storage). If all product is diverted (i.e., none is consumed by U.S. consumers), then 100% is diverted to low-valued, alternative use or disposed of. For each of the three scenarios (low, medium, and high), three levels of export diversion, 0%, 50%, and 100%, are considered. The assumptions underlying the scenarios for disease outbreaks for egg layers can be described similarly. The assumptions of each scenario are summarized in Table 4.2 (See Appendix).

4.4.2.3 Empirical results

The data used in the economic model include time-series data on the levels of production, price, consumption, exports, and stock for the period between the year of 1981 and 2004. The model is also calibrated by dynamic simulation over the same periods. Through calibration, the baseline-solved value of the endogenous variables equals the actual value. The baseline projections are developed in the first quarter of 2000 and cover the period 2000.1-2004.2. Effects of alternative scenarios are measured relative to this period. The firm-level production impacts and market-level changes in equilibrium prices and output are evaluated. Table 4.3 and Figure 4.6-4.12 (in the Appendix) provide simulation results of the broiler sector for the base line and the high-range shock with 0% export diversion under the environment of market power. The first four quarters of the scenarios are listed individually in the table and the remaining quarters are averaged annually since the impacts of external shocks are becoming smaller. The results from other cases and other sectors are not listed here because of space limitations.

The simulation results indicate that if HPAI is introduced into the United States, restrictions imposed on chicken trade will result in excess supply in the domestic market. Consequently, the HPAI market price of poultry products is lower than before because producers are not able to adjust production decisions in the very short run. From Table 4.3, a 50% decrease in export results in approximately a 35% decrease in the retail chicken price.

After trade restrictions are removed, the simulation reveals chicken prices recover above the level without an HPAI shock. Producers respond to the reduction of poultry prices by operating on a lower production function. But the long run impact of the HPAI shock on production is generally quite small. Only a larger demand or supply shock results in production decreasing by more than one percent from the baseline scenario. Producers are able to recover after the shock and sometimes achieve higher production than before the shock. As the retail price decreases, the ending stocks and per capita consumption of chicken increase due to the decrease in retail price.

The HPAI shocks also affect the other meat markets to some extent. For example, the AI outbreak has a negative demand shock on poultry. At the same time, the increase in chicken supply dominates market response and market prices decrease. The fall in poultry prices has a negative effect on demand for other meat products and leads a decrease in the prices in other meat markets. The magnitude of the substitution effect depends on substitution elasticities among these meat products and the degree of market power.

Table 4.5 presents the simulation results of chicken's total value under the environment of market power in comparison to a situation with perfect competition $(\lambda = 0)$. We can find the absolute value of the change in chicken's total value is higher with the existence of market power. That is, market power is more likely to lead to a higher change in the producer's surplus and deepen the effects of HPAI. As can be seen in Figure 4.1, the difference between the two scenarios is low and it amounts to no more than 0.2% in term of changes in case of perfect competition. The vertical dashed line in the figure separates the periods with trade restrictions and without restrictions (when they are relaxed).

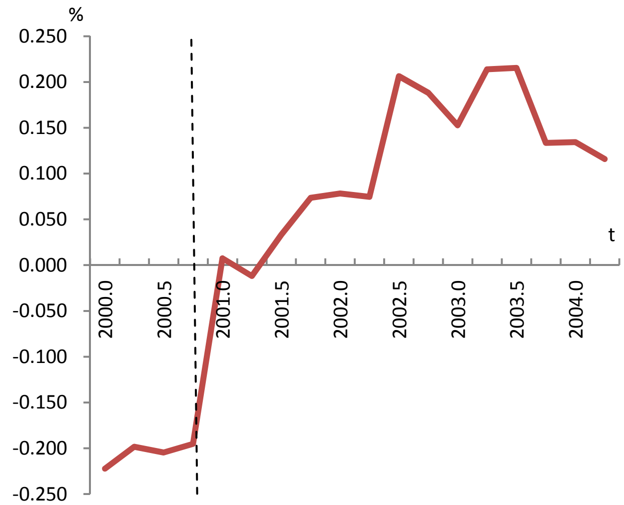

Figure 4.1. Percentage change in chicken's total value (with and without market power)

The changing patterns of the egg-layer sector are similar to those observed in the poultry sector except that per-capita consumption of eggs decreases from the beginning. Simulation results are summarized in Table 4.4 and Figure 4.13-4.19 (in the Appendix). For egg- layer sector, there are almost no differences between the simulations in case of perfect competition and market power. This is not surprising because we found no market power in egg-layer industry.

Now let's address the question of whether and how much market power influences the price margin along the supply chain. Although the existence of market power has varying impacts on different meat products, we focus on the broiler sector and layer sector only. As we indicated before, the farmers are paid for farming services instead of products. We analyze if there is a change in price margin at the retail level relative to the wholesale level in the presence of the HPAI shock.

