The Economics of Voluntary Traceability in Multi-Ingredient Food Chains

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ABSTRACT

The consumption of multi-ingredient foods is increasing across the globe. Traceability can be used as a tool to gather information about and manage food safety risks associated with these types of products. The authors investigate the choice of voluntary traceability in three-tiered multi-ingredient food supply chains. They propose a framework based on vertical control and agency theory to model three dimensions of traceability systems: depth, breadth, and precision. Their analysis has three main results. First, full traceability is feasible as long as there are net benefits to a downstream firm that demands traceability across all ingredients. Second, horizontal network externalities are positive because an increase in the level of traceability in one ingredient requires a similar increase in others. Finally, vertical network effects will be positive insofar as willingness to pay and probabilities of food safety hazards increase. [EconLit Classification: Q130, L140].

1. INTRODUCTION

Consumers around the world are increasingly buying and consuming food products that require minimum time spent on preparation before being consumed. These products frequently contain multiple ingredients where different agricultural commodities or processed inputs are combined into a final foodstuff sold directly to consumers. Producing, processing, and supplying these products presents new and challenging problems. Cross-contamination may increase due to bottlenecks and a higher chance of opportunistic behavior by agents supplying the final processor. There may be a need for identity preservation of inputs. Finally, externalities may emerge between supply chains that in the recent past were considered independent.

Traceability systems may be used to improve the management of information within and between firms, to respond to consumer demand, and to reduce the risk of food safety hazards in supply chains for multi-ingredient products. Typically, the production of multi-ingredient products involves a recipe and final quality critically depends on the quality of the components. Examples of multi-ingredient products abound, ranging from packed mixed salads to frozen pizzas. Implementing traceability in supply chains for these products is a complex coordination problem that may require new institutional arrangements.

Our goal here is to analyze the economic implications of a voluntary traceability system in a supply chain producing multi-ingredient foods. It analyzes interfirm traceability in multi-ingredient food production as a coordination problem, investigating the conditions under which none, a limited number, or all firms provide traceability. It models traceability as a flow of information that has dimensions of depth, breadth, and precision. More specifically, the objective is to determine the optimal level of traceability in multi-ingredient food chains and how this level is influenced by network effects.

In 2002, through regulation (EC) 178/2002, the European Parliament and the Council (2002) laid down the general principles and requirements of food law, created the European Food Safety Authority, and imposed procedures in matters of food safety. One of the measures aimed at assuring safer food is mandatory traceability, which became effective in January 2005. This regulation defines traceability as the ‘‘ability to trace and follow a food, feed, food-producing animal or substance intended to be, or expected to be incorporated into a food or feed through all stages of production, processing, and distribution’’ (p. 8). From this definition, it can be inferred that traceability implies a flow of information between firms, involves interfirm coordination, and covers both single and multi-ingredient foods.

Meuwissen, Velthuis, Hogeveen, and Huirne (2003) place the firm and supply chain within a broader European framework to improve food safety that has three levels. At the broadest level are the European Commission’s food safety and hygiene rules. Then each member state has its own specific country-level standards. Finally, at a more specific level, there are private standards for certification. Folbert and Dagevos (2000) suggest that European Union (EU) consumers and legislators are concerned not only with the safety of foods, but also with how food is obtained. Thus, safety is not the sole motivator for traceability adoption. It may also correct market failures, reduce costs of identification of origins of products, and reduce transaction costs (Hobbs, 2004; Hobbs, Bailey, Dickinson, & Haghiri, 2005). This may explain why traceability is being so widely adopted in Europe and why retailers in the EU are pushing for more stringent systems than required by legislation.

Information is a valuable asset for firms (Sporleder & Moss, 2002). It facilitates trade and can lead to considerable efficiencies throughout the supply chain. Consumers and firms may be willing to pay a premium for information. A traceability system is a tool through which information flowing among parties in a supply chain can be more effectively and efficiently managed. It can also improve logistics operations and minimize the impact of food safety hazards (Hobbs, 2004; Meuwissen et al., 2003). However, traceability is costly, as it requires gathering, storing, and sharing information. In addition, its benefits may not be evenly distributed across the supply chain, which may lead to the adoption of suboptimal traceability. It is therefore of critical importance to analyze the coordination, structural, and institutional implications of traceability adoption.

2. OPERATIONS RESEARCH AND ECONOMIC APPROACHES TO TRACEABILITY ANALYSIS

There is already a sizable literature on the economics of traceability systems. Moe (1998) distinguishes two types of traceability: chain traceability tracks a batch and its history through production, transport, storage, processing, distribution, and sales. Internal traceability documents all production processes within a firm. Although the economic studies on traceability generally focus on the first type, operations research and management science studies have focused on implementation of internal traceability.

In operations research and management science, traceability is seen as an information system devised to coordinate information between different divisions within a firm. For example, Dupuy, Botta-Genoulaz, and Guinet (2005) use an operations research approach to improve a traceability system. They formulate an optimization problem that minimizes the size of recalled production batches. Similarly, Jansen-Veullers, van Dorp, and Beulens (2003) present a solution for an information management system within a firm to support traceability. Their system integrates process, control, information, and information infrastructure layers.

Hofstede (2002) discusses transparency in netchains, defined as a new interdisciplinary field of research derived from technology and information systems on the one hand and social sciences on the other. The concept combines network and supply chain management approaches, mixed with economics and other social sciences. Hofstede argues that the formation of netchains is associated with the need to exchange goods and money, but he also points out how critical information is and argues it constitutes the life force of netchains.

Trienekens and Beulens (2001) suggest that only part of the information generated by a supplier about its products and processes is passed down to the buyer. The information flow is decoupled from the product flow, which implies that only an aggregate level of information moves with the product along the supply chain. The challenge is then to devise a way to maintain the relation between the aggregate information transferred and the detailed information retained by the supplier.

The importance of the operations research literature is that it clearly relates traceability to information systems. This perspective envisions the construction of a traceability system as an optimization problem aiming to govern the flow of information between different departments of a firm. When considering the case for traceability implementation along a food chain, it may be more appropriate to approach it as a network problem. The analysis of traceability in this article builds on the operations research insights, but takes an economics approach.

The economics perspective on traceability has two fundamental streams: the demand and supply sides. From the demand side the main problem is to determine consumer's willingness to pay for traceability. Dickinson and Bailey (2002) find that American consumers are willing to pay a premium for traceability in beef and pork sandwiches. Hobbs et al. (2005) obtain similar results when using experimental auctions in the United States and Canada to determine consumer willingness to pay for traceability in beef and pork. Banterle and Stranieri (2008) find that a majority of consumers they surveyed in Italy said that having a mandatory traceability code on fresh meat is important. Moreover, they find that 84% of the respondents mentioned that beef labelling should mention the country of origin of the animal. As yet, there are no similar surveys on the willingness to pay for and interest in traceability in multi-ingredient foods.

In this article, we analyze the economics of the supply of traceability systems for multi-ingredient foods. The economic impacts of traceability adoption in food chains have only recently started to be played out. Hobbs (2004) focuses on the role of traceability in the food system and distinguishes "ex post reactive systems that allow the traceback of affected products in the event of a contamination problem so as to minimize social costs, ex post systems that facilitate the allocation of liability, and information systems that provide ex ante quality verification'' (p. 397). Traceability has three main functions: (a) reduce costs associated with risks of food safety occurrences, (b) strengthen liability incentives, and (c) allow for ex ante verification of credence quality attributes.

