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The Economics of Traceability for Multi-Ingredient Products: A Network Approach

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Paper Presented at the Annual Meeting of the
American Agricultural Economics Association
Providence, Rhode Island
July 24-27, 2005

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The Economics of Traceability for Multi-Ingredient Products: A Network Approach

Abstract: The consumption of multi-ingredient foods is increasing across the globe as consumers spend less time preparing meals. Traceability is now extensively used to reduce information imperfections in food markets and recent EU law suggests it will be implemented for manufactured meals as well. We present a model developed to understand how information on different ingredients flows through supply chains for multi-ingredient food products. The network model has three tiers linked by contracts for levels of quality and information. The model is useful for analyzing tradeoffs and network effects emerging in the choice of traceability levels.

Keywords: Traceability, multi-ingredient foods, network models

The Economics of Traceability for Multi-Ingredient Products: A Network Approach

Asymmetries in or the absence of information on critical attributes cause uncertainty in food supply chains. This is particularly true for food safety, including potential bioterrorism risks, where multiple parties have an interest in timely access to information. Both public and private authorities have advocated traceability as the best tool to solve or at least reduce issues associated with inadequate information. Several public traceability systems are already in place; they differ across countries and industries, in levels of sophistication, and in whether they are mandatory or voluntary. At the same time, private systems are proliferating.

To date studies of the supply of traceability have focused on single ingredient products. These may or not be processed along the supply chain but are not combined with other products until they reach the consumer. However, in the United States and many other countries consumers are increasingly buying and consuming pre-prepared meals or meal products that minimize time spent on preparation. Many of these products have multiple ingredients and involve a level of processing where an industrial cooking facility prepares and packages the final product.

In addition, when analyzing the economics of traceability the network structure of food supply chains and its effects must be recognized and taken into account. Food supply chains involve relationships between firms at different stages, whose actions impact other firms and consumers with whom they may not have direct contact. When the network structure of supply chains is not considered, comparison of different traceability systems and their effects on competitiveness and the liability exposure of firms may be incomplete. The model developed here focuses on the economics of traceability for multi-ingredient products, while recognizing network effects.

Network Approaches to the Economics of Markets and Traceability

There is a growing body of literature analyzing the economic impact of traceability. However, analysis is lacking that considers the many important elements of traceability systems in a single framework. Traceability involves coordination of different agents, the sharing of information, close links to quality assurance systems, and the development of new types of organizations. Economists have considered each of these aspects of traceability extensively but independently.

Traceability is a supply chain issue as it involves coordination of product attributes and process information among producers, processors, and distributors. Externalities emerging from imperfect information may be considerably amplified as the number of agents in the supply chain increases. Furthermore, more complex quality assurance and management systems are required as the number of participants at each level and the number of levels in the supply chain increase. The literature on networks and supply chains provides a framework for building an integrated perspective on markets for quality and information. Two main streams of this literature derive from industrial organization and from operations research and management science.

From the industrial organization perspective, the term network relates more to the characteristics of a good or a commodity than to firms in supply chains. In their seminal paper, Katz and Shapiro (1985) discuss products whose utility of consumption rises with the number of consumers using them. They identify three positive consumption externalities: 1) those generated by the physical effect of the number of purchasers on the quality of the product; 2) indirect effects leading to consumption externalities, and 3) effects on the quality and availability of post-sale service for durable goods due to the experience and size of the network. These externalities are common in products such as telephones, computers and associated software, stereos, cars, and a wide variety of other products. Katz and Shapiro develop models of oligopolies where consumption externalities are present and analyze the effects on competition and compatibility decisions. They conclude that the expectations of consumers play an important role in markets where network externalities are present and that public intervention may be required when the source of network externalities is a compatibility decision.

Economides (1996) suggests that network externalities imply a need for some sort of coordination or compatibility between firms producing goods subject to such effects. He distinguishes the "macro" approach to network externalities, which assumes their existence and analyzes the impact of such effects, from the "micro" approach that seeks to explain the original cause of such effects. Economides proposes a classification of networks and models to analyze cases of compatibility and incompatibility, effects on industry structure, the importance of sequential games, and markets for adapters and add-ons. He employs a variety of game theory models to illustrate different problems arising in network products and markets, using examples from the telecommunications market. The main conclusion is that lessons learned in markets where network effects are prevalent apply to other markets structures where vertical relations exist.

While most food products cannot be classified as network products (Shy 2001), network externalities arise in several ways. An example of the kind of network externalities Katz and Shapiro (1985), Economides (1996), and Shy (2001) focus on is the effect of microwave technology on the market for ready to eat frozen meals: there was not much incentive for the food industry to produce microwave meals until a sufficient number of households adopted the technology. Information on the characteristics of food production and processing, which constitute the base of traceability, can be analyzed as a network product. Agents in the supply chain may have to engage in or avoid actions depending on what they know about what other agents in the supply chain are doing. In addition, many agricultural commodities are complementary, as in the case of bread and butter, and therefore presumably subject to positive network externalities.

Though these examples illustrate situations where network approaches would be welcome in analyzing food markets, to date there is not much research on food as a network product. The industrial organization approach to network economics emphasizes the need to analyze coordination and the impacts of each firm's actions on other agents in the supply chain.

From an operations research and management science perspective, network economics addresses many different issues from decisions on optimal flows of products or production, to storage and distribution locations and the strategic behavior of firms and regulating authorities at different levels of supply chains. Fearne (1998), for example, uses an operations research perspective to describe the evolution of the British beef supply chain. He focuses on motivations for horizontal and vertical relationships, developing the concept of a "learning chain," where competition is increasing between food chains, rather than between partners within a supply chain. Supply chains that establish strong bonds among partners, and that are able and committed to learning from their mistakes, will have a better chance of succeeding.

The management science approach uses mathematical network models to obtain quantitative solutions to highly complex problems involving several different agents who are linked by different paths in multiple tiered supply chains. Most problems are addressed using computational algorithms, such as those based in variation inequality. Nagurney (1999) presents this methodology and illustrates its application to transportation, information, financial, energy, and communication networks. This literature provides important insights into how network externalities influence product flows and provides solutions to problems in which different criteria of optimization can be simultaneously considered.