Without the existence of market power, the demand and supply shocks play no role in determining the price margin. Correspondingly, if market power does characterize the market, then the demand or/and the supply shifter might influence the wholesale and retail prices to varying degrees and thus change the price margin. The econometric analyses of Lloyd et al. (2006) show that the price margin is positively affected by the demand shifter and negatively affected by the supply shifter. Whether and how the food scares change the price margin depends on which effect is dominant. We denote by p_{i0} and p_{i1} the baseline (no shock) and forecasted (with shock) poultry prices, where i indicates the wholesale $(i = w)$ and retail $(i = r)$ levels. Then we can obtain the change of the forecasted price margin and the baseline price margin $(p_{r1-}p_{w1})-(p_{r0-}p_{w0})$. Table 4.6 and Figures 4.2 and 4.3 show the change in poultry price margin resulting from an HPAI outbreak.

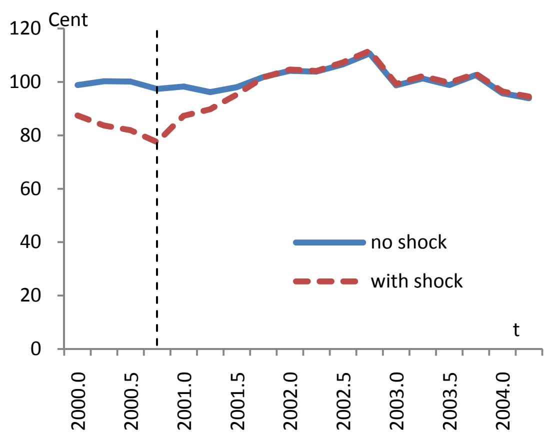

Figure 4.2. Wholesale - Retail poultry price margin

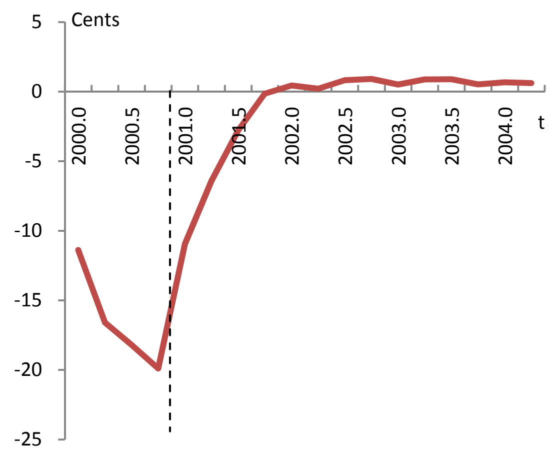

Figure 4.3. Change in Wholesale - Retail poultry price margin

The results illustrated in figures 4.2 and 4.3 suggest that the wholesale-retail margin of poultry products decreases for the first eight quarters following the shock. Recall that immediately after the outbreak of HPAI, the large scale export ban (supply shifter) leads to excess supply in domestic market. Due to the lag structure of supply functions, the trade restriction causes the retail price to decrease more than the wholesale price, and thus narrows the price margin. At the same time, the concern over food safety among consumers (demand shifter) also leads to lower retail price. Because impacts of the demand shock are greater on the upstream rather than downstream level with the existence of market power, the demand shock has the effect of widening the price margin. The decrease in price margin in this period suggests that the impacts of the supply shock dominate.

After the trade restriction is removed, the impact of the supply shock diminishes. On the demand side, the retail price rebounds with the recovery of poultry consumption. The wholesale level price response is lower than the retail price response. The impact of the demand shifter is greater than that of the supply shifter. Therefore, from the ninth quarter after the outbreak, the wholesale-retail price margin starts to increase and becomes wider. The results are consistent with the empirical findings of Bernard and Willett (1996) who indicated that the national retail price of poultry products showed upward asymmetry from the wholesale to retail level. Because the magnitude of market power is relatively low in the poultry market, we find the change in the price margin is quite small in absolute value and remains nearly constant in the long run.

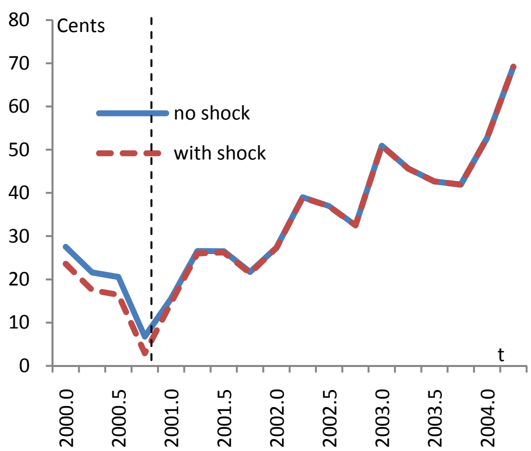

Figure 4.4. Wholesale - Retail egg price margin

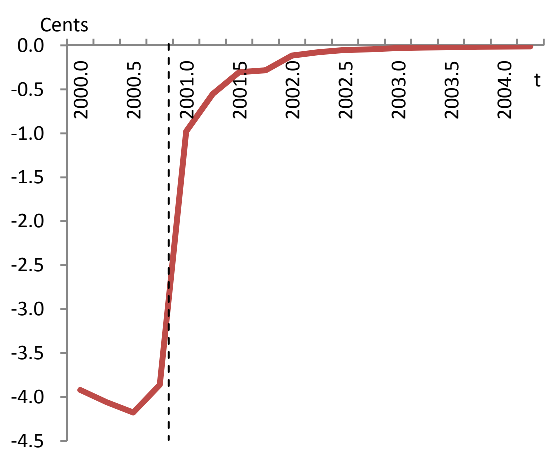

Figure 4.5. Change in Wholesale - Retail egg price margin

The changes in egg price margin resulting from the HPAI shock are represented by Table 4.7 and Figures 4.4 and 4.5. The results indicate that the supply shock leads the price margin to decrease immediately after the outbreak of HPAI. Since there does not exist market power in egg-layer sector, the price margin is not affected by the food scare after the trade restriction is removed.