Meuwissen et al. (2003) identify three key questions: What is the breakeven point for levels of traceability? What are the impacts of traceability on current liability and recall insurance schemes? How can regulatory incentives 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 levels of automation, inventory, personnel, and documentation) and maintenance (through auditing). The benefits include increased transparency, reduced risk of liability claims,[1] more effective recalls, enhanced logistics, improved control of livestock epidemics, possible positive effects on trade, easier product licensing, and possible price premiums.

According to Golan et al. (2004), in Europe traceability has mainly been motivated by regulations; in the United States it tends to be solely motivated by market conditions. They survey several different systems of traceability in agri-food industries and characterize them using three dimensions: depth (how far up and downstream the system goes), breadth (how many attributes are traced), and precision (e.g., to what extent the origin is correctly identified). Golan et al. (2004) find that there is no single best way to introduce traceability and there is a large variability in the characteristics of systems within and across industries, depending on specific attributes of products or motivations to introduce traceability. They also suggest that it is impossible to have full traceability in food, regardless of mandatory or voluntary systems, and that choices have to be made on which attributes will be traceable.

Starbird and Amanor-Boadu (2004) use a principal-agent model approach to analyze the implications of introducing traceability in a food supply chain where there is an inspection protocol. The producer is the agent and knows how safe the product is; 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.

Additional recent research has focused on different aspects of relationships between traceability, inspection, and incentives, including liability, in producing quality for single-ingredient products. Starbird and Amanor-Boadu (2007) propose a principal-agent model where traceability is an exogenous variable that influences the nature of contractual relations between agents in the supply chain. Traceability may or not be demanded in the contract depending on inspection failure costs and the possibility of identifying unsafe producers. Pouliot and Summer (2008) model the supply of safe food in a two-stage marketing channel, where homogeneous farms sell output to homogenous marketers who, in turn, sell to consumers. When traceability is not available, firms are anonymous and may free-ride on producers of safer food. Unsafe food can originate either at the farm or marketer levels and food-safety incidents increase in the number of firms in the supply chain and with imperfect traceability systems. Finally, Resende-Filho and Buhr (2008) propose a principal-

[1]Meuwissen et al. (2003) write in the context of the EU where there is a limited liability rule. In the United States where a strict liability rule prevails this may not necessarily be the case.

agent model where the choice of investment in traceability depends on the benefits from linking cattle feeder practices with the quality of retail beef cuts. They find that the larger investment costs are the higher is the rate of traceback success. However, the lowest traceback success rate studied is the optimal choice for packers. These results indicate important factors to be considered in analyzing the performance of traceability systems for single-ingredient products.

Implementing traceability in multi-ingredient food chains involves the coordination of several different firms. Traceability is an information management tool and its effectiveness and efficiency may be affected by information asymmetries and imperfections. As in Starbird and Amanor-Boadu (2004), we use a principal-agent model, but in our case we analyze traceability as an endogenous variable.

To model traceability in multi-ingredient food chains we combine a model of vertical control proposed by Royer (1998) with agency theory. Royer's model provides a way to relate and transfer information between firms, whereas agency theory provides a governance structure to manage the flow of information. Our analysis assumes that the costs of traceability to a firm, namely those of designing, implementing, and operating an internal information system, are given. It departs from previous analysis on the economics of traceability by proposing a three-tiered supply chain model to analyze the choice of traceability in multi-ingredient products and by modeling traceability as a level of information rather than a zero-one choice. We analyze the conditions for no, partial, or full traceability and investigate the impact of network effects on optimal traceability levels.

3. A MODEL OF VOLUNTARY TRACEABILITY IN A MULTI-INGREDIENT SUPPLY CHAIN

Food supply chains involve a large number of firms, taking different actions in different tiers of the chain. Globalization has brought increasing complexity to food networks. In today's global chains, there are vertical and horizontal links between different firms at any giving point in a supply chain. In this section, we propose to model a traceability system in a three-tiered chain governed by contracts. The network structure in our model corresponds to the type "B" traceability system proposed in Meuwissen et al. (2003), where at each tier of the supply chain there must be traceability from every upstream firm in the chain.

Figure 1 shows the structure of the supply chain that we model. The firm in the third tier downstream is a producer of a multi-ingredient product, for example, a pizza, and buys ingredients (e.g., cheese or tomato paste) from different intermediate processors (e.g., cheese or tomato paste producers) in the second tier. To produce the ingredients, firms in the second tier purchase inputs (e.g., milk or tomatoes) from farmers in the first tier. Each firm in the first and second tiers is specialized, producing a single output and related information. The second-tier firms depend on inputs supplied by a single and specialized supplier in the first tier. Hence, each firm has only one link within the network structure. For instance if farm a_{11} produces tomatoes, it will sell only to the tomato paste processor a_{21}. Agents in the first tier can be thought of either as a single farm or as a producer's organization, e.g., a cooperative. Note that within the same tier of the supply chain there is heterogeneity in hazards and costs of traceability across firms producing different ingredients (e.g., milk vs. tomatoes, cheese vs. tomato paste). There is also

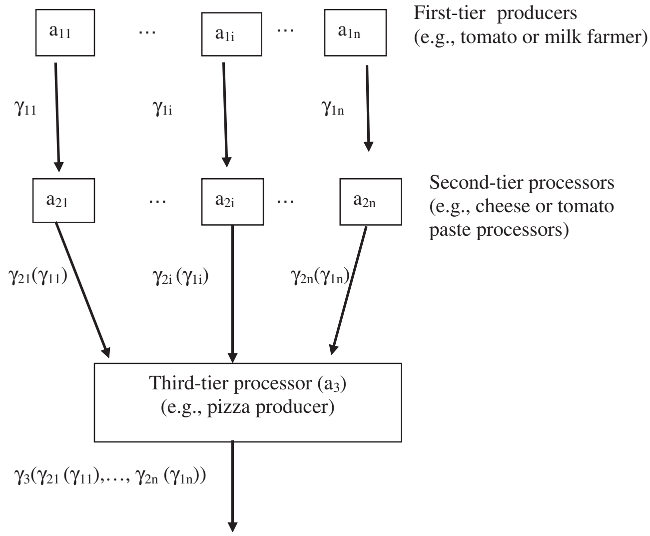

Figure 1 Network structure of a multi-ingredient food traceability system.

heterogeneity between firms in the same ingredient supply chain across tiers (e.g., milk vs. cheese, tomatoes vs. tomato paste). This heterogeneity will result in differences in the level of traceability provided by firms.

3.1. Assumptions

In the context of this article traceability is voluntary, which implies that every firm in the food chain has the option not to adopt traceability. Trinekens and Beulens (2001) argue that information flows in traceability systems must relate to product flows, they also claim that the flows do not have to occur simultaneously and may even be decoupled. In this article, we assume that the product and information are decoupled. We also assume that information can be contracted independently.