For example, Dong, Zhang, Yan, and Nagurney (2005) develop an application of networks models, based on the variation inequality methodology, to multi-tiered supply chains where agents have multiple and different criteria and there is uncertainty. They consider a supply chain composed of manufacturers, distributors, and retailers who compete within a tier but cooperate between tiers. Their conclusions provide equilibrium conditions for all agents in the network. The result is an integrated view of the supply chain that optimizes the flows for the entire system rather than for individual components. The management science approach provides a powerful mathematical framework with which to analyze the supply chain as an integrated system of independent agents.

In addition, contract theory provides a convenient framework to analyze the flow of information among participants in a supply chain. The relationships between parties at different stages of a food supply chain are often modeled as contracts, where one of the parties, the principal, needs the other party, an agent, to engage in a costly activity that benefits the principal. The principal-agent model is particularly suited for the analysis of cases where information is costly. In such cases different organizational forms may be more economical than the price system in obtaining efficient outcomes (Silberberg and Suen 2001).

Moral hazard and adverse selection are also issues successfully tackled using a principal-agent model. Typically the principal decides what unobservable level of effort e, in an interval limited by minimum and maximum levels, will be induced from an agent. A contract is designed to obtain such an effort level, with the compensation scheme linked to effort levels (Tirole 1988).

Principal-agent models are widely used to analyze imperfect information issues in agricultural and food markets from analysis of poultry contracts to quality assurance system applications. Starbird (2005), for example, uses such a model to examine how inspection policies affect food safety. A principal decides what price w to pay for higher or lower levels of technology and methods used to improve food safety. His main conclusion is that the sampling inspection policy has a significant impact on the production of safer food.

The challenge in this paper is to merge the principal agent model into a network economics framework. This goal is accomplished by modeling the principal as using a price scheme to obtain appropriate levels of quality and information from agents at different levels in the supply chain network.

The Demand for and Supply of Traceability

Several different approaches to traceability systems for agricultural and food products are already in place. They differ across countries and products, and have been motivated by a wide variety of scientific, social, and economic factors. Public and private decisions to adopt traceability systems have important economic implications (Hobbs 2003, Golan et al. 2003). In addition to their impact on food safety, traceability systems can affect animal health and production management decisions (see Disney et al. 2001; Petit 2001; Vitiello and Thaler 2001). Traceability also affects the structure of supply chains because it requires coordination and allocation of costs and benefits among participants in order to work efficiently (Kola and Latvala 2002).

The economic impacts of traceability have only recently started to be played out. Meuwissen, Velthuis, Hogeveen, and Huirne (2003) identify three gaps in the literature: 1) what is the break even point for levels of traceability, 2) what are the impacts on current liability and recall insurance schemes, 3) how can regulatory incentives be created to avoid free-riding? They offer an overview of potential costs and benefits of traceability and certification in meat supply chains. Traceability costs are associated with system implementation (e.g., changes in procedures, decreased flexibility, and increased automation, inventory, personnel, and documentation) and maintenance (through auditing). The benefits include increased transparency, reduced risk of liability claims, more effective recalls, enhanced logistics, improved control of livestock epidemics, possible positive effects on trade, easier product licensing, and possible price premia.

Hobbs (2002) focuses on the role of traceability in the food system and distinguishes “between ex post trace back systems and ex-ante quality verification systems (p.1)". Traceability has three main functions: 1) reduce costs associated with risks of food safety occurrences; 2) strengthen liability incentives, and 3) allow for ex ante verification of credence quality attributes. The main problem yet to be solved is how to make sure that the information flow is credible.

Golan et al. (2003) suggest that traceability is a "record-keeping system primarily used to help keep foods with different attributes separate from one another (p. 27)." They address the question of the usefulness of mandatory traceability as a policy choice. They suggest that mandatory traceability for product differentiation, when it does not target specific attributes of value to consumers, will be too costly and unnecessary. Also mandatory traceability may be inefficient for the purpose of increasing food system safety, as it would reduce the incentives for firms to innovate in order to improve safety levels.

According to Golan et al. (2004), while in Europe traceability has been mainly motivated by regulations, in the US it tends to be motivated by economic incentives. They surveyed several different systems of traceability in agro-food industries and characterized them using three dimensions: depth (how far up and downstream the system goes), breadth (how many attributes are traced), and precision (to what extent the origin is correctly identified). They found that there is no single best way to introduce traceability and there is a large variability in the characteristics of system within and across industries, depending on specific attributes of products or motivations to introduce traceability. Souza-Monteiro and Caswell (2004) describe and compare mandatory and voluntary traceability systems for beef supply chains found in seven countries in terms of their depth, breadth, and precision. They show there are considerable differences among countries and that the European Union and Japan have the most sophisticated systems. Different motivations, specific product characteristics, and even socio-cultural patterns may determine what levels of traceability are acceptable and to what extent traceability should be adopted.

The Demand for Traceability

Dickinson and Bailey (2002) analyze the existence of a market for meat traceability in the US. Since there is no publicly available data to measure the market for traceability in the US, the authors turned to a laboratory experiment to estimate the willingness to pay for traceability. Their experimental design follows the one proposed by Shogren, Shin, Hayes, and Kliebenstein (1994), in which participants make bids to upgrade a beef or pork sandwich.

The results suggest that consumers from all groups were willing to pay more for food safety assurance, a guarantee of humane animal treatment, or no growth hormones than for traceability. This study also revealed that traceability was more valued when combined with the other attributes tested. The main conclusion is that, if the results obtained in the experimental design can be verified with other trials, a profitable market for traceability and other assurance systems may exist in the United States.

Similar experiments conducted by Hobbs (2002, 2003) in Saskatchewan and Ontario, showed that Canadians would be willing to pay a premium of less than 10% for traceability on a beef sandwich worth C$2.50. However most consumers associated other meat characteristics (such as safety and natural production) with traceability, which may have inflated the bid values reported. Based on these results, Hobbs concluded that consumers are not willing to pay for traceability alone. Hence, to have appeal to consumers traceability systems should be linked with quality assurance for credence goods and provide information before consumption. A further conclusion is that the credibility of the source of information matters. Canadian consumers view government agencies and independent quality assurance firms as more credible sources of information.

Overall, the results of research in Canada and the United States suggest that traceability alone does not appeal to consumers. Rather it has value to consumers when it is associated with a desirable quality assurance system or other product attributes.