4.5 Conclusions

This study is motivated by the lack of knowledge about the market structure's influence on the U.S. meat sectors following a potential HPAI shock on the broiler industry. A simulation approach is used to analyze the responses of producers and consumers on a potential HPAI scare in a market setting. Specifically, this study recognizes that suppliers in the meat industry may exert market power to make adjustments that affect the market environment in which they operate. The results suggest that the poultry retail price margin relative to the wholesale level of poultry products becomes smaller immediately after an HPAI outbreak (or shock) and then becomes wider with the recovery of poultry consumption. However, the results show that the magnitude of market power is relatively low in poultry market. Further work could be done to analyze the potential impacts of market power by relaxing the assumption that total expenditure on all meat products is fixed. Moreover, sensitivity of these simulation results could be examined to regional data.

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APPENDIX C

Table 4.2. Assumptions used in scenario analysis

Broiler scenarios

Range	Outbreak duration (days)	Broilers infected	Fraction broiler industry infected	Fraction of broiler industry affected by export bans exported	Export ban duration (days)	Consumer demand shift during outbreak	Consumer demand shift, in quarter following outbreak
low	90	2,500,000	0.2%	10%	135	5%	0%
med	180	5,000,000	0.4%	25%	270	8%	0%
high	270	10,000,000	0.7%	50%	405	14%	10%

Layer scenarios

Range	Outbreak duration (days)	Layers infected	Fraction layer industry infected	Fraction of broiler industry affected by export bans exported	Export ban duration (days)	Consumer demand shift during outbreak	Consumer demand shift, in quarter following outbreak
low	90	1,475,060	0.5%	10%	135	5%	0%
med	180	14,750,600	5.0%	10%	270	8%	0%
high	270	29,500,000	10.0%	10%	405	14%	10%

Table 4.3. Broiler sector simulation results for the high-range scenario (baseline and 0% export diversion)

Broilers	unit	2000.00	2000.25	2000.50	2000.75	2001	2002	2003	2004
Baseline									
Per Capita Consumption	Retail lb	23.46	23.85	22.99	22.68	23.42	24.86	25.40	26.34
Export	Thousand lbs	1135383.7	1189349.8	1275979.6	1317640.6	1388821.1	1201783.1	1230003.2	1014866.8
Ending Stock	Thousand lbs	795596.0	811422.0	815723.0	810293.0	682990.5	798225.3	662037.5	604163.5
Wholesale Price	$/cwt	54.58	55.70	56.81	57.56	59.11	55.52	61.96	76.25
Retail Price	$/lb	1.53	1.56	1.57	1.55	1.58	1.62	1.62	1.71
Production	Thousand lbs	7603368.0	7754304.0	7593955.0	7543544.0	7816452.2	8059930.5	8187249.0	8343283.0
Total Value (Retail Price*Production)	Thousand $	11662761	12095972	11919678	11688814	12327614	13044947	13290221	14275113
Scenario (high 0 xd)									
Per Capita Consumption	Retail lb	25.35	24.96	23.63	23.77	23.22	24.79	25.45	26.34
Export	Thousand lbs	583927.6	609507.0	651291.2	670485.5	1299213.4	1201115.4	1229662.0	1014419.2
Ending Stock	Thousand lbs	813722.2	825608.7	827587.7	820476.6	682612.1	797899.9	661874.5	604000.0
Wholesale Price	$/cwt	11.62	22.60	30.48	38.41	67.26	57.16	62.41	77.11
Retail Price	$/lb	0.99	1.06	1.12	1.16	1.61	1.64	1.63	1.73
Production	Thousand lbs	7585902.1	7472632.4	7140643.7	7191648.7	7608896.0	8040145.5	8200621.4	8342146.0
Total Value (Retail Price*Production)	Thousand $	7513701	7946950	8029144	8335680	12234584	13192615	13405573	14398132
Change of Total Value	Thousand $	-4149059	-4149022	-3890534	-3353134	-93030	147668	115353	123019

Table 4.4. Layer sector simulation results for the high-range scenario (baseline and 0% export diversion)