Early articles on the economics of traceability model it as a discrete choice; a firm either has it or not (Hobbs, 2004). Golan et al. (2004) define traceability as multidimensional (depth, breadth, and precision), and many researchers (see, e.g., Starbird & Amanor-Boadu, 2007; Pouliot & Sumner, 2008) embrace this definition; nevertheless, most models and empirical work to date treat traceability as one-dimensional. For example, Pouliot and Sumner (2008) define the degree of traceability as the probability of correctly identifying the source of a food product. However, as the Golan et al. definition suggests, traceability systems can carry information on multiple attributes (e.g., safety, organic production processes), at different depths (e.g., two-tier vs. three-tier supply chains), and with different levels of precision.

Here we define the level of traceability as the precision of information provided by each firm in the supply chain; the higher the level of traceability the more accurate will be information on a given food product. The level of precision can reflect, for example, the size of the lot to which the information refers. Additionally our framework includes a measure of depth (the number of traceable vertical links in the chain) and breadth (the number of ingredients for which there will be traceability).

We assume that traceability can be decomposed into units of information. Each unit increases the precision of information and has the same monetary value. Although our definition of the traceability level is novel, Goldsmith and Bender (2004) argue that there is a continuum for the value of identity preservation. This implies that for some products (e.g., organic foods) having more identity information is valuable; for others (e.g., commodities) it is not. The following assumptions are used in developing the model.

Assumption 1: Firms maximize profits and they can profit from traceability. Firms get compensation for additional units of traceability they provide; hence, profits are the difference between the revenues from traceability and its respective costs. When firms accept a contract to provide traceability, they may get a premium per unit of traceability exchanged downstream.

Assumption 2: To have traceability for a multi-ingredient food, the risk neutral third-tier firm offers a contract to each ingredient producer in the second tier. Risk neutrality is a standard assumption in principal-agent models and implies that the principal does not require a rent for bearing the risk. In contrast, a risk-averse third-tier firm would require more traceability to decrease the food safety losses; the opposite would be expected if the third-tier firm is a risk-seeker.

The contract specifies the levels of traceability each firm in the first and second tiers must provide and the respective compensation. Thus, there are two sets of contracts: first, the third-tier firm offers a contract to second-tier firms, which, in turn, propose a contract to farmers in the first tier. Each contract calls for a specific level of traceability. Thus, there is heterogeneity across ingredients and tiers (e.g., the level of information required for fresh tomatoes is different from that for milk, which, in turn, is different from that required for tomato paste or cheese). However, we assume homogeneity between firms in the same tier producing the same ingredient. For example, the contract for fresh tomatoes is the same for every producer selling to a tomato paste processor. First- and second-tier firms have a choice in taking a contract requiring traceability because they have an outside option of selling their output in a spot market.

Assumption 3: Traceability levels are additive and each unit of information has the same value. Traceability is a vertical and downstream flow of information. Traceability levels are denoted as γ. Subscripts identify the location of firms in the supply chain: The first subscript identifies the tier where the firm is located; the second identifies a given firm. For example, γ_{1i} identifies the level of traceability chosen by the *ith* firm in the first tier. To have traceability and create new information, downstream firms must offer a contract to obtain traceability upstream. Thus, assume a linearly increasing chain relationship between upstream and downstream traceability levels, i.e., $\gamma_3 = \gamma_3(\gamma_{21}, \dots, \gamma_{2n})$, $\gamma_{2i} = \gamma_{2i}(\gamma_{1i})$, $\gamma_3' > 0, \gamma_3'' = 0$, and $\gamma_{2i}' > 0, \gamma_{2i}'' = 0 (I = 1, \dots, n)$. Note that the third-tier level of traceability is indirectly impacted by each first-tier firm. Further assume that if no information is gathered upstream, it is impossible for second- and third-tier firms to have traceability, thus, $\gamma_{2i}(0) = 0 (I = 1, \dots, n)$ and $\gamma_3(0) = 0$.

Assumption 4: The first- and second-tier firms receive a price premium p per unit of traceability provided when they take a contract. The premium is only for the level of traceability corresponding to the output sold by each firm in the first and second tiers, profits from output sales are entirely captured in the fixed profits term. This is consistent with the idea of Hobbs (2004) who suggests that traceability can bring a "goodwill premium plus a premium due to greater consumer confidence" (p. 401). Furthermore, several studies analyzing the demand for traceability conducted in the United States, Canada, and Spain suggest that consumers are willing to pay a premium or assign a positive value to traceability (Gracia & Zeballos, 2005; Hobbs et al., 2005). Again, subscripts identify the tier and the firm receiving the premium. For instance, p_{21} is the premium for the traceability level γ_{21} provided by Firm 1 in the second tier to the third tier. Note that the premiums paid to the first- and second-tier firms are endogenous variables, but given Assumption 1 above, the premium p_3 paid by consumers to the third-tier firm is exogenous.

Assumption 5: Traceability is costly, as each firm has to invest in an internal information system to obtain and transfer information. Hobbs (2004) mentions five different costs: the direct costs of the traceability system, the impact of due diligence decisions on production costs, and three additional costs that are incurred only if a safety problem occurs. The logistics and operations research literature suggests there are internal costs when implementing an information system to support traceability (Goldsmith & Bender, 2004; Jansen-Veullers et al., 2003; Velthuis, Mourits, & Hogeveen, 2008; Vernede, Verdenius, & Broeze, 2003). Here costs of traceability are denoted as c, subscripts are then used to identify the location of the firm in the food chain. We assume the costs of traceability are increasing and convex with units of information, i.e., $c = c(\gamma), c' > 0$, and $c'' > 0$. Furthermore, to simplify the analysis assume that information systems are compatible across firms. This implies that there is no additional cost linked to compatibility and transfer costs are zero.

Assumption 6: Meuwissen et al. (2003) suggest that "traceability systems require a credible and complete information (in the sense of what has been agreed on) system along all participants in the supply chain" (p. 169). Here we assume that the cost of providing traceability is common knowledge and the principal has full information on the types of agents and their effort levels. Relaxing these assumptions would complicate contract design and lead to information rents. We further assume that when firms take a contract to provide traceability downstream that all traceable information is true.

Assumption 7: Along with consumer demand, traceability may be motivated by the need to mitigate exposure to losses linked to food safety hazards. Hobbs (2004) states that "… a liability cost is imposed on firms that have not exhibited due diligence in reducing the potential for a food hazard problem" (p. 402). Meuwissen et al. (2003) commenting on the new EU food laws argue, "food safety is the primary responsibility of food producers" (p. 167). Here we assume the third-tier firm may incur a liability loss (L) in the event of a food safety hazard, which occurs with probability $\psi \in [0, 1]$. However, the loss can be mitigated if there is traceability. Assume that losses decrease at an increasing rate with traceability levels from the third-tier firm, i.e., $L = L(\gamma_3), L' < 0$, and $L'' > 0$; further assume that if the third-tier firm does not adopt traceability, it faces the maximum possible loss.