The Supply of Traceability

To date the analysis of the supply of traceability has mainly focused on the meat and grain sectors. For example, Buhr (2003) analyzed the adoption of traceability in the European meat and poultry sectors. His findings suggest that information asymmetry between final product handler and consumer is one of the reasons to introduce traceability. However a stronger motivation is to reduce information issues among participants in the supply chain. Incentives to adopt traceability are larger when there is: 1) high production uncertainty, 2) more doubt associated with moral hazard and opportunistic behavior, 3) increasing monitoring costs, and 4) incapacity to identify traits.

Starbird and Amanor-Boadu (2004) analyze the implications of introducing traceability in a food supply chain where there is an inspection protocol. They model the relationship between a producer and processor, using principal agent theory. The producer is the agent and knows how safe the product is, while the processor (the principal) does not know the quality and safety of the product. The processor wants to offer a price that maximizes his profit while forcing the producer to deliver information and a safe product.

The model developed here departs from the current analysis on the economics of traceability in two key ways. First, it embeds the informational and quality assurance aspects of traceability in a network model. The linking of information and quality assurance is important because research on demand for traceability suggests there may be little value to consumers for traceability alone. Furthermore, a network approach is necessary to capture interrelationships between members of a supply chain. The second point of departure in the model is the consideration of multi-ingredient foods. These products are becoming an increasing share of food purchases and can pose complex challenges for traceability, including how much traceability to apply to different ingredients and the benefits and costs of traceability throughout the supply chain.

Modeling Traceability in Multi-Ingredient Supply Chains

Traceability is a flow of higher or lower levels of information on input and product characteristics, including origin and process attributes, across agents in the supply chain. In the model developed here, information and quality levels are choice variables in an optimization problem involving agents in a food supply chain.

We use the three-tiered network structure presented in figure 1 to model traceability in supply chains for multi-ingredient products. This is a hierarchical and directed network. According to Jackson (2005), a hierarchical network is one where a single actor chooses flows; the decisions depend on a single agent. He defines directed networks as those where three or more agents do not necessarily need to be connected in order for flows to occur between them.

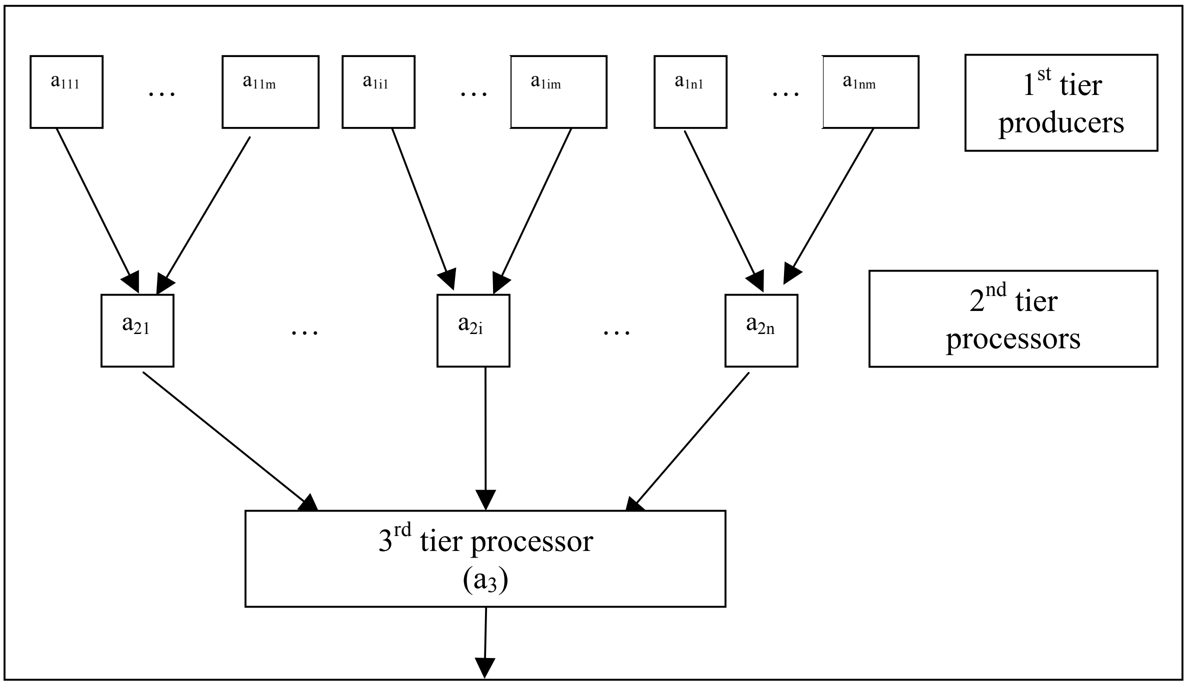

Figure 1. Network Structure of a Multi-Ingredient Product Supply Chain

The structure of figure 1 reflects agricultural and food supply chains. Upstream, the 1st tier involves a large number of production agents as is seen at the farm level in many food supply chains. The other two tiers in the model involve processing. The 2nd tier processors produce intermediate products or ingredients. The 3rd tier processor produces the final output, which is sold to consumers. In this network, a flow of products with chosen quality levels and associated information moves downstream.

An example of this network structure is a supply chain for frozen pizza manufacturing. In the 1st tier are the producers of commodities (tomatoes, wheat, milk, etc.). The agents in the 2nd tier are processors of tomato paste, flour, and cheese. Finally, the 3rd tier processor is the pizza manufacturer selling to consumers.

This paper focuses on transactions within the network. In reality, any of the agents considered may be, and often are, involved in other markets. These markets will be considered through the presence of an outside option. The model assumes that the 3rd tier processor only sells one product; again this is a simplification of the reality.

The network represented in figure 1 can be thought of as a two-stage vertical coordination game, where each player has full information about other agent's strategy sets. In the first stage, each of a finite number (n) of 2nd tier processors chooses levels of quality and information to pass downstream, while using prices to induce the quality and information levels of the inputs purchased from a pool of m farms in the 1st tier. In the 2nd stage the 3rd tier processor decides what levels of information and quality will be required from n different ingredient producers.

The 3rd tier processor is assumed to be the principal, and the other participants are agents, hence the designation as a hierarchical network. Note however that there are really two levels of hierarchy because each 2nd tier firm acts as principal with respect to its 1st tier producers. Furthermore in this network we assume that there are no direct transactions between the 3rd tier processor and the 1st tier agents. This hierarchy does not necessarily imply the existence of market power, which is an issue not discussed in this paper.