Layers	unit	2000.00	2000.25	2000.50	2000.75	2001	2002	2003	2004
Baseline									
Per Capita Consumption	Dozen	5.96	5.75	5.77	6.16	5.97	5.96	6.02	5.93
Export	Thousand Dozen	41037.93	37366.58	44717.83	48023.82	47485.22	43496.10	36490.88	30773.74
Ending Stock	Thousand Dozen	10626.42	10711.47	10952.16	11367.50	11466.21	9702.35	13208.43	14238.04
Wholesale Price	Cents/ dozen	68.07	66.05	68.80	86.05	70.35	69.24	79.16	89.45
Retail Price	$/ dozen	0.96	0.88	0.89	0.93	0.93	1.03	1.24	1.50
Production	Millions	1760166.7	1748833.3	1758166.7	1793833.3	1796895.8	1817645.8	1824104.2	1833083.3
Total Value (Retail Price*Production)	Thousand $	140226611	127713412	130934579	138723111	139140794	156402277	189405025	229696243
Scenario (high 0 xd)									
Per Capita Consumption	Dozen	5.70	5.27	5.17	5.70	5.84	5.96	6.02	5.93
Export	Thousand Dozen	38087.3	34240.4	40645.4	43549.1	46726.2	43478.5	36490.8	30774.3
Ending Stock	Thousand Dozen	10682.9	10754.4	10979.1	11388.1	11448.3	9701.4	13208.4	14238.1
Wholesale Price	Cents/ dozen	54.59	60.89	66.95	84.97	75.73	69.58	79.18	89.46
Retail Price	$/ dozen	0.78	0.78	0.83	0.88	0.98	1.03	1.24	1.50
Production	Millions	1685061.7	1614044.7	1589358.3	1664304.7	1758676.5	1815651.2	1824092.5	1833121.9
Total Value (Retail Price*Production)	Thousand $	109807854	105479551	110381395	121848890	143109572	156633343	189406040	229688108
Change of Total Value	Thousand $	-30418757	-22233861	-20553184	-16874221	3968778	231067	1015	-8135

Table 4.5. Chicken's total value (with and without market power)

Year	Total Value (Thousand $) (A)	Total Value (Thousand $) (B)	Difference (Thousand $) (B-A)	Percentage change (%) ((B-A)/A*100)
2000.00	7530444.3	7513701.5	-16742.8	-0.222
2000.25	7962746.9	7946950.1	-15796.9	-0.198
2000.50	8045606.1	8029143.6	-16462.4	-0.205
2000.75	8351977.2	8335680.2	-16297.1	-0.195
2001.00	11233413.0	11234249.3	836.3	0.007
2001.25	12030931.7	12029508.8	-1422.9	-0.012
2001.50	12739123.9	12743343.1	4219.2	0.033
2001.75	12944686.4	12954209.3	9522.9	0.074
2002.00	12681005.2	12690917.7	9912.6	0.078
2002.25	13167207.6	13177024.0	9816.4	0.075
2002.50	13671533.5	13699751.7	28218.2	0.206
2002.75	13172967.7	13197754.3	24786.7	0.188
2003.00	12400530.9	12419457.9	18927.0	0.153
2003.25	13505642.8	13534522.5	28879.7	0.214
2003.50	13830233.4	13860031.7	29798.3	0.215
2003.75	13811804.1	13830231.7	18427.7	0.133
2004.00	13969827.6	13988586.4	18758.8	0.134
2004.25	14795833.7	14812960.9	17127.2	0.116

Note: A-without Market Power; B-with Market Power

Table 4.6. Wholesale price, retail price and price margin before and after shocks (unit: cents/lb)-poultry

Year	p_{w0}	p_{r0}	p_{w1}	p_{r1}	$p_{w1}-p_{w0}$	$p_{r1}-p_{r0}$	$p_{r0}-p_{w0}$	$p_{r1}-p_{w1}$	$(p_{r1}-p_{w1})-(p_{r0}-p_{w0})$
2000.00	54.58	153.39	11.62	99.05	-42.96	-54.34	98.81	87.42	-11.38
2000.25	55.70	155.99	22.66	106.35	-33.05	-49.64	100.29	83.69	-16.60
2000.50	56.81	156.96	30.48	112.44	-26.33	-44.52	100.15	81.96	-18.19
2000.75	57.56	154.95	38.41	115.91	-19.14	-39.04	97.39	77.49	-19.90
2001.00	57.76	156.06	69.91	157.26	12.15	1.21	98.29	87.35	-10.94
2001.25	59.25	155.46	65.66	155.46	6.41	0.00	96.21	89.81	-6.41
2001.50	61.09	159.15	67.84	163.12	6.75	3.98	98.06	95.29	-2.78
2001.75	58.35	160.19	65.62	167.32	7.28	7.13	101.84	101.70	-0.14
2002.00	55.98	160.16	58.64	163.26	2.66	3.10	104.18	104.62	0.44
2002.25	56.11	160.00	55.56	159.66	-0.55	-0.34	103.89	104.10	0.21
2002.50	56.28	162.81	59.65	167.01	3.37	4.20	106.53	107.36	0.83
2002.75	53.71	164.43	54.78	166.41	1.07	1.98	110.72	111.63	0.91
2003.00	60.32	159.06	59.55	158.79	-0.77	-0.27	98.74	99.25	0.51
2003.25	59.59	160.88	61.86	164.03	2.27	3.15	101.29	102.17	0.88
2003.50	63.36	162.17	64.24	163.94	0.88	1.77	98.81	99.70	0.89
2003.75	64.58	167.20	63.98	167.12	-0.60	-0.08	102.62	103.14	0.52
2004.00	73.19	168.95	74.49	170.92	1.31	1.97	95.76	96.43	0.67
2004.25	79.31	173.24	79.72	174.27	0.41	1.02	93.93	94.54	0.61