3.2. Model

The model explores the general conditions for the voluntary adoption of no, partial, or full traceability in a three-tiered multi-ingredient supply chain. The problem of each firm in the supply chain is introduced starting with firms in the first tier. In this tier, each firm produces a different commodity, and thus has different information to insert in the traceability system. However, they face a similar problem of deciding whether to take a contract from the second-tier firm based on the revenues and costs of traceability. The first-tier firm producing the *ith* commodity has the following objective function.

$$\underset{\gamma_{1i}}{Max}\, \Pi_{1\mathrm{i}} = p_{1i}\gamma_{1i} - c_{1i}(\gamma_{1i}) \tag{1}$$

The first term denotes the total revenue from traceability; the second represents the costs of traceability for the first-tier firm producing the *ith* ingredient. Of course, in real transactions there are no contracts for just the provision of traceability. The choice of traceability can be seen as part of a larger contract where all other clauses of the contractual arrangement are held constant.

To supply traceable ingredients downstream, each second-tier firm must propose a contract to obtain traced commodities from the corresponding first-tier firm. Note that second-tier firms are simultaneously a principal and an agent. Again, each firm in the second tier produces a different ingredient, which may have a different value and require different traceability levels. Consider the case of the second-tier firm producing the *ith* ingredient, which is produced from the *ith* commodity obtained upstream. From Assumption 3 above, to provide a traceable ingredient to the third-tier firm, a second-tier firm must have traceability from a first-tier firm to which it offers a contract. The first-tier firm will only accept a contract if it gets at least its reservation utility, here assumed to be zero. Thus, the *ith* first-tier firm's participation constraint is given by

$$p_{1i}\gamma_{1i} \geq c_{1i}(\gamma_{1i}) \tag{2}$$

From this expression, the second-tier firm sets the premium per traceability level assuring participation from the first-tier firm. Note that in this model the first-tier firm takes a contract if the premium for traceability set by the second-tier firm corresponds to the average costs of traceability. To assure the first-tier firm provides the level of traceability (γ_{1i}^*) set in the contract, the *ith* second-tier firm sets the following payment scheme.

$$p_{1i} = \begin{cases} \dfrac{c_{1i}(\gamma_{1i})}{\gamma_{1i}} & \text{if } \gamma_{1i} \geq \gamma_{1i}^* \\ 0 & \text{if } \gamma_{1i} < \gamma_{1i}^* \end{cases} \tag{3}$$

This payment scheme implies that the participation constraint binds, which is the case given Assumption 6 on full and complete information. The upper term in the curled bracket is derived from the participation constraint in Equation (2) and states that the *ith* first-tier firm will receive p_{1i} for providing the contracted level of traceability γ_{1i}^*. The second term corresponds to the incentive compatibility constraint and can be seen as a punishment for breaking the contractual level of traceability. Note that the second-tier firm has no incentive to pay more than the average costs of traceability, whereas the first-tier firm will get no benefit from providing more than the contracted level of traceability. Thus, the payment scheme in Equation (3) provides incentives for the provision of an efficient level of traceability.

The problem of the second-tier firm producing the *ith* ingredient is formulated as

$$\begin{aligned}
\underset{\gamma_{2i}}{Max}\, \Pi_{2\mathrm{i}} &= p_{2i}\gamma_{2i} - p_{1i}\gamma_{1i} - c_{2i}(\gamma_{2i}) \\
\text{s.t.: } \gamma_{2i} &= \gamma_{2i}(\gamma_{1i}) \\
p_{1i} &\leq \frac{c_{1i}(\gamma_{1i})}{\gamma_{1i}}
\end{aligned} \tag{4}$$

where p_{2i} denotes the compensation paid by the third-tier firm for the level of traceability γ_{2i}, and c_{2i} are the costs of traceability incurred by the second-tier firm. Second-tier firms are conditioned in two ways. The first is through the chain relationship and dependency constraint associated with traceability levels. This constraint is similar to those used in vertical models to assure a flow of goods across vertically linked firms (Royer, 1998). The second is by the participation and incentive compatibility constraints that are used to assure first-tier firms provide the levels of traceability agreed to in their respective contracts.

Given that the participation constraint binds under the payment scheme in Equation (3), the problem of the second-tier firm can be reformulated substituting the constraints into the objective function:

$$\underset{\gamma_{1i}}{Max}\, \Pi_{2\mathrm{i}} = p_{2i}\gamma_{2i}(\gamma_{1i}) - c_{1i}(\gamma_{1i}) - c_{2i}(\gamma_{2i}(\gamma_{1i})) \tag{5}$$

Following Dickinson and Bailey (2002), assume that consumers are willing to pay a premium (p_3) for traceability. To assure this information to consumers, the downstream firm must offer a contract for the provision of traceability to at least one ingredient producer in the second tier. The traceability level offered by the third-tier firm depends on a vector of traceability levels across inputs from the second tier. Recall that though the number of traceable links denotes the depth of the system and the number of ingredients traced its breadth, the level of traceability is associated with the precision of information in the traceability system. From Assumption 7, along with consumer willingness to pay, the third-tier firm demands traceability upstream to mitigate liability losses associated with food safety hazards. The different ingredients may have different probabilities of causing a hazard. For instance, cheese may have a higher risk of contamination than flour. Thus, heterogeneity between firms in the tier comes from the fact they produce different ingredients and it is unlikely that the costs of traceability are identical across products. Each firm in the same tier is distinct and may be required to provide different levels of traceability to the third-tier firm. This point is well documented in Golan et al. (2004) who find different traceability systems across food industries. In this model, rather than operating in isolation each industry is linked downstream through supplying the same buyer.

Suppose that the third-tier firm offers a contract to the second-tier firm producing the *ith* ingredient. This firm will only take a contract if it gets its reservation utility, again assumed to be zero, i.e.,

$$p_{2i}\gamma_{2i} \geq p_{1i}\gamma_{1i} + c_{2i}(\gamma_{2i}) \tag{6}$$

This expression says that unless the third-tier firm offers a contract for traceability to the *ith* second-tier firm such that its revenue at least compensates for costs of traceability incurred by the second-tier firm, a contract will not be accepted. From Equation (6), it can be seen that compensation to second-tier firms per level of traceability must equal at least the average costs. Additionally, to ensure that the contractual level of traceability (γ_{2i}^*) is provided by the second-tier firm producing the *ith* ingredient, the third-tier firm sets the following payment scheme.

$$p_{2i} = \begin{cases} \dfrac{p_{1i}\gamma_{1i} + c_{2i}(\gamma_{2i})}{\gamma_2} & \text{if } \gamma_{2i} \geq \gamma_{2i}^* \\ 0 & \text{if } \gamma_{2i} < \gamma_{2i}^* \end{cases} \tag{7}$$

As in the case of the contract offered by second-tier firms upstream, the first condition is the participation constraint derived from Equation (6); the second is the incentive compatibility constraint ensuring the second-tier firm will offer the traceability level set in the contract or have a zero premium. Again note that from Assumption 6, this payment scheme assures an efficient level of traceability because the third-tier firm does not have to pay more than the average cost of traceability and the second-tier firm is not paid above its costs for providing an additional level of traceability.