Here the principal maximizes its profits, choosing the levels of information and quality from its suppliers. These levels of information and quality are important because they influence the probability of incurring a loss, imposed by an external party that monitors the final output of the supply chain. The total loss imposed on the 3rd tier processor is related to the probability of occurrence of a food safety hazard and to the levels of information and quality acquired. If the 3rd tier processor has high levels of information and quality, then not only does it have a better chance of preventing any hazard but it is also possible that these levels will create goodwill with the external party resulting is a lower loss being imposed. Therefore acquiring high levels of quality and information has advantages both in prevention and mitigation of losses. Another benefit of having more information and quality may be that the technological process of the 3rd tier can be more efficient. Studies on demand for traceability have not clearly established the existence of a premium price for traceability (Dickinson and Bailey 2002; Hobbs, Bailey, Dickinson, and Haghiri 2005). Here we assume that the price is not influenced by the information.

The model is complex because the quality and information levels change vertically and horizontally at different stages of the supply chain. Another complexity emerges in the assumption of heterogeneity between agents in the 2nd tier that produce different products. In addition, their products have asymmetric (with respect to the 3rd tier processor) quality and information levels. Finally, there are different agents at both the 1st and 2nd tier of the network, which prevents the simplification of the analysis based on representative firms. Each ingredient used to produce the final product may present different food safety hazards, which have to be taken into account by a rational 3rd tier processor.

Risks of food safety hazards can be significantly mitigated using appropriate production processes and technologies. These are constantly changing and in real markets at any level of the supply chain there is a distribution of firms operating with different technologies. To simplify the problem we assume that there are no differences in risks associated with processing technologies between producers of the same product in the 1st tier. We also will not consider processing costs throughout, as we assume they do not affect decisions over quality and information levels, and assume agents in the 1st tier producing the same input have the same levels of information and quality. The level of information is the quantity of information on origin, product attributes, or processing technologies; these levels are bounded by a minimum and maximum amount of information that agents have available.

The flow of product and information along the supply chain is governed by the objective function of the 3rd tier processor and by participation and incentive compatibility constraints for the other tiers of the supply chain. The participation constraints are conditions that have to be met in order for product to flow between 1st tier producers and 2nd tier processors and between the 2nd tier and the 3rd tier processor. Incentive compatibility constraints guarantee that agents share higher levels of information. Table 1 shows the variables, parameters, and agents used in the model.

The quality and information variables are treated as indexes. A critical assumption is that the information exchanged is truthful. The index of quality contains all the relevant quality attributes and the information index comprises all pieces of information that are relevant for the agents of the supply chain. We use the symbols $\underline{\theta}_i, \underline{\gamma}_i, \underline{\Theta}_i$ and $\underline{\Gamma}_i$ to denote lower levels of quality and information respectively at the 1st and 2nd tiers. This means that all quality attributes are lower and the relevant pieces of information are fewer. The symbols $\overline{\theta}_i, \overline{\gamma}_i, \overline{\Theta}_i$ and $\overline{\Gamma}_i$ represent higher levels of quality and information respectively for the 1st and 2nd tiers of the supply chain.

Table 1. List of Variables, Parameters, and Agents

Symbol	Definition
P	Price of final output
ρ_i	Price paid to 2nd tier processor *i*, by the 3rd tier processor
p_i	Price paid by 2nd tier processor *i* to its 1st tier suppliers
$g[\sum_i \alpha_i . f_i(m.q_i), \Theta, \Gamma]$	Quantity of final output obtained at the 3rd tier level and sold to consumers
$f_i(m.q_i)$	Quantity of intermediary product sold by 2nd tier processor *i*
q_i	Quantity of commodity supplied by each of *m* 1st tier producers
Π	Profits of 3rd tier processor
Ψ	Probability of final output hazards faced by 3rd tier processor
Γ	Vector of information levels
Θ	Vector of quality levels
Γ_i	Level of information at each of the 2nd tier processors
γ_i	Level of information at the each of 1st tier producers
Θ_i	Quality level at each of the 2nd tier processors
θ_i	Quality level at the each of 1st tier producers
m	Number of agents supplying to each 2nd d tier processor
n	Number of 2nd tier agents and of ingredients used on final output
c_1	Cost of quality borne by each of the 1st tier producers
c_2	Cost of information borne by each of the 1st tier producers
c_3	Cost of quality borne by each of the 2nd tier processors
c_4	Cost of information borne by each of the 2nd tier processors
L	Loss incurred by the 3rd tier processor
U_i	Outside options of the 2nd tier processors
O_i	Outside options of the 1st tier agents
α_i	Proportion of ingredient *i* used in the final output

We assume that agents in the 1st tier are endowed with a quantity (q_i) of input to sell, which has levels of quality ($\theta_i \in [\underline{\theta}_i, \overline{\theta}_i]$) and information ($\gamma_i \in [\underline{\gamma}_i, \overline{\gamma}_i]$) that may or not be passed down. Each unit of input is sold at a price ($p_i(\theta_i, \gamma_i)$). The marginal costs of quality and information are assumed to be constant. Agents in the 1st tier make decisions on the levels of quality and information to pass down based on the following:

$$\begin{aligned} &\underset{\theta_i,\gamma_i}{Max}\; p_i(\theta_i, \gamma_i).q_i - c_1.\theta_i - c_2.\gamma_i \\ &s.t.\ \theta_i \in [\underline{\theta}_i, \overline{\theta}_i],\ \gamma_i \in [\underline{\gamma}_i, \overline{\gamma}_i] \end{aligned} \tag{1}$$

The Kuhn-Tucker conditions for this problem are as follows:

$$\frac{\partial p_i}{\partial \theta_i}.q_i - c_1 \begin{cases} \geq 0, \theta_i = \overline{\theta}_i \\ < 0, \theta_i = \underline{\theta}_i \end{cases} \tag{1a}$$

and

$$\frac{\partial p_i}{\partial \gamma_i}.q_i - c_2 \begin{cases} \geq 0, \gamma_i = \overline{\gamma}_i \\ < 0, \gamma_i = \underline{\gamma}_i \end{cases} \tag{1b}$$