Table 4.7. Wholesale price, retail price and price margin before and after shocks (unit: cents/lb)-layer

Year	p_{w0}	p_{r0}	p_{w1}	p_{r1}	$p_{w1}-p_{w0}$	$p_{r1}-p_{r0}$	$p_{r0}-p_{w0}$	$p_{r1}-p_{w1}$	$(p_{r1}-p_{w1})-(p_{r0}-p_{w0})$
2000.00	68.07	95.60	54.59	78.20	-13.48	-17.40	27.53	23.61	-3.92
2000.25	66.05	87.63	60.89	78.42	-5.15	-9.21	21.59	17.53	-4.06
2000.50	68.80	89.37	66.95	83.34	-1.85	-6.03	20.57	16.39	-4.18
2000.75	86.05	92.80	84.97	87.86	-1.08	-4.94	6.75	2.89	-3.86
2001.00	79.14	94.67	90.80	105.35	11.66	10.68	15.53	14.55	-0.98
2001.25	67.73	94.30	73.45	99.47	5.72	5.17	26.57	26.01	-0.55
2001.50	63.70	90.23	66.36	92.59	2.66	2.36	26.54	26.23	-0.30
2001.75	70.82	92.53	72.32	93.75	1.50	1.21	21.71	21.43	-0.28
2002.00	71.68	99.07	72.39	99.66	0.71	0.59	27.38	27.27	-0.12
2002.25	61.65	100.63	62.01	100.91	0.36	0.28	38.98	38.91	-0.08
2002.50	66.32	103.27	66.50	103.40	0.18	0.13	36.95	36.90	-0.05
2002.75	77.33	109.83	77.43	109.89	0.10	0.06	32.51	32.46	-0.04
2003.00	68.19	119.10	68.24	119.12	0.05	0.02	50.91	50.88	-0.03
2003.25	65.66	111.30	65.69	111.30	0.02	0.00	45.64	45.61	-0.02
2003.50	80.14	122.80	80.15	122.79	0.01	-0.01	42.66	42.64	-0.02
2003.75	102.63	144.57	102.64	144.56	0.00	-0.01	41.93	41.92	-0.01
2004.00	106.61	159.37	106.61	159.36	0.00	-0.01	52.76	52.75	-0.01
2004.25	72.30	141.50	72.30	141.49	0.00	-0.01	69.20	69.19	-0.01