The problem of the third-tier firm is quite complex, as this firm must design a set of contracts to obtain traceability from up to n different firms in the second tier. This denotes the breadth of the system, which in this model is the number of ingredients. Furthermore, given Assumption 3 on the chain relationship between traceability levels, the third-tier firm is further constrained by the provision of traceability by first-tier firms to second-tier firms. Let γ_1 and γ_2 represent column vectors with n elements each corresponding to traceability levels from each firm in the first and second tiers, respectively. The objective function of the third-tier firm is

$$\begin{aligned} \underset{\gamma_3}{Max}\, \mathrm{E}[\Pi_3] &= p_3\gamma_3 - \sum_{i=1}^{n} p_{2i}\gamma_{2i} - c_3(\gamma_3) - \psi L(\gamma_3) \\ \text{s.t.: } \gamma_3 &= \gamma_3(\Gamma_2) \\ \gamma_{21} &= \gamma_{21}(\gamma_{11}), \ldots, \gamma_{2n} = \gamma_{2n}(\gamma_{1n}) \\ \Gamma_1 &\geq 0 \\ p_{21} &\geq \frac{p_{11}\gamma_{11} + c_{21}(\gamma_{21})}{\gamma_{11}}, \ldots, p_{2n} \geq \frac{p_{1n}\gamma_{1n} + c_{2n}(\gamma_{2n})}{\gamma_{1n}} \\ p_{11} &\geq \frac{c_{11}(\gamma_{11})}{\gamma_{11}}, \ldots, p_{1n} \geq \frac{c_{1n}(\gamma_{1n})}{\gamma_{1n}} \end{aligned} \tag{8}$$

In this expression, p_3 is the premium paid to the third-tier firm for providing traceability, the remaining notation is as defined above. These are expected total profits because the expression includes a probability of a food safety event. The third-tier firm has to consider a larger number of constraints. The participation constraints bind by the payment schemes in Equations (3) and (7) specified above. Thus, we can sequentially substitute the constraints for the first-tier firm into the corresponding second-tier firm's problem and then into the third-tier firm's problem, yielding

$$\begin{aligned} \underset{\Gamma_1}{Max}\, \Pi_3 = {} & p_3\gamma_3(\gamma_{21}(\gamma_{11}), \ldots, \gamma_{2n}(\gamma_{1n})) - \left[\sum_{i=1}^{n} c_{1i}(\gamma_{1i}) + \sum_{i=1}^{n} c_{2i}(\gamma_{2i}(\gamma_{1i}))\right] \\ & - c_3(\gamma_3(\gamma_{21}(\gamma_{11}), \ldots, \gamma_{2n}(\gamma_{1n}))) - \psi L(\gamma_3(\gamma_{21}(\gamma_{11}), \ldots, \gamma_{2n}(\gamma_{1n}))) \\ \text{s.t.: } & \Gamma_1 \geq 0 \end{aligned} \tag{9}$$

This problem has n necessary conditions, leading to n optimal levels of traceability for the commodities produced by first-tier firms. Because of the functional relationship between up- and downstream traceability levels and full information, the third-tier firm sets the level of traceability for each ingredient upstream. This defines the depth (through the tiers of the system), breadth (whether ingredients have traceability), and precision (the optimal level of traceability) for the system. Given space limitations, only the necessary condition for setting the level of traceability provided by the first-tier firm producing the *ith* commodity that maximizes the first-tier firm's expected profits is shown.

$$\frac{\partial \Pi_3}{\partial \gamma_{1i}} = 0 \Rightarrow p_3 \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{2i}} \gamma'_{2i} - \psi L'(\bullet) \gamma'_{2i} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{2i}} = c'_{1i} + c'_{2i} \gamma'_{2i} + c'_3(\bullet) \gamma'_{2i} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{2i}} \quad (10)$$

The left-hand side of the second equality shows the indirect marginal benefits of having traceability from the *ith* firm. There are two marginal benefits: The first is the effect on an additional premium and the second is the reduction in expected marginal loss due to food safety hazards. Although the expected marginal loss term has a negative sign, recall that by Assumption 7 the value of the liability loss decreases with traceability. The right-hand side shows the aggregate marginal costs of traceability borne by each firm in each tier involved in the production of the *ith* ingredient. The contracted levels of traceability for the corresponding second-tier firms and the third-tier firm are derived using the constraints of the problem of the third-tier firm and the levels of traceability for each first-tier firm. Then, using the participation constraints, the premiums offered in the contracts proposed to second- and first-tier firms are also obtained. This problem has $2(n+n)+1$ endogenous variables and two exogenous variables (the premium for traceability paid by consumers and the probability of a food safety hazard).

To assure that the necessary conditions implicitly define the optimal levels of traceability that maximize the expected profit function, the second-order condition must be checked. This involves evaluation of the Hessian matrix for the profit maximization as shown below.

$$H = \begin{bmatrix} \partial^2 \Pi_3/\partial \gamma_{11}^2 & \cdots & \partial^2 \Pi_3/\partial \gamma_{11}\partial \gamma_{1i} & \cdots & \partial^2 \Pi_3/\partial \gamma_{11}\partial \gamma_{1n} \\ \vdots & \ddots & \vdots & \cdots & \vdots \\ \partial^2 \Pi_3/\partial \gamma_{11} & \cdots & \partial^2 \Pi_3/\partial \gamma_{1i}^2 & \cdots & \partial^2 \Pi_3/\partial \gamma_{1i}\partial \gamma_{1n} \\ \vdots & \cdots & \vdots & \ddots & \vdots \\ \partial^2 \Pi_3/\partial \gamma_{11}\partial \gamma_{1n} & \cdots & \partial^2 \Pi_3/\partial \gamma_{1i}\partial \gamma_{1n} & \cdots & \partial^2 \Pi_3/\partial \gamma_{1n}^2 \end{bmatrix} \quad (11)$$

Because the expected profit function is concave, for the necessary conditions to define a maximum, the Hessian must be negative semidefinite; it will be if $(-1)^n |H_n| > 0$. An alternative way to assess whether the first-order conditions define a maximum of the profit function is to use the mathematical theorem relating the shape of the function to its extreme points. This theorem says that if a function is concave, then its extreme point is a maximum (Baldani, Bradfield, & Turner, 1996). Because the revenue from traceability is linear, the costs and the expected loss functions are convex (by Assumptions 5 and 7, respectively), and the traceability functions are linearly increasing, the profit function is concave. Thus, the first-order conditions implicitly define the optimal level of traceability that each first-tier firm must provide.

To examine whether traceability is feasible, we check border solutions looking at the Kuhn–Tucker conditions:

$$\begin{array}{lll} \gamma_{11} \geq 0, & \dfrac{\partial \Pi_3}{\partial \gamma_{11}} \leq 0 \ \text{ and } & \dfrac{\partial \Pi_3}{\partial \gamma_{11}} \gamma_{11} = 0 \\ \vdots & \vdots & \vdots \\ \gamma_{1n} \geq 0, & \dfrac{\partial \Pi_3}{\partial \gamma_{1n}} \leq 0 \ \text{ and } & \dfrac{\partial \Pi_3}{\partial \gamma_{1n}} \gamma_{1n} = 0 \end{array} \tag{12}$$

Each of these conditions must hold simultaneously. There will be a border solution for the provision of traceability from each first-tier firm if marginal profits to the third-tier firm decrease as traceability levels become positive. This occurs when the first Kuhn–Tucker condition binds and the second holds as a strict inequality. In this case, there is no traceability because the third-tier firm will not adopt traceability and no contracts are offered to firms in the first and second tiers. If at least one first-order condition binds, a positive level of traceability is provided for a limited number of ingredients and there will be partial adoption of traceability. Finally, if all the necessary conditions bind, there will be full traceability with every ingredient used in the production of the multi-ingredient product of the third-tier firm being traceable and every firm in the first and second tiers getting a contract to provide traceability.