The agents in the 1st tier may decide not to sell to the 2nd tier processor; they have an outside option in a market where they can sell with a reservation profit level (O_i). The participation constraint for the 1st tier agents is derived as:

$$p_i(\theta_i, \gamma_i).q_i - c_1\theta_i - c_2\gamma_i \geq O_i \tag{2}$$

Assuming agents are indifferent between accepting a contract or not, we have:

$$p_i(\theta_i, \gamma_i) \geq \frac{1}{q_i}[O_i + c_1.\theta_i + c_2.\gamma_i] \tag{3}$$

The incentive compatibility constraint must take into account that the 2nd tier processor may induce lower or higher levels of quality and information through varying prices. Using the Kuhn-Tucker conditions (1a) and (1b) above, each agent in the 1st tier will provide high levels of information and quality if and only if:

$$\frac{\partial p_i}{\partial \theta_i} \geq \frac{c_1}{q_i} \quad \text{and} \quad \frac{\partial p_i}{\partial \gamma_i} \geq \frac{c_2}{q_i}$$

If lower levels of information and quality are enough, a fixed price that satisfies condition (3) is sufficient. The price schedule for the 1st tier agents is then defined as:

$$(4) \qquad p_i(\theta_i, \gamma_i) = \begin{cases} \dfrac{1}{q_i}[O_i + c_1.\overline{\theta}_i + c_2.\overline{\gamma}_i] \text{ if } (\theta_i, \gamma_i) = (\overline{\theta}_i, \overline{\gamma}_i) \\ \dfrac{1}{q_i}[O_i + c_1.\underline{\theta}_i + c_2.\underline{\gamma}_i] \text{ otherwise} \end{cases}$$

The 2nd tier processor plays a critical role in the establishment of a farm to fork traceability system because it acquires information from 1st tier producers, which it may or not pass downstream. When information obtained from 1st tier producers is not passed down, the traceability system is called one up-one down (i.e., information is maintained between adjacent members of the supply chain but not passed to non-adjacent parts of the supply chain). Again, agents in the 2nd tier may choose to induce higher or lower levels of information depending on the price they offer to 1st tier agents, as shown in equation 4.

At the 2nd tier stage of the supply chain, the production process changes the characteristics of the initial product and generates new quality and information levels. In the model there is the same finite number (*m*) of agents in the 1st tier supplying each of the 2nd tier processors; the total cost of acquiring information rises over the number of suppliers. However the higher the levels of quality and information obtained, the lower is the cost of acquiring new quality and information levels by processors on the 2nd tier.

The objective function of the 2nd tier processor is similar to that of 1st tier agents: it chooses quality and information levels to maximize profits. However, each agent on the

2nd tier has a different production function and produces a different product. They each have different levels of quality and information. The principal at the 3rd tier knows the implications of the different levels of quality and information on its objective function. Hence the objective function for each 2nd tier processor is:

$$\underset{\Theta_i,\Gamma_i}{Max}\ \rho_i(\Theta_i,\Gamma_i).f_i(m.q_i) - c_3(\theta_i).\Theta_i - c_4(\gamma_i).\Gamma_i - m(O_i + c_1.\theta_i + c_2.\gamma_i)$$

(5) $$s.t.\ \Theta_i \in [\underline{\Theta}_i, \overline{\Theta}_i] \text{ and } \Gamma_i \in [\underline{\Gamma}_i, \overline{\Gamma}_i]$$

$$c_3(\theta_i) = \begin{cases} c_3(\overline{\theta}_i) \\ c_3(\underline{\theta}_i) \end{cases} \text{ and } c_4(\gamma_i) = \begin{cases} c_4(\overline{\gamma}_i) \\ c_4(\underline{\gamma}_i) \end{cases}$$

The fourth term in the objective function is the cost of acquiring input from the 1st tier (equation (4) is substituted here). As with agents in the 1st tier, the information and quality levels are bounded by lower and higher levels. We assume that all production (f_i), cost of quality, and cost of information levels are continuous functions. The costs of obtaining more information or quality are lower, the higher are the levels obtained from 1st tier producers. However, these costs are still linear over the new levels of quality and information. This highlights a tradeoff between the price paid for inputs and costs of information that may be passed down.

The Kuhn-Tucker conditions for the problem of each 2nd tier firm are given by:

(5a) $$\frac{\partial \rho_i}{\partial \Theta_i}.f_i(m.q_i) - c_3(\theta_i) \begin{cases} \geq 0, \Theta_i = \overline{\Theta}_i \\ < 0, \Theta_i = \underline{\Theta}_i \end{cases}$$

and

(5b) $$\frac{\partial \rho_i}{\partial \Gamma_i}.f_i(m.q_i) - c_4(\gamma_i) \begin{cases} \geq 0, \Gamma_i = \overline{\Gamma}_i \\ < 0, \Gamma_i = \underline{\Gamma}_i \end{cases}$$

As with agents in the 1st tier, the 2nd tier processors have an outside option for selling their product in which they earn a reservation profit (U_i). Taking this into account from the expression (5) above, the participation constraint for the 2nd tier processors is:

(6) $$\rho_i(\Theta_i,\Gamma_i)f_i(m.q_i) - c_3(\theta_i).\Theta_i - c_4(\gamma_i).\Gamma_i - m(O_i + c_1.\theta_i + c_4.\gamma_i) \geq U_i$$

If each firm is indifferent between accepting a contract from the 3rd tier processor and getting the reservation profit, the following price schedule follows from the participation constraint:

(7) $$\rho_i(\Theta_i,\Gamma_i) = \frac{1}{f_i(m.q_i)}\{U_i + c_3(\theta_i).\Theta_i + c_4(\gamma_i).\Gamma_i + m(O_i + c_1.\theta_i + c_4.\gamma_i)\}$$

The price schedule faced by 2nd tier processors has more cases than that of the 1st tier producers. We will assume that a high level of quality and information passed down by each 2nd tier processor (that is $\overline{\Theta}_i, \overline{\Gamma}_i$) to the 3rd tier implies that information and quality obtained from the 1st tier is passed to the 3rd tier principal. However this does not necessarily mean that higher values are contracted with 1st tier producers. When lower levels of information are contracted there is no obligation of passing down information on the 1st tier to the 3rd tier processor.