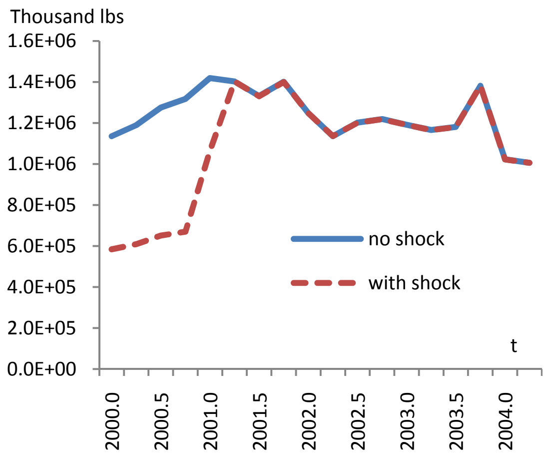

Figure 4.6. Young chicken exports

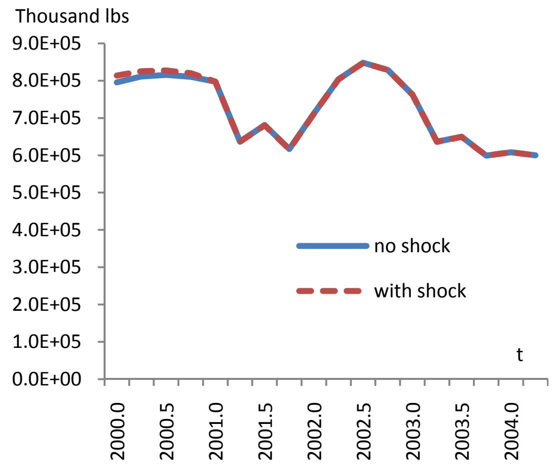

Figure 4.7. Young chicken ending stock

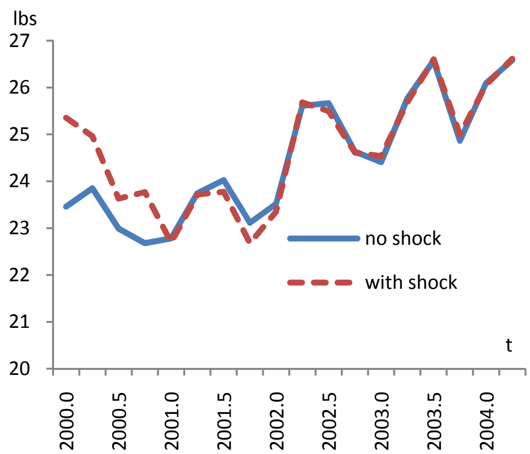

Figure 4.8. Per capital chicken consumption

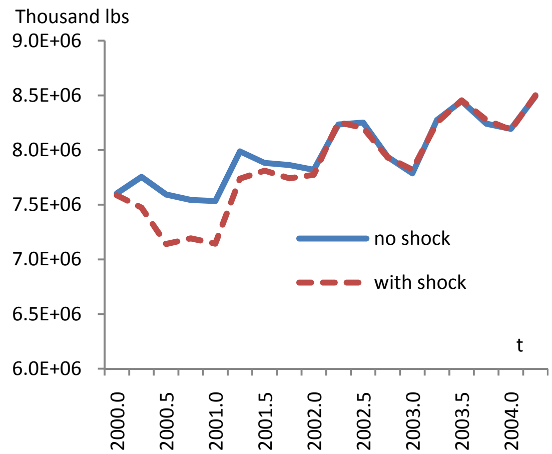

Figure 4.9. Young chicken production

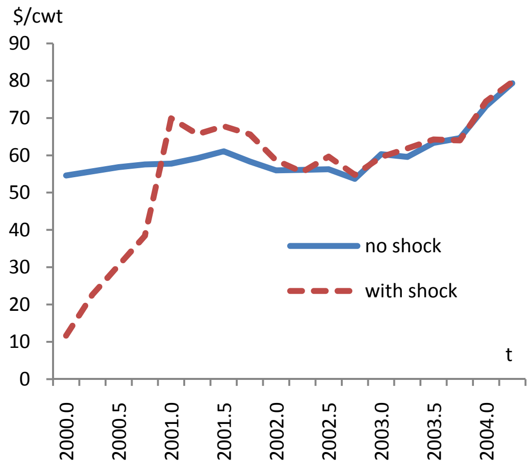

Figure 4.10. Wholesale chicken price

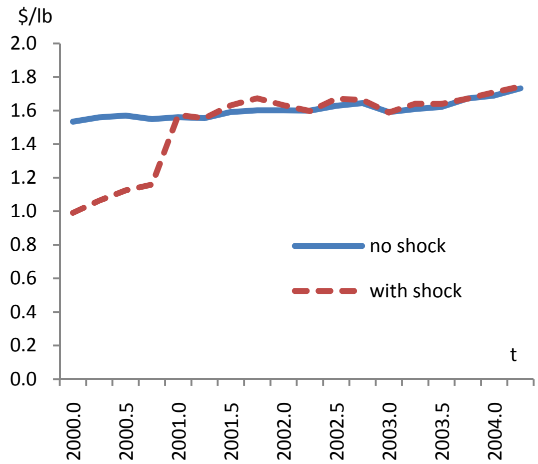

Figure 4.11. Retail chicken price

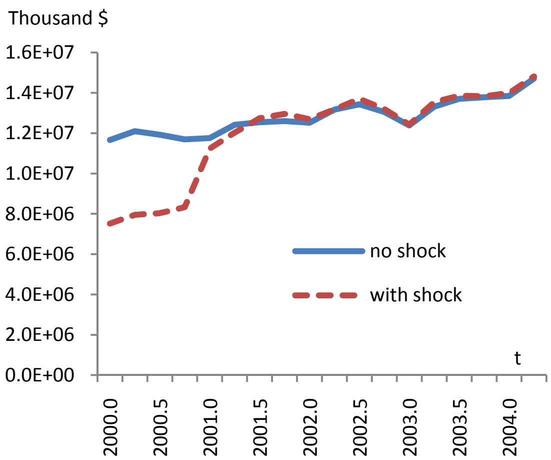

Figure 4.12. Total chicken value

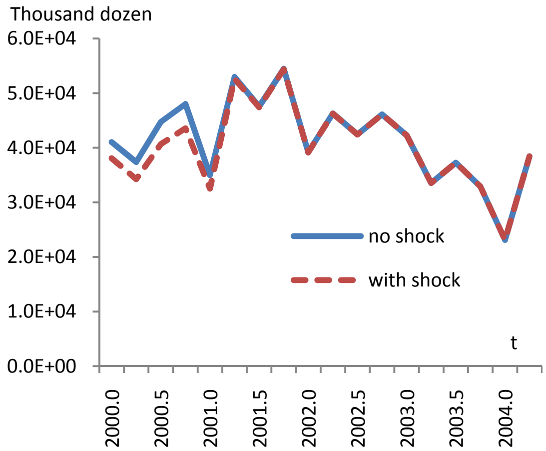

Figure 4.13. Egg exports

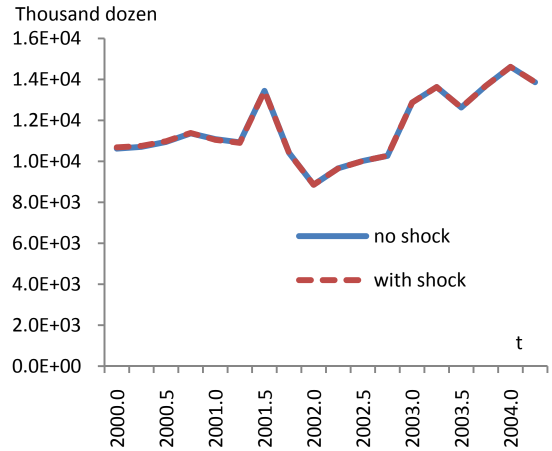

Figure 4.14. Egg ending stock

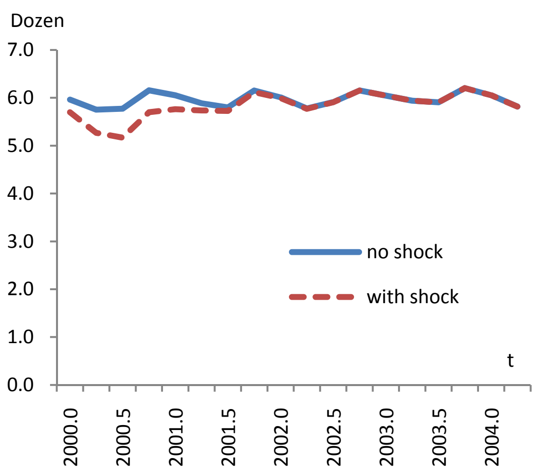

Figure 4.15 Per capita egg consumption