4. RESULTS AND DISCUSSION

An important issue in the economics of traceability adoption is whether it is desirable and efficient to have full traceability. In the context of this study, full traceability is defined as having traceability from the first-tier in the food chain for every ingredient used by the third-tier firm producing the final output. The previous section discusses the conditions for no, partial, or full traceability in the general case. Here we illustrate our general results using the case of a supply chain for a product composed of three ingredients and focusing on the optimizing condition of the third-tier firm (i.e., $n = 3$, $\gamma_2 = \gamma_{21}, \gamma_{22}, \gamma_{23}$ and $\gamma_1 = \gamma_{11}, \gamma_{12}, \gamma_{13}$). This example is further used to illustrate horizontal and vertical network effects on the optimal level of information contracted for with first-tier firms. In our context, network effects are indirect and due to complementarities across levels of traceability for each ingredient. The results of this case study can be generalized to the n ingredient case above. However, the more ingredients are considered the larger are the computational requirements. Once the constraints are substituted into the model with three ingredients, the third-tier firm maximizes expected profits now defined as

$$\begin{aligned} \underset{\Gamma_1}{Max}\, \mathrm{E}[\Pi_3] =& p_3\gamma_3(\gamma_{21}(\gamma_{11}), \gamma_{22}(\gamma_{12}), \gamma_{23}(\gamma_{13})) - \left[\sum_{i=1}^{3} c_{1i}(\gamma_{1i}) + \sum_{i=1}^{3} c_{2i}(\gamma_{2i}(\gamma_{1i}))\right] \\ & - c_3(\gamma_3(\gamma_{21}(\gamma_{11}), \gamma_{22}(\gamma_{12}), \gamma_{23}(\gamma_{13}))) - \psi L(\gamma_3(\gamma_{21}(\gamma_{11}), \gamma_{22}(\gamma_{12}), \gamma_{23}(\gamma_{13}))) \\ \text{s.t.: } & \Gamma_1 \geq 0 \end{aligned} \tag{13}$$

The first-order necessary conditions for the maximization of expected profits for the third-tier firm are

$$\frac{\partial E[\Pi_3]}{\partial \gamma_{11}} = 0 \Rightarrow p_3 \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} \gamma'_{21} - \psi L'(\bullet)\gamma'_{21} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} = c'_{11} + c'_{21}\gamma'_{21} + c'_3(\bullet)\gamma'_{21} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} \tag{14}$$

$$\frac{\partial E[\Pi_3]}{\partial \gamma_{12}} = 0 \Rightarrow p_3 \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{22}} \gamma'_{22} - \psi L'(\bullet)\gamma'_{22} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{22}} = c'_{12} + c'_{22}\gamma'_{22} + c'_3(\bullet)\gamma'_{22} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{22}} \tag{15}$$

$$\frac{\partial E[\Pi_3]}{\partial \gamma_{13}} = 0 \Rightarrow p_3 \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{23}} \gamma'_{23} - \psi L'(\bullet)\gamma'_{23} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{23}} = c'_{13} + c'_{23}\gamma'_{23} + c'_3(\bullet)\gamma'_{23} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{23}} \tag{16}$$

Provided that the sufficient condition for maximum expected profits is met, solving Equations (14)–(16) simultaneously yields the optimal choices of traceability for each first-tier firm. These are a function of consumer willingness to pay for traceability (p_3) and the probability (ψ) of a food safety hazard. Once the optimal levels of traceability provided by each first-tier firm are set, the remaining endogenous variables are defined using the constraints for the third-tier firm. Table 1 summarizes the compensation and traceability levels that would be offered in the contracts between the third-tier and each second-tier firm, and between them and the first-tier firms.

Along with the objective function Equation (13), Table 1 shows that the higher the level of traceability for each ingredient, the higher the costs incurred by the third-tier firm. This leads to the question of whether this firm will choose to have no, partial, or full traceability.

Traceability is feasible if the third-tier firm offers a contract with the payment scheme in Equation (7) to at least one of the firms in the second tier, which, in turn, must offer a contract to the corresponding first-tier firm. As every ingredient is

TABLE 1. Traceability Levels and Premiums Along the Supply Chain

	Firms	Compensation	Traceability level
First-tier contracts	11	$p_{11} = \dfrac{c_{11}(\gamma_{11}(p_3,\psi))}{\gamma_{11}(p_3,\psi)}$	$\gamma_{11} = \gamma_{11}(p_3,\psi)$
	12	$p_{12} = \dfrac{c_{12}(\gamma_{12}(p_3,\psi))}{\gamma_{12}(p_3,\psi)}$	$\gamma_{12} = \gamma_{12}(p_3,\psi)$
	13	$p_{13} = \dfrac{c_{13}(\gamma_{13}(p_3,\psi))}{\gamma_{13}(p_3,\psi)}$	$\gamma_{13} = \gamma_{13}(p_3,\psi)$
Second-tier contracts	21	$p_{21} = \dfrac{c_{11}(\gamma_{11}(\bullet)) + c_{21}(\gamma_{21}(\gamma_{11}(\bullet)))}{\gamma_{21}(\gamma_{11}(\bullet))}$	$\gamma_{21} = \gamma_{21}(\gamma_{11}(p_3,\psi))$
	22	$p_{22} = \dfrac{c_{12}(\gamma_{12}(\bullet)) + c_{22}(\gamma_{22}(\gamma_{12}(\bullet)))}{\gamma_{22}(\gamma_{12}(\bullet))}$	$\gamma_{22} = \gamma_{22}(\gamma_{12}(p_3,\psi))$
	23	$p_{23} = \dfrac{c_{13}(\gamma_{13}(\bullet)) + c_{23}(\gamma_{23}(\gamma_{13}(\bullet)))}{\gamma_{23}(\gamma_{13}(\bullet))}$	$\gamma_{23} = \gamma_{23}(\gamma_{13}(p_3,\psi))$
Third-tier contracts	3	p_3	$\gamma_3 = \gamma_3(\gamma_{21}(\gamma_{11}(\bullet)), \gamma_{22}(\gamma_{12}(\bullet)), \gamma_{23}(\gamma_{13}(\bullet)))$

distinct with different production processes, they will have distinct traceability levels and premiums. Furthermore, as risks differ from one ingredient to another, their respective traceability levels will have different impacts on loss mitigation. Also, note that though additional levels of upstream traceability have an indirect impact on benefits, they directly affect costs. The following propositions are presented for this analysis. This discussion is based on the Kuhn–Tucker conditions.

$$\gamma_{1i} \geq 0, \ \frac{\partial E[\Pi_3]}{\partial \gamma_{1i}} \leq 0, \quad \text{and} \quad \frac{\partial E[\Pi_3]}{\partial \gamma_{1i}} \gamma_{1i} = 0, \quad i = 1, 2, 3 \tag{17}$$

Proposition 1: If the marginal costs of having traceability from every firm in the first-tier exceed the marginal benefits to the third-tier firm, then traceability is not implemented.