In a sense the 2nd tier processors are less constrained than agents at the 1st tier. If they accept a price for levels of quality and information, they can offer a price to induce levels of quality and information from the 1st tier that have a direct impact in reducing costs. There is a tradeoff between the cost of information and quality induced on the 1st tier and the cost of these levels for the 2nd tier processors. This leads to opportunities for rent seeking conditioned on what contract is offered by the 3rd tier processor and the ratio of costs of information in the 2nd tier to information and quality prices in the 1st tier.

Furthermore the price offered to 2nd tier firms may indirectly affect the decision on what price to offer 1st tier agents. An important network effect emerges through the costs of quality and information faced by 2nd tier processors.

The objective function of the 3rd tier processor has three terms: total revenues, which depend on price and quantity sold; a cost associated with purchase of inputs; and a loss function. The objective function of the principal is defined as:

$$
\begin{aligned}
&\underset{\Theta,\Gamma}{\mathrm{Max}}\ \Pi = P.g\{\sum_i \alpha_i.f_i(m.q_i),\Theta,\Gamma\} - \sum_{i=1}^{n}\{U_i + c_3(\theta_i).\Theta_i + c_4(\gamma_i).\Gamma_i + m(O_i + c_1.\theta_i + c_2.\gamma_i)\} \\
(8) \qquad &\qquad - \Psi.L(\Theta,\Gamma) \\
&\text{s.t. } (\Theta,\Gamma) \in \mathrm{X}
\end{aligned}
$$

where X is a compact set and g is a continuous function. As before all other costs are assumed to be zero. Also let $\Theta = [\Theta_1,...,\Theta_n]$ and $\Gamma = [\Gamma_1,...,\Gamma_n]$, P is the price paid by consumers, $Q = g\{\sum_i \alpha_i.f_i(m.q_i),\Theta,\Gamma\}$ is the total output sold, and α_i is the fixed but not necessarily equal proportion with which each of the ingredients is used in the production of final output ($\sum_{i=1}^{n}\alpha_i = 1$). The maximization occurs over a vector of quality (**Θ**) and information (**Γ**) levels induced on each of the suppliers of ingredients. The remaining variables are as defined in table 1.

For the first term of equation (8), the total revenue term, we assume that the price paid by consumers is exogenous and independent of quality and information levels. This is a restrictive assumption in the case of quality where there is empirical evidence that consumers are willing to pay a premium for quality but is much less restrictive in the case of information where there is no clear evidence that consumers are willing to pay a premium for traceability. This assumption does not mean that information and quality levels for ingredients have no impact on the revenues of the 3rd tier processor. In the model they do a have positive impact on the processing of the final output, as more information on and quality levels in the ingredients improve productivity and efficiency through the impact on the production function *g*.

The second term in the objective function, the costs associated with acquiring ingredients, depends on the levels of quality and information that the principal wants for each ingredient. The price schedule offered to each 2nd tier processor induces these levels of quality and information.

Finally the third term of the objective function is a loss function that captures the probability of a loss due to safety hazards emerging in the final output. For this model, these hazards are assumed to be due only to the ingredients used in the production of the final output. A hazard occurs with probability ($\Psi \in [0,1]$), which is associated with a loss. We assume that when a hazard occurs an external party observes it perfectly and imposes a penalty (the loss). When the 3rd tier processor has high levels of quality in and information on the ingredients it uses, the external party takes this into account and reduces the total value of the loss when a hazard occurs. This is another incentive for the 3rd tier processor to demand high levels of quality and information for purchased ingredients.

The model developed here has a broad range of applications. First it can be seen as an institution and then be compared with other institutional settings for traceability. This model proposes an institutional arrangement where traceability is voluntary; it is entirely up to the 3rd tier processor to decide on which ingredients traceability will be imposed. Also all other parties in the supply chain may choose to sell on their reserve, outside option market where information and quality are not as important. Second one may derive the conditions for full traceability, i.e., the case where all ingredients carry full traceability information. Another application is to analyze tradeoffs between quality and information levels. Fourth, the model can illustrate tradeoffs between the costs of traceability and opportunities for reduction in food safety losses. Finally this model may be used to analyze how decisions taken by one element of a multi-tiered supply chain impact other firms. The model has applications beyond the food industry (for example in the production of personal computers); with appropriate adjustments it can be used to illustrate situations emerging in operations research or to obtain quantitative results.

The model is formulated as a network in order to enable the analysis of network effects. A first network effect emerges with positive and negative externalities related to complementarities between ingredients. For example, these complementarities exist between the ingredients supplied by the 2nd tier processors because if any of the ingredients underperforms then the final product will be affected. A second network effect emerges due to the indirect influence of a party at one tier of the network on the transactions between parties on the other two tiers. An example is the decision of a 2nd tier processor when choosing which level of information and quality it demands from 1st tier producers. Note that the 3rd tier firm does not trade with 1st tier firms, nevertheless the objective function of the 3rd tier firm includes the levels of information and quality induced from the 1st tier, which denotes a network effect.

Model Interpretation

The model presented above can be analyzed in diverse ways. Here we derive three results based on different combinations of levels of information to illustrate tradeoffs and network effects emerging in the model. The first model interpretation focuses on the choice on which ingredients will have traceability. This implies a tradeoff between the cost of information and the reduction of the probability of losses associated with different levels of information. The other two model interpretations focus on the network effects associated with complementarities between ingredients used by the 3rd tier processor and with the levels of information demanded from the 1st tier producers when the price paid to the 2nd tier processor is fixed and a low level of information is elicited.

For the first interpretation, we assume a one-to-one relationship between the quality and information levels, e.g., a low quality level corresponds to a low level of information and the same for high levels. We further assume that for the ingredient under consideration, the impact of higher levels of information on revenues is negligible, in other words the marginal effect of information in the production function (g) of the 3rd tier processor is small. This allows a focus on the tradeoff between the prices associated with higher levels of information and their impact on reducing the expected loss due to food safety hazards. Depending on the magnitude of this price relative to the reduction of losses, the principal will demand a higher or lower level of information flow or traceability from 2nd tier processors.