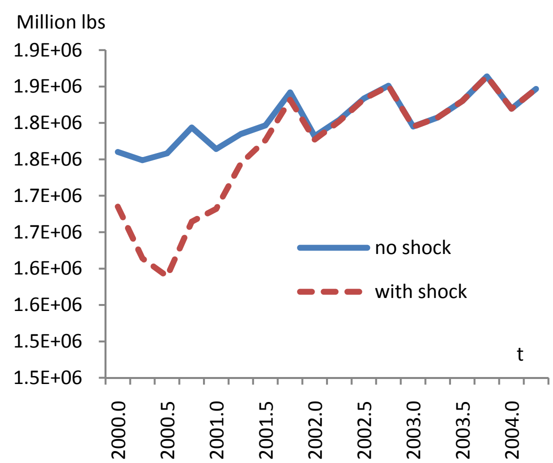

Figure 4.16 Egg production

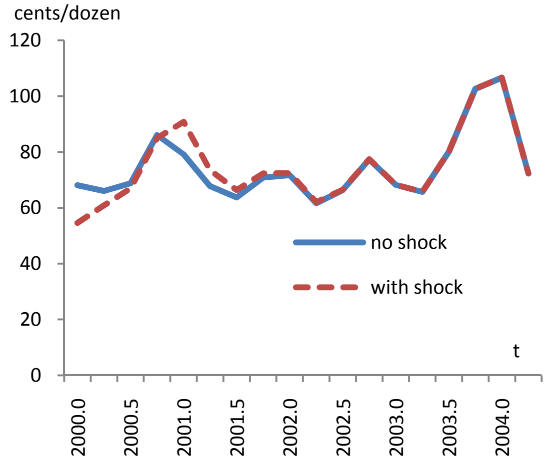

Figure 4.17. Wholesale egg price

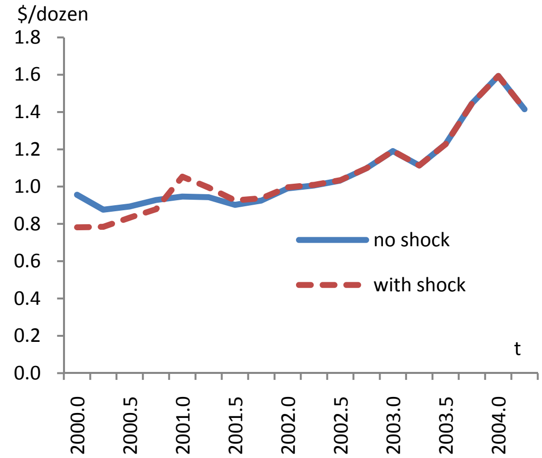

Figure 4.18 Retail egg price

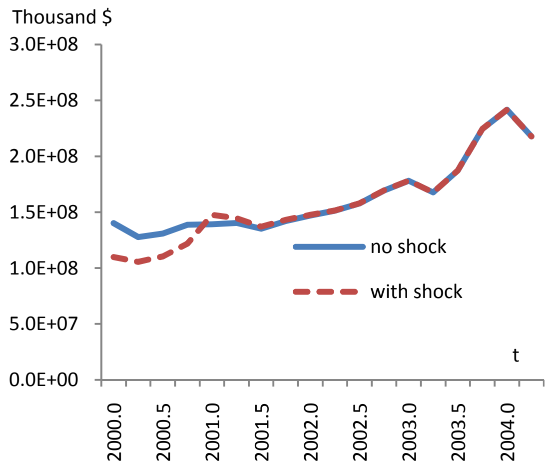

Figure 4.19 Total egg value

CHAPTER 5. GENERAL CONCLUSIONS

This dissertation examines the economic impacts of foodborne illnesses with a main focus on the supply side. The organization of the dissertation is characterized by three stand-alone studies, each examining an independent subject on food safety problems. The integrating theme lies in their common interest in understanding the influence of food safety failure on agricultural market sectors, and efforts and solutions to improve food safety along the whole supply chain.