Traceability is not implemented if there are border solutions to each of the first-order conditions Equations (14)–(16). From the Kuhn–Tucker conditions in Equation (17), the third-tier firm has no incentive to adopt traceability if for each ingredient the marginal expected profits are decreasing as traceability becomes positive. In other words, traceability is not feasible if the sum of the premium paid by consumers and the marginal expected risk mitigation from having traceability does not cover its aggregate marginal costs along the supply chain.

Verbeke (2005) suggests that consumers may face an overload of information and be unable to understand the information provided by single-ingredient traceability systems. Consumers may find it even harder to use information provided by traceability systems for multi-ingredient foods, which may hinder willingness to pay for traceability in these products. It may also be harder to assess the food safety risks of each ingredient used in a recipe for a multi-ingredient food, leading to uncertainties about how traceability could mitigate those risks. These factors pose challenges for the voluntary implementation of any traceability in supply chains for multi-ingredient foods.

Proposition 2: Partial traceability will occur if, for at least one ingredient, the marginal benefits to the third-tier firm equal the marginal costs incurred along the food chain.

Suppose that for one of the three ingredients considered the marginal profits from traceability are zero. This occurs if for at least one of the first-order conditions Equations (14)–(16) there is a positive level of traceability or, in other words, there is an interior solution for the choice of traceability for at least one ingredient.

There are a number of reasons to have only partial traceability in multi-ingredient food supply chains. The third-tier firm may know from risk assessment reports that not all ingredients used in the recipe are equally hazardous. Because the costs of implementing traceability rise with the number of ingredients traced, firms may use these assessments to decide to have traceability for a limited number of ingredients. Additionally, although consumers may not be willing to pay for the costs of having traceability for all the ingredients in a food product, they may be aware that certain ingredients are more hazardous and be willing to pay a premium for having traceability for them.

Proposition 3: Full traceability will emerge if each of the three providers of ingredients to the third-tier firm and each of the first-tier firms supplying them accepts a contract for the provision of traceability downstream.

Full traceability requires the existence of an interior solution for each of the necessary conditions Equations (14)–(16). In terms of the Kuhn–Tucker conditions in Equation (17), this requires that for each ingredient the first equation holds as a strict inequality, whereas the remaining equations bind. In this case, and if the second-order condition is met, each first-tier firm receives a contract from the corresponding second-tier firm to provide the level of traceability that maximizes the third-tier firm's expected profits. Similarly, each second-tier firm receives a contract from the third-tier firm setting a level of traceability and an appropriate premium.

In some cases, the production of ingredients may involve processes that mingle the inputs to the ingredient in such a way that it becomes virtually impossible to maintain a flow of information. For example, milk from different producers may be mixed in a tank before arriving at a cheese processor making the linkage between a cheese output and the farm on which the milk originated less precise. In such cases, the level of traceability may have an upper bound. However, unless there is traceability from the farm it will be impossible to identify where an eventual food safety accident originated. In such cases, mitigation of food safety hazards may be a strong driver for full traceability and this may require new forms of organizing the supply chain.

Our traceability model enables the analysis of horizontal and vertical network effects. Horizontal effects relate to how changes in levels of traceability for one ingredient impact the levels of traceability of another ingredient. Vertical network effects occur when a change in the contract between two firms in the chain impacts a third firm contracting with only one of the initial firms. For example, there is a vertical network effect in the supply chain when a decision taken by the third-tier firm impacts the levels of traceability and premiums set in the contracts from second-tier to first-tier firms. Vertical effects can be derived from changes in premiums paid by consumers and/or in probabilities of food safety hazards.

To investigate the signs of horizontal and vertical effects, the objective function of the third-tier firm is altered to include only one choice variable. The traceability levels of the remaining ingredients become fixed and can be treated as parameters. Using this modification it is possible to evaluate how the optimal level of traceability specified in the contract offered to one of the first-tier firms changes with the level set for another firm. This is a horizontal network effect. Similarly, this formulation facilitates the interpretation of vertical network effects. Fixing the levels of traceability for ingredients 2 and 3, the expected profits of the third-tier firm become

$$\begin{aligned}\underset{\gamma_{11}}{Max}\,\Pi_3 = {} & p_3\gamma_3(\gamma_{21}(\gamma_{11});\gamma_{22}(\gamma_{12}),\gamma_{23}(\gamma_{13})) - \left[\sum_{i=1}^{3} c_{1i}(\gamma_{1i}) + \sum_{i=1}^{3} c_{2i}(\gamma_{2i}(\gamma_{1i}))\right] \\ & - c_3(\gamma_3(\gamma_{21}(\gamma_{11});\gamma_{22}(\gamma_{12}),\gamma_{23}(\gamma_{13}))) - \psi L(\gamma_3(\gamma_{21}(\gamma_{11});\gamma_{22}(\gamma_{12}),\gamma_{23}(\gamma_{13}))) \\ & \text{s.t.: } \gamma_{11},\gamma_{12},\gamma_{13} \geq 0 \end{aligned} \tag{18}$$

The semicolon separates the traceability levels for the second and third ingredients, which are now exogenous. The first-order necessary condition for maximization of expected profits is

$$\frac{\partial \Pi_3}{\partial \gamma_{11}} = 0 \Rightarrow p_3 \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} \gamma'_{21} - \psi L'(\bullet)\gamma'_{21} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} = c'_{11} + c'_{21}\gamma'_{21} + c'_3(\bullet)\gamma'_{21} \frac{\partial \gamma_3(\bullet)}{\partial \gamma_{21}} \tag{19}$$

This expression implicitly defines the optimal level of traceability for ingredient 1 from the first-tier as a function of the traceability levels on ingredients 2 and 3, the premium paid by consumers, and the probability of a food safety hazard, i.e., $\gamma_{11}^{*} = \gamma_{11}(\gamma_{12}, \gamma_{13}, p_3, \psi)$. The second-order condition for an optimum is

$$\frac{\partial^2 \Pi_3}{\gamma_{11}^2} = -\, c_{11}''11 - c_{21}''21(\gamma_{21}')^2 - c_{21}''\gamma_{21}'' + p_3\gamma_{21}''\gamma_3' + p_3(\gamma_{21}')^2\gamma_3' \\ -\psi L'\gamma_{21}''\gamma_3' - \psi L''(\gamma_{21}'\gamma_3')^2 - \psi L'(\gamma_{21}')^2\gamma_3'' - c_3'\gamma_{21}''\gamma_3' - c_3''(\gamma_{21}'\gamma_3')^2 - c_3'(\gamma_{21}')^2\gamma_3'' \tag{20}$$

Given Assumptions 3, 5, and 7 on the relation between traceability levels across the supply chain and the proprieties of the cost and liability loss functions, expression 19 can be simplified and signed as

$$\frac{\partial^2 \Pi_3}{\gamma_{11}^2} = -c_{11}'' - c_{21}''(\gamma_{21}')^2 - \psi L''(\gamma_{21}'\gamma_3')^2 - c_3''(\gamma_{21}'\gamma_3')^2 < 0 \tag{21}$$

Because the second-order condition for an optimum is verified by the implicit function theorem, the necessary condition defines the optimal level of traceability written in a contract with firm 1 in the first tier. From this expression, we can do comparative statics analysis. A horizontal network effect is a change in the level of traceability specified in the contract of one of the first-tier firms, when the level of traceability set for another firm changes. The result below presents the horizontal network effect of the impact of a change in the traceability level for firm 2 in the first tier on the traceability level set for firm 1 in the same tier.