This result is obtained by rewriting the objective function of the 3rd tier processor (equation (8)), substituting the second term with the price as defined by equation 7:

(9) $$P.g\{\sum_{i}\alpha_i.f_i(m.q_i),\Theta,\Gamma\}-\sum_{i=1}^{n}\rho_i(\Theta_i,\Gamma_i).f_i(m.q_i)-\Psi.L(\Theta,\Gamma)$$

When deciding what level of information to induce from the producer of ingredient 1, the 3rd tier processor uses the following marginal condition derived from the equation above:

(10) $$\frac{\partial L(\cdot)}{\partial \Gamma_1}.\Psi+\frac{\partial \rho_1(\cdot)}{\partial \Gamma_1}.f_1(\cdot)=0$$

The marginal effect of information in the first term of equation 9 is not included in this equation because, as noted above, the effect of levels of information for ingredient 1 on the total output produced is assumed to be very small.

To interpret equation 10, note that we assumed that the losses are decreasing with the information levels, while the prices paid are increasing in such levels. Also note that the loss is a 'bad' and the firm wants this term to have the smallest possible value. This expression says that the marginal effect of information levels on the probable loss must be equal to the marginal increase in the cost of acquiring ingredients due to more information. If the price paid for higher levels of information is larger than the reduction in the probable loss, the 3rd tier processor will only pay for lower levels of information, offering a fixed price. Otherwise higher levels of information are demanded.

One of main reasons for formulating this model as a network is to account for network effects. Two interpretations of the model illustrate why it is important to account for these effects. The first relates to the effect of complementarities. In this model, all ingredients enter the final product on fixed but not equal proportions. Thus the 3rd tier producer is forced to use all ingredients and all ingredients are complements in the production of the final product. However, because the ingredients have different impacts on the probable loss, through their quality and information levels, it is possible that different prices will be paid to different ingredients, depending (among other factors) on which respective levels of quality and information the 3rd tier processor requires. Furthermore, if a lower level of information for a given ingredient is contracted, and it is later found that a food safety hazard emerges due to this ingredient, the 3rd tier processor and possibly all its suppliers may face the maximum loss. Regardless of the prices offered to induce levels of information from the 2nd tier processors, there is always a chance that losses will emerge due to an ingredient that was thought to be less risky.

A second network effect is associated with the choices of the 2nd tier processors. Suppose a fixed price is offered to a firm at this tier by the 3rd tier processor, meaning that only low levels of information and quality are required. Will the 2nd tier processor necessarily contract a lower level of quality and information from its 1st tier suppliers? The answer is not clear-cut. On the one hand, higher levels of information will require a higher price. On the other hand, the costs of obtaining information in the 2nd tier (even if at lower levels) will be smaller if higher levels of information are obtained from the 1st tier processors. A network effect emerges because the levels of information and quality of the 1st tier agents enter the objective function of the 3rd tier processor. The sign and magnitude of this network effect depend on how the costs of information compare in the 1st and 2nd tiers.

Let us now turn to the circumstances in which a 2nd tier processor would demand higher levels of information from 1st tier producers, even if it is only required to offer lower information levels to the 3rd tier processor. The participation constraint of the 2nd tier processor given by equation 7 can be rewritten substituting equation 4 (the participation constraint for firms in the 1st tier) for the fourth term inside the curled brackets, and assuming that a lower level of information from the 2nd tier is enough for the 3rd tier:

$$(7a) \qquad \rho_i(\Theta_i, \underline{\Gamma}_i) = \frac{1}{f_i(m.q_i)}\{U_i + c_3(\theta_i).\Theta_i + c_4(\gamma_i).\underline{\Gamma}_i + p_i(\theta_i, \gamma_i)\}$$

This expression can be used to derive another comparing the tradeoff between the costs of quality and information on the 2nd tier and prices paid to 1st tier producers. First create two expressions for the participation constraint of the 2nd tier processor: one where higher levels of information are required from the 1st tier and the other with lower levels of information. Subtracting these two equations and collecting and eliminating common terms gives:

$$(11) \qquad c_4(\underline{\gamma}_i).\underline{\Gamma}_i + p_i(\theta_i, \underline{\gamma}_i) = c_4(\overline{\gamma}_i).\underline{\Gamma}_i + p_i(\theta_i, \overline{\gamma}_i)$$

If this equality holds, the 2nd tier processor is indifferent between demanding higher or lower levels of information from the 1st tier. Note however that the cost of information generated by the 2nd tier is decreasing with the levels of information from the 1st tier so that:

$$(12) \qquad c_4(\underline{\gamma}_i).\underline{\Gamma}_i > c_4(\overline{\gamma}_i).\underline{\Gamma}_i$$

Hence there are opportunities for cost savings for the 2nd tier processor when obtaining more information from its 1st tier suppliers. This occurs when the differences in prices paid to firms in the 1st tier for higher or lower levels of information are smaller than the respective difference in cost savings. In other words, if the expression (13) below holds, 2nd tier processors will demand high levels of information from 1st tier producers. This in turn impacts the profits of the 3rd tier processor, generating a network effect:

$$(13) \qquad c_4(\underline{\gamma}_i).\underline{\Gamma}_i - c_4(\overline{\gamma}_i).\underline{\Gamma}_i > p_i(\theta_i, \overline{\gamma}_i) - p_i(\theta_i, \underline{\gamma}_i)$$

This section develops three examples of the insights provided by the model. First, interpretation of the model indicates that the level of information (traceability) produced by the supply chain critically depends on the relative magnitude of the costs of information relative to opportunities for savings due to reductions in the probable losses. Imposing high traceability levels on the most risky ingredients does not necessarily prevent the occurrence of losses, showing the importance of taking complementarities into account. Finally, a network effect emerges from the model in which low levels of information induced from a 2nd tier processor by the 3rd tier processor do not necessarily mean lower levels of information demanded by a 2nd tier processors from its 1st tier suppliers.

Conclusions

This paper proposes a new model for analyzing the adoption of traceability in supply chains for multi-ingredient products. Traceability is defined as a flow of an index of information between stages of a food supply chain. The aim is to understand how information flows occur in a supply chain with three tiers and heterogeneity among participants. The model draws on the network economics and contract theory literature to develop a directed and hierarchical network structure.

This paper contributes to the literature in two important ways. The first is in highlighting the importance of considering the existence of network effects in analyzing traceability. These effects have not been taken into account in research on traceability thus far. The second is in considering the case of multi-ingredient products, while accounting for heterogeneity in supply chain relationships. Here a producer of a multi-ingredient product chooses levels of information or traceability and quality to reduce exposure to losses associated with food safety hazards and to improve productivity. However, higher levels of information and quality are more costly. In our formulation, network effects are made explicit in the objective function of the 3rd tier processor, for when this party chooses the price to pay for each ingredient, it influences the choices of information and quality levels offered by the remaining participants of the supply chain.