Chapter 2 presents a theoretic analysis on how and under what conditions, monitoring activities might mitigate the fraudulent activities of food growers under a voluntary marketing agreement. The crucial distinction between our paper and studies to date is that we allow for endogenous detection in an on-farm inspection setting, i.e., the detection rate of noncompliance with GAP, which depends on the effort the producer implements and how much auditing resource is spent by enforcement activities. We examine the relationship between monitoring methods, producers' returns, and the probability of a food safety failure. Results reveal that in responding to monitoring activities by enforcement agency, farmers increase their efforts to adopt GAPs up until perfect compliance is achieved. Meanwhile, to avoid being identified as the source of food safety incidents, farms adopt GAPs voluntarily to reduce their food-borne risk, even in absence of monitoring. Findings from this study also suggest that if the monitoring resource is not enough to cover the necessary inspection costs of achieving optimal safety level, the agency will discriminate among farms to maximize total producers' surplus. The general rule of allocating inspection resources is to allocate them such that the total amount of decreased fraud in terms of safety effort for each farm is same. When auditing resources are very low, the size effect is dominant and larger farms will be inspected first; when the resources are large enough, the cost effect is dominant and the agency will target small farms first. The optimal auditing probability for small farms always has a larger rate of increase than for large farms.

Chapter 3 develops implications of food safety for contract design in the fruit and vegetables industry. This research is novel in considering the interaction between safety effort and quality effort on the behavior of the grower, and incorporating the traceability system into the analysis of the contract design. The study provides theoretical evidence on the proposition that, when high safety effort is fully observable and implemented, the processor induces high quality effort with lowest cost when quality effort and safety effort are complements and with highest cost when the two efforts are substitutes. The results also reveal that, if the processor finds that inducing high quality effort is valuable, he has no incentive to implement high safety effort simultaneously when the two efforts are independent or substitutes.

Simulations based on the assumption that the safety effort is unobservable and traceability is in place suggest further that the final payment to unsafe product is not higher than that to safe product; the expected payment to the grower always decreases with the increase in the traceability rate (i.e., rate of tracing product to source of hazard); the expected payment is lowest under complementary conditions, and is highest when the two efforts are substitutes. The change in traceability rate does not influence the payments to safe products; if the product is detected as unsafe, with the increase of traceability rate, the payment difference between high quality product and low quality product decreases when the efforts are complementary, increases when they are substitutes, and does not change when they are independent. The penalty applied to unsafe product decreases with the increase of the traceability rate, and is always highest when the two efforts are substitutes.

In Chapter 4 an empirical analysis is developed to evaluate the potential risk and effects of HPAI disease in the United States. In contrast with similar studies that take an assumption that the livestock and meat industries are competitive, this study incorporates market structure into the analysis in modeling the price transmission of HPAI shocks. Findings imply that the estimated market power index is statistically significant for the beef, pork and chicken sectors, and suggests that, to some extent, market power exists in these industries. The results also indicate that the overall concentration on the national level for all livestock sectors is quite small in terms of magnitude.

The simulation results indicate that if HPAI is introduced into the United States, restrictions imposed on chicken trade will result in excess supply in the domestic market. The market price of poultry products with an HPAI outbreak is lower than before because producers are not able to adjust production decisions in the very short run. After trade restrictions are removed, the simulation reveals chicken prices recover above the level without an HPAI shock. Producers respond to the reduction of poultry prices by operating with a lower production. But the long run impact of the HPAI shock on production is generally quite small. Producers are able to recover after the shock and sometimes achieve higher production than before the shock. As the retail price decreases, the ending stocks and per capita consumption of chicken increase due to the decrease in the retail price. The HPAI shocks also affect the other meat markets to some extent. In the short run, the decreasing demand for poultry substitutes would decrease prices in those markets and would have feedback effects on the demand of poultry products. The magnitude of the substitution effect depends on substitution elasticities among these meat products and the degree of market power. The results also suggest that the retail price margin relative to the wholesale level of poultry products becomes smaller immediately after the HPAI shock and then becomes wider with the recovery of poultry consumption. However, our results show that the magnitude of the effect of market power is relatively low in the poultry market. We find that the change of price margin is small in absolute value and remains almost constant in the long run.

This dissertation models and analyzes the economic impacts of food safety problems. In order to capture the essence of these questions and focus on the critical factors we opt for sacrificing some other considerations in our theoretical analysis. This approach, on one hand, provides a clear picture how efforts can improve food safety along the supply chain. On the other hand, it leaves much room for improvement in the future. Extensions to this dissertation could span across several directions as follows.

In Chapter 2, we analyze the optimal monitoring policy taking the assumption that all farms are risk neutral and have the same risk preference. A more complicated analysis could be developed when the risk preferences differ. Second, the monitoring resource is assumed to be exogenous in our model. A useful extension would be to examine the design of an efficient user-fee scheme in a second-best policy setting. Third, the industry response to contamination seems to be dynamic, and more discussion of dynamic response may lead to interesting implications.

In Chapter 3, the assumption on the two realizations of quality level could be extended to continuous levels. The provision on quantity could be included in the model to reflect as well as possible, the reality. In addition, to analyze more closely the nature of the contract in the fruit and vegetable industry, the payment to the grower could be expressed in an explicit form, such as a linear function which includes a base payment and quality premium. Including these ingredients could enable these models to consider a deeper understanding of the performance of food safety on agricultural supply chain.

In Chapter 4, we analyze the economic impacts of a potential HPAI shock on U.S. meat industries on the national level. Further work could be done to determine the sensitivity of these results to regional data.

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