$$\frac{\partial\gamma_{11}^{*}(\gamma_{12}, \gamma_{13}, p_3, \psi)}{\partial\gamma_{12}} = \frac{(p_3 - \psi L' - c')(\partial^2\gamma_3/\partial\gamma_{11}\partial\gamma_{12})\gamma_{21}'\gamma_{33}' - (\psi L'' + c_3'')\partial\gamma_3/\partial\gamma_{11}\partial\gamma_3/\partial\gamma_{12}}{-c_{11}'' - c_{21}''(\gamma_{21}')^2 - \psi L''(\gamma_{21}'\partial\gamma_3/\partial\gamma_{11})^2 - c_3''(\gamma_{21}'\partial\gamma_3/\partial\gamma_{11})^2} \tag{22}$$

The denominator is the second-order condition and is therefore negative. In the numerator, the term $\partial^2\gamma_3/\partial\gamma_{11}\partial\gamma_{12}$ is the cross-partial effect of changes in the traceability level from firm 1 in the first tier on the third-tier firm's traceability level, when the traceability levels set for the second firm in the first tier also changes. By Assumption 3 on the linearity of the traceability function, this cross-partial must be zero; thus the sign of the numerator solely depends on the second term. Recall that, by Assumptions 5 and 7, both the loss and cost functions are convex. Thus, the numerator is also negative and the horizontal network effect is positive. If the level of traceability in the contract for any first-tier firm changes, then the levels of traceability that other first-tier firms must provide will change in the same direction.

This is an unanticipated result. It would be expected that depending on whether traceability levels are substitutes, complements, or independent, horizontal network effects would be, respectively, negative, positive, or zero. The result shows that traceability levels across different ingredients are complementary. It suggests that in multi-ingredient supply chains traceability levels will not increase for one ingredient alone, which may indicate that the response to a requirement for more traceability will be somewhat inelastic.

The vertical effects in the model result from a change in the premium and in the probability of a food safety hazard. These are network effects because they indirectly impact the level of traceability (and corresponding premium) offered to the first-tier firm producing ingredient 1, when the third-tier firm is affected by exogenous factors.

The vertical network effect of changes in the premium paid by consumers is

$$\frac{\partial \gamma_{11}^{*}(\gamma_{12}, \gamma_{13}, p_3, \psi)}{\partial p_3} = -\frac{\gamma_{21}' \partial \gamma_3 / \partial \gamma_{11}}{-c_{11}'' - c_{21}''(\gamma_{21}')^2 - \psi L''(\gamma_{21}' \partial \gamma_3 / \partial \gamma_{11})^2 - c_3''(\gamma_{21}' \partial \gamma_3 / \partial \gamma_{11})^2} \tag{23}$$

In this expression, the denominator is the second-order condition, which by Equation (21) is negative. By Assumption 3 on the traceability functions, the numerator is positive therefore the sign of the fraction is negative. However, the sign of this result is the opposite of the sign of the fraction and thus is positive. This result suggests that the higher the premium for traceability consumers are willing to pay, the more traceability is required from upstream firms. Thus, this vertical network effect is positive. The importance of this result is that to have additional levels of traceability in a multi-ingredient supply chains it suffices to motivate the leader of the chain.

The impact of a change in the probability of a food safety hazard on the level of traceability demanded from the first-tier firm producing the ingredient is

$$\frac{\partial \gamma_{11}^{*}(\gamma_{12}, \gamma_{13}, p_3, \psi)}{\partial \psi} = \frac{L' \gamma_{21}' \partial \gamma_3 / \partial \gamma_{11}}{-c_{11}'' - c_{21}''(\gamma_{21}')^2 - \psi L''(\gamma_{21}' \partial \gamma_3 / \partial \gamma_{11})^2 - c_3''(\gamma_{21}' \partial \gamma_3 / \partial \gamma_{11})^2} \tag{24}$$

As in Expression 23, the denominator is the second-order condition and has a negative sign. To sign the numerator, recall that from Assumption 3 the traceability functions are increasing in levels of traceability, whereas from Assumption 7 the loss function is decreasing, thus the sign of the numerator is also negative. Because two negatives become a positive, this vertical network effect is also positive. Thus, more precise traceability information is expected from each ingredient as the probability of a food safety hazard in a multi-ingredient product increases and to the extent that traceability mitigates the ex-post consequences of these hazards.

5. CONCLUSIONS AND FUTURE RESEARCH

We present a formal network model to analyze interfirm voluntary traceability systems for multi-ingredient foods. Its formulation draws on vertical control and agency theories to analyze traceability adoption along a multi-ingredient food chain as a coordination and institutional problem. The model is used to analyze traceability adoption in a supply chain with three tiers producing a final output composed of n ingredients. The third-tier firm contracts for traceability from upstream firms in response to consumer willingness to pay and/or the opportunity to mitigate food safety losses. To implement traceability this firm must take into account the costs incurred by each firm in the supply chain. The model also takes the important steps of defining traceability as a continuum of information rather than a yes or no decision and recognizing possible heterogeneity in traceability needs across the depth (tiers), breadth (number of ingredients), and precision of information required in multi-ingredient supply chains.

Full traceability is defined as the existence of a vertical and downstream flow of information from every firm in the first tier, through second-tier firms to a third-tier firm selling a multi-ingredient product to consumers. Full traceability is feasible if the marginal benefits of having traceability for each ingredient outweigh the marginal costs incurred by each firm in the food chain. Partial traceability adoption, in which the third-tier firm only contracts for traceability on a limited number of ingredients, may result in considerable savings and responds to the fact that some of the ingredients composing a multi-ingredient food may have very limited probabilities of food safety hazards or enter into the final product in small proportions, resulting in lower benefits than costs from traceability.

Our model is suited to investigate both horizontal and vertical network effects. The analysis suggests that the horizontal network effects of traceability are always positive, implying that traceability levels are complements across the ingredients composing the output of the third-tier firm. Vertical network effects result from changes in traceability premiums paid by consumers to the third-tier firm and in the probabilities of food safety hazards. Vertical effects are positive if consumers' willingness to pay for traceability increases or the probabilities of food safety hazards increase.

A possible extension of our work would consider different representations of multi-ingredient supply chains. Simulations may provide additional insights into how incentives for partial and full traceability impact its adoption and the extent of network effects. Another approach to future research is to explore the parameterization of the probabilities of food safety hazards for each ingredient to analyze criteria for the decision of which ingredients to trace in the case of partial traceability adoption.

ACKNOWLEDGMENTS

This paper is part of Diogo Souza-Monteiro's Ph.D. thesis at the University of Massachusetts-Amherst. This research was supported by a doctoral fellowship from the Portuguese Foundation for Science and Technology (FCT) and by a USDA Cooperative State Research, Education, and Extension Service (CSREES) Special Grant to the Food Marketing Policy Center, University of Connecticut and by subcontract at the University of Massachusetts Amherst. The authors would like to thank very helpful comments from two reviewers, the participants at the 7th International Conference in International Chains and Networks, and a seminar at the University of Reading (UK) where earlier versions of this paper were presented. Reamining errors are the author' sole responsibility.

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