The model can be extended in several ways. First the assumption that the information revealed is true can be relaxed, which means that some sort of certification mechanism would need to be added. Second the information level of the 2nd tier processor may be a function of the information obtained at the 1st tier level. The model could be extended to account for full traceability in a more explicit way. Third the objective function of the principal (the 3rd tier processor) could be formulated so that the probability of a loss is directly associated with the quality and information levels of the ingredients. Finally a loss function could be added to the objective function of the 2nd tier processor, to express the possibility of a transfer of losses from the 3rd tier processor to its suppliers.

This model addresses an institutional setting where firms have total liberty to decide whether and to what extent traceability is adopted. An extension to the model would adapt it to a context where traceability is mandatory; in such a case a governmental authority steps in and imposes a certain level of required information. Comparing the voluntary and mandatory institutional settings for the model can provide insights into why we already observe differences in traceability systems worldwide. The present model assumes full information about other agents' strategy sets in the supply chain. If this assumption were relaxed, the market would require revelation and monitoring mechanisms. Finally a critical aspect of the model is the definition of the loss function. We assume there is a known probability of failures due to safety hazards and that the probability is associated with the final product. This probability could be expanded so that it becomes a function of the quality of the ingredients, production technologies, and security policies.

References

Amanor-Boadu, V. and Starbird, S. A. 2003. "The Value of Anonymity in Supply Chain Relationships." Selected paper for AAEA Annual Meeting, Montreal, Quebec, Canada, 23-27 July.

Buhr, B. L. 2003. “Traceability and Information Technology in the Meat Supply Chain: Implications for Firm Organization and Market Structure.” *Journal of Food Distribution Research* 34(3):13-26.

Dickinson, D. L. and D. Bailey. 2002. “Meat Traceability: Are U.S. Consumers Willing to Pay for It?” *J. Agr. Res. Econ.* 27(2):348-364.

Disney, W.T., J. W. Green, K.W. Forsythe, J.F. Wiemers, and S. Weber. 2001. “Benefit-Cost Analysis of Animal Identification for Disease Prevention and Control.” *Rev. Sci. et Techique de l’Office Internacional des Epizooties* 20(2):385-405.

Dong, J., Zhang, D., Yan, H. and Nagurney, A. 2005. “Multitiered Supply Chains Networks: Multicriteria Decision-Making under Uncertainty.” *Annals of Operations Research* 135(1): 155-178.

Economides, N. 1996. "The Economics of Networks." *International Journal of Industrial Organization* 14(6):673-699.

Fearne, A. 1998. “The Evolution of Partnerships in the Meat Supply Chain: Insights from the British Beef Industry”. *Supply Chain Management: An International Journal* 3(4):214-231.

Golan, E, B. Krissoff, F. Kuchler, K. Nelson, G. Price, and L. Calvin. 2003. “Traceability for Food Safety and Quality Assurance: Mandatory Systems Often Miss the Mark.” *Current Agr., Food, & Resource Issues* 4:27-35.

-----. 2004. *Traceability in the U.S. Food Supply: Economic Theory and Industry Studies*. Washington DC: U.S. Department of Agriculture, ERS Agr. Econ. Rep. 830, March.

Hobbs, J. E. 2002. "Consumer Demand for Traceability." Paper present at the International Agricultural Trade Research Consortium Annual Conference,Monterey, CA, 15-17 December.

------. 2003. "Traceability in Meat Supply Chains." *Current Agr., Food, & Resource Issues* 4:36-49.

Hobbs, J. E., Bailey, D., Dickinson, D. L., and Haghiri, M. 2005. "Traceability in the Canadian Red Meat Sector: Do Consumers Care?" *Canadian Journal of Agricultural Economics* 53:47–65.

Jackson, M. O. 2005. "A Survey of Models of Network Formation: Stability and Efficiency," In G. Demange and M. Wooders, eds. *Group Formation in Economics; Networks, Clubs, and Coalitions*. Cambridge, UK: Cambridge University Press, pp. 11-57.

Katz, M. and Shapiro, C. 1985. "Network Externalities, Competition and Compatibility." *American Economic Review* 75(4): 424-40.

Kola, J. and T. Latvala. 2002. "Demand for Credence Characteristics in Beef." Selected paper presented at the AAEA-WAEA Annual Meeting, Long Beach, CA, July, 28-31.

Meuwissen, M. P. M, A. G. J. Velthuis, H. Hogeveen, and R. B.M. Huirne. 2003. "Traceability and Certification in Meat Supply Chains." *Journal of Agribusiness* 21(2):167-181.

Nagurney, A. 1999. *Network Economics: A Variational Inequality Approach* 2nd ed. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Petit, R.G. 2001. "Traceability in the Food Animal Industry and Supermarket Chains." *Rev. Sci. et Techique de l'Office Internacional des Epizooties* 20(2):584-597.

Shogren, J. F., Shin, S.Y., Hayes, D. J. and Kliebenstein, J.B. 1994. "Resolving differences in willingness to pay and willingness to accept. *American Economic Review* 84(2): 255–270.

Shy, Oz. 2001. *The Economics of Network Industries*. Cambridge, UK: Cambridge University Press.

Silberberg, E. and Suen, W. 2001. *The Structure of Economics: A Mathematical Analysis.* 3rd. ed. New York, NY: Irwin/McGraw Hill.

Souza Monteiro, D. and Caswell, J. 2004. "The Economics of Implementing Traceability in Beef Supply Chains: Trends in Major Producing and Trading Countries." Paper presented at NAREA Annual Meeting, Halifax, Nova Scotia, Canada, 20-23 June.

Starbird, S. A. and Amanor-Boadu, V. 2004. "Traceability, Inspection, and Food Safety." Selected Paper for the AAEA Annual Meeting, Denver, CO, 1-4 August.

Starbird, S. A. 2005. " Moral Hazard, Inspection Policy and Food Safety" *American Journal of Agricultural Economics* 87(1): 15-27.

Tirole, J. 1988. *The Theory of Industrial Organization*. Cambridge, MA: The MIT Press.

Vitiello, D. J. and A. M Thaler. 2001. "Animal Identification: Links to Food Safety." *Revue Scientifique et Techique de l'Office Internacional des Epizooties* 20 (2):598-